R-3604/2-AF

A New View of Weapon System Reliability and Maintainability

J. R. Gebman, D. W. McIver, H. L. Shulman

RAND

PROJECT AIR FORCE

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R-3604/2-AF A New View of Weapon System Reliability and Maintainability. J. R. Gebman, D. W. McIver, H. L. Shulman. January 1989.

This report presents a new approach for evaluating weapon system reliability and maintainability (R&M). The approach is based on the frequency with which faults in equipment degrade its ability to dependably deliver the full measure of its designed capabilities, and on the efficiency with which maintenance technicians remove faults, thereby restoring those capabilities. The authors identify promising opportunities for strengthening policies and procedures that could address these weaknesses and improve the overall management of R&M. To strengthen the support process, they make the following recommendations: (1) debrief pilots for all indications of faults, (2) track performance of avionics by equipment serial number, (3) share information about fault symptoms across maintenance levels (flight line to shop to depot), and (4) establish a special program to repair problem units or components. In addition to changes in the support process, the authors suggest some adjustments to the product improvement process and the acquisition process. (See also R-2908/1, N-2479, N-2499, N-2549.)

R-3604/2-AF

A New View of Weapon System Reliability and Maintainability

J. R. Gebman, D. W. McIver, H. L. Shulman

January 1989

A Project AIR FORCE report
prepared for the
United States Air Force

RAND

PREFACE

This report and its executive summary[1] integrate the final results of the project "Methods and Strategies for Improving Weapon System Reliability and Maintainability" conducted within RAND's Project AIR FORCE Resource Management Program. This project, sponsored by the Air Force Special Assistant for Reliability and Maintainability, examined tactical aircraft weapon systems.

BACKGROUND

The Air Force Special Assistant for Reliability and Maintainability and The RAND Corporation jointly developed the research plan that called for RAND to develop methods and strategies for improving weapon system reliability and maintainability (R&M). The sponsor and RAND agreed that the research should concentrate on tactical aircraft weapon systems and answer four questions:

- What kinds of payoffs or benefits can the Air Force expect from improved R&M?
- What kind of information currently contained in the Air Force Maintenance Data Collection (MDC) system is useful in the management of R&M?
- Are warranties an effective way to achieve better R&M?
- Can R&M be improved so that present and future U.S. fighter aircraft can deliver their full designed capability and maintain their margin of superiority in the face of a growing Soviet threat?

Answers to these questions and the supporting research are documented in:

> J. B. Abell, T. F. Kirkwood, R. L. Petruschell, and G. K. Smith, *The Cost and Performance Implications of Reliability Improvements in the F-16A/B Aircraft,* The RAND Corporation, N-2499-AF, March 1988.

> R. L. Petruschell, G. K. Smith, and T. F. Kirkwood, *Using the Air Force Maintenance Data Collection System Data to Identify*

[1]R-3604/1-AF.

Candidates for Improvement in Reliability and Maintainability, The RAND Corporation, N-2549-AF, March 1987.

J. P. Stucker and G. K. Smith, *Warranties for Weapons: Theory and Initial Assessment*, The RAND Corporation, N-2479-AF, April 1987.

J. R. Gebman and H. L. Shulman, with C. L. Batten, *A Strategy for Reforming Avionics Acquisition and Support*, The RAND Corporation, R-2908/2-AF, and *Executive Summary*, R-2908/1-AF, July 1988.

This last effort involved RAND's participation in special data collection and analysis for the F-15 C/D radar and the F-16 A/B radar. It was part of the Air Force's special program on F-15/F-16 Radar R&M Improvement. This special program was an outgrowth of a previous RAND project examining acquisition and support of aviation electronics (avionics) equipment.

SUMMARY

A new approach for viewing weapon system reliability and maintainability (R&M) is developed to illuminate the dominant R&M-related weaknesses in the Air Force's support, improvement, and acquisition of complex aircraft weapon systems. This report identifies promising opportunities for strengthening policies and procedures that could address these weaknesses and strengthen the overall management of R&M.

VIEWS OF RELIABILITY AND MAINTAINABILITY

In an earlier era it may have been appropriate to assume:

- If the operators don't complain about it, it isn't broken.
- If technicians can't duplicate alleged symptoms, it isn't broken.
- If it isn't broken, don't fix it.
- If it was broken, it's fixed as soon as the technicians decide that their actions have corrected the problem.

Although the complexities of mission essential military equipment have long defied such simple assumptions, the processes for acquiring, improving, and supporting complex systems continue to be driven by a set of measures that reinforces such a traditional view of R&M:

- Fully mission capable (FMC) rate: a measure of availability influenced largely by the pilot's subjective assessment of whether maintenance is needed;
- Mean time between failure (MTBF): a measure of reliability influenced mostly by whether technicians in the air base's shop execute a repair action;
- Mean time to repair (MTTR): a measure of how quickly the technicians on the flight line complete their work.

For highly visible failures, such as total failure of a major subsystem, such measures have been very meaningful. Meaningfulness breaks down, however, as the visible symptoms of failure become more obscure. With the continuing progress in the reliability of Air Force equipment, total failure is becoming increasingly rare. Today, the dominant problem with most equipment is not in totally lost performance, but is in the form of degraded performance.

For complex military equipment that provides combat-essential functions, we believe that the primary objective of R&M should be dependable delivery of the full measure of capabilities that the equipment is designed to deliver during its operational life.

Currently, the main threat to this objective comes from the type of performance-eroding fault that manifests symptoms only in particular situations. **Faults with such nonstationary observability are what we term Type B faults.** In contrast, a **Type A** fault is one where symptoms are observable no matter when or where the faulty item of equipment is operated or tested. Faults with such stationary observability have the kind of visibility that is needed for the traditional measures of R&M to be meaningful. However, equipments frequently afflicted with Type B faults require a new approach.

The new approach must deal with Type A and Type B faults and it must provide full visibility of the phenomena that determine R&M:

- **Fault initiation,**
- **Fault removal.**

To do this, we propose a view of R&M based upon:

- The **frequency with which new faults initiate** within equipment degrade the equipment's ability to dependably deliver the full measure of its designed capabilities.
- The **efficiency with which maintenance technicians remove faults**, thereby fully restoring designed capabilities.

To apply such considerations to an assessment of the R&M situation for a particular subsystem, the Air Force must be able to detect degradations in the performance of subsystems. In many instances, however, the Air Force lacks a direct and definitive capability to do this in the environment of routine operations. In such situations it must rely on indications gleaned from *both* pilot observations and symptoms detected by built-in tests (BIT). **Although an indication of difficulty from a single flight may not provide satisfactory evidence of a fault, it nonetheless needs to be documented and interpreted in the context of any related indications so important patterns may come to be recognized.**

THE SUPPORT PROCESS

The weapon system support process hinders technicians when they attempt to solve the extraordinarily difficult challenges presented by Type B faults because the current process:

- Provides too little information about avionics equipment performance during routine training flights,
- Fails to track avionics equipment performance by serial number,
- Inadequately integrates maintenance efforts and fault information across maintenance levels,
- Has inadequate capabilities to fix bad actor equipment.

To strengthen the support process we recommend debriefing pilots for all indications of faults, tracking performance of avionics by equipment serial number, sharing meaningful information about fault symptoms across maintenance levels (flight line to shop to depot), and establishing a special program to repair bad actor equipment.

Debrief Pilots for All Indications of Faults

Pilots need to share with *maintenance all indications of difficulties* that they and the BIT detect in the operation of complex weapon systems. They do not necessarily have to request maintenance every time they notice an indication, but they need to help maintenance track the performance history of complex subsystems.

Track Performance of Avionics by Equipment Serial Number

The performance-oriented tracking of complex subsystems that begins with pilot debriefs needs to continue with careful tracking of the subsystem's major components (both LRUs and SRUs), each of which has a unique serial number. Maintenance needs to keep accurate and updated records of which units are being circulated between the aircraft on the flight line and the shop and depot. This step is essential in helping the shop and depot track and identify the bad actors that are in greatest need of special attention.

Share Information About Fault Symptoms Across Maintenance Levels

Because the support process must use different tests and different pass/fail criteria at each maintenance level, sharing of meaningful information is especially important to verify that a maintenance action has addressed the same fault that was detected at the previous maintenance level. Such verification is especially needed when one is trying to rectify Type B faults. One beneficial way to improve information sharing would be to provide **test translation dictionaries** that would enable avionics technicians at one maintenance level to translate test results from another level into terms they would find useful for identifying bad actors.

Fix the Bad Actors

The next key element of the strategy for improving the support process is to repair the problem units or components so that they do not circulate between the support process and airplanes in degraded condition. To improve the efficiency of repairing bad actors, we recommend improved fault-isolation capabilities:

- Direct entry into test sequences for specific sections of lengthy ground avionics tests at both the base and depot,
- Loop testing for specific tests at both the base and depot,
- Special environmental and system bench capabilities for depots.

THE PRODUCT IMPROVEMENT PROCESS

The product improvement process can improve the reliability of the airborne equipment and increase the capability of the support process to remove faults efficiently. However, the process is limited as a tool for improving R&M because it

- Functions with inadequate information about dominant R&M problems,
- Fails to implement important improvements in a timely way.

To strengthen the responsiveness of the product improvement process to the root causes of a weapon system's dominant R&M problems, we propose a strategy that includes improving the flow of information from the field, increasing field engineering, and expediting improvements.

Improve Information from the Field

By applying the proposed new view of R&M to data already being acquired by the Air Force's existing maintenance data collection system, the Air Force can better identify areas where further R&M investigation is most needed.[1] Further improvement can come from monitoring and analyzing information from the previously proposed tracking of avionics performance by equipment serial number. Monitoring and analyzing problematic equipment and the reasons why the routine support process fails to correct their problems would make the product improvement process more aware of the dominant problems that are undermining fault isolation capabilities.

Increase Field Engineering

After the initial fielding of a weapon system, additional engineering is required for any system—especially sophisticated systems—to raise the maturity of its R&M characteristics to a suitably acceptable level. One way to do this is to get equipment contractor engineers more involved in understanding R&M from the viewpoint of the operators and the maintainers in the field. Although a capability to do performance-oriented tracking of equipment (especially after attempted repairs) will help, an actual presence in the field will be required to identify the root causes of dominant problems in the more complex subsystems.

Expedite Important Improvements

Problems could be identified earlier if acquisition programs routinely included more detailed data collection efforts by the contractors for the more complex subsystems. If the Air Force developed special procedures that would expedite management and would preprovision funds, critical improvements would be accelerated.

THE ACQUISITION PROCESS

The acquisition process represents the first line of defense for R&M. Weapon systems with better R&M characteristics would lessen the need for product improvement and lighten the support burden. How-

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[1]R. L. Petruschell, G. K. Smith, and T. F. Kirkwood, *Using the Air Force Maintenance Data Collection System Data to Identify Candidates for Improvement.*

ever, the effectiveness of the acquisition process, in terms of R&M, is limited because it

- Fails to use a meaningful set of management measures for R&M,
- Lacks a process for setting rationally based R&M goals,
- Does not assure delivery of needed levels of R&M.

To strengthen the role of the acquisition process in managing weapon system R&M, we recommend expanding awareness of R&M deficiencies, emphasizing fault removal efficiency, accelerating maturation of avionics, and reorganizing avionics development.

Expand Awareness of R&M Deficiencies. To improve the R&M record of the acquisition process, the government and industry organizations that are responsible for the development of new equipment need to expand their awareness of dominant R&M deficiencies.

Emphasize Fault Removal Efficiency. Improved awareness of the dominant problems is only an initial step that needs to be followed by a greater emphasis on fault removal efficiency in new developments.

Accelerate Maturation of Avionics. This element of the strategy for strengthening the acquisition process aims at more timely and fuller achievement of R&M goals. Although it emphasizes aviation electronics (avionics), because this class of equipment currently presents the greatest R&M challenges, the concept of maturation is applicable to the development of very complex systems.

Our general concept views the research and development of complex weapon systems as a process that has six basic phases:

- Technology development
- Critical component development
- Subassembly development
- Assembly/unit development
- Subsystem development
- Weapon system[2] integration development.

An orderly and efficient development program will invest just the right amount of time and resources in each phase; and although phases will overlap, they will be neither initiated nor terminated too early. During each basic phase, we use the concept of maturity as a qualitative gauge of the status of development efforts.

Whether one is initiating or terminating a phase, the decision should be based on scientifically accumulated evidence of progress and an

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[2]Including the ground support equipment peculiar to that weapon system.

objective assessment of the likelihood that lingering difficulties can be resolved before the next phase gets too far along.

Throughout the development process, there is pressure to initiate the next basic phase sooner rather than later. Even when done too soon, development programs often survive, although R&M characteristics may suffer. Coping with the pressures during the latter phases has been the chief consideration of RAND's recent avionics research, which has yielded a proposal that is a form of the general concept of maturation that we call maturational development.[3] To implement this concept for subsystem and weapon system integration development, the Air Force needs a formal period in the acquisition process in which development programs are required to set aside time and resources for:

- Measuring operational experience, organizing and recording R&M-related data, interpreting the data, and drawing conclusions about the causes of the problems that are responsible for any R&M shortfalls.
- Correcting R&M deficiencies before transfer of program management responsibility to the Air Force Logistics Command.

We see a formal maturational development phase as most beneficial for three classes of complex combat-essential avionics subsystems:

- New subsystems that are just beginning development,
- Already fielded subsystems that are being modified to improve their functional performance,
- Already fielded subsystems where improvements in R&M would substantially narrow the gap between designed and operationally available performance.

The cost to retrofit R&M improvements can be quite high. Maturational development offers the largest benefit-to-cost ratio when aimed at new avionics subsystems that are just beginning development (Phase V of the development of a weapon system). In such cases, it should occur *before high-rate production* to avoid high retrofit costs.[4]

Reorganize Avionics Development. This final element aims at reducing the R&M-related development problems that occur

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[3]Gebman, Shulman, and Batten, 1988.

[4]Approaches that would provide the time to incorporate a maturational development phase include: (1) defer the onset of high rate production, and (2) start full-scale engineering development early. The Air Force's System Program Office for the Advanced Tactical Fighter is working towards implementing a combination of such approaches.

throughout weapon system development. We propose a reorganization of avionics development responsibilities that has two goals:

- Expediting the maturation and application of new technologies by improving government and industry sponsored R&D during critical component development, subassembly development, and assembly/unit development.[5]
- Institutionalizing maturational development during subsystem and weapon system integration development.

Ideally, subsystem development (Phase V) would start far enough ahead of weapon system integration development (Phase VI) to allow a maturational development effort to be underway before Phase VI begins. Although a Phase V application of maturational development would require hosting the subsystem on a different weapon system for the gathering of operational experience, the advantage of early development of critical subsystems is that design improvements can be incorporated before high rate production starts for the new host weapon system.

Such reorganization and the attendant increased role for the government in avionics development will increase the cost of acquiring avionics equipment, at least initially. Moreover, elements of the overall strategy for strengthening the support process, the product improvement process, and other aspects of the acquisition will also increase costs. However, the extent of weapon system R&M improvement will determine reduction in total lifecycle costs. Moreover, improved R&M management will increase the readiness of equipment to deliver the full measure of capabilities that it is designed to deliver, especially in combat.

[5]See Gebman, Shulman, and Batten, 1988, for details.

ACKNOWLEDGMENTS

Throughout our efforts, we have received continued assistance from Brigadier General Frank Goodell, the Air Force Special Assistant for Reliability and Maintainability, his staff, other elements of Headquarters United States Air Force, Headquarters Tactical Air Command, Headquarters United States Air Forces Europe, Warner-Robins Air Logistics Center, Ogden Air Logistics Center, the F-15 System Program Office, the F-16 System Program Office, and the Strike Systems Program Office.

In particular we are indebted to Lieutenant Colonel Paul Cunningham, USAF, Captain Glen Titus, USAF, and Phil Stone of Headquarters, TAC, for their advice and support; to Major Louis Medal, USAF; and to Major Paul J. Wolf, USAF. We are also indebted to Lieutenant Colonel James Masters, USAF, AF/LEXY, and T. J. O'Malley, Randall M. King, Lauretta Burke, and Virginia Mattern of the Logistics Management Institute; to Victor J. Presutti, Jr., Captain Mindy Grant, USAF, Michael Niklas, Leonard Kramer, and Donald Keaton of the Air Force Logistics Command; and to our RAND colleagues, Joseph Large, Donald Emerson, Milton Kamins, and Robert Paulson.

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During the 1984–1985 special data collection and analysis efforts on the F-15 and F-16 radars, we especially benefited from the assistance of Major Rodney Fisher and Robert Benitez, who were the program managers for the F-15/F-16 Radar Reliability and Maintainability Improvement Program data collection and analysis phase. This phase was administered by the Aeronautical Systems Division Strike Systems Program Office, which received engineering support from Lieutenant Dale Evers and Robert Reed of the Air Force Acquisition Logistics Center, and program technical direction support from Gary Munoz and Gene Swenson of Support Systems Associates, Inc. Charles Spruck led the Hughes Aircraft Radar Systems Group data collection and analysis for the F-15 radar, and Roy Pyle led the Westinghouse Defense and

Electronics Center data collection and analysis for the F-16 radar. William McAllister led the group providing assistance from McDonnell Douglas, the prime contractor for the F-15; James Ross led the group providing assistance from General Dynamics, the prime contractor for the F-16. Participating F-15 units were the 1st Tactical Fighter Wing (TFW) at Langley AFB, Virginia, and the 36th TFW at Bitburg Air Base, FRG; participating F-16 units were the 50th TFW at Hahn Air Base, FRG, and the 388th TFW at Hill AFB, Utah.

RAND's Project AIR FORCE Resource Management Program, which was directed by Michael Rich and then Charles Kelley, provided continuing support, guidance, and encouragement.

Finally, we wish to thank Morton G. Berman and Martin Goldsmith for their thoughtful and thorough reviews.

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

AFB	Air Force Base
AFLC	Air Force Logistics Command
AFSC	Air Force Systems Command
AIS	Avionics Intermediate Shop
ASD	Aeronautical Systems Division
ATF	Advanced Tactical Fighter
BIT	Built-In Test
CND	Could Not Duplicate
ECM	Electronic Counter Measures
ECS	Environmental Cooling System
FMC	Fully Mission Capable
FSED	Full-Scale Engineering Development
HUD	Head-Up Display
INS	Inertial Navigation System
IOC	Initial Operational Capability
LPRF	Low Power Radio Frequency
LRU	Line Replaceable Unit
MTBF	Mean Time between Failures
MTBI	Mean Time between Indications of Faults
MTBR	Mean Time between Removals
PC	Personal Computer
PMD	Program Management Direction
PMRT	Program Management Responsibility Transfer
PORTER	Performance Oriented Tracking of Equipment Repair
R&M	Reliability and Maintainability
SMS	Stores Management System
SPO	System Program Office
SRU	Shop Replaceable Unit
SSAI	Support Systems Associates, Inc.
TEWS	Tactical Electronic Warfare System
TFW	Tactical Fighter Wing
VHSIC	Very High Speed Integrated Circuits

I. INTRODUCTION

Although the Air Force and industry deserve much credit for improving reliability and maintainability (R&M) in aircraft weapon systems, there is a major gap in the current emphasis, a consequence of reliance on measures that display only an incomplete picture of the R&M landscape. Important missing situations are problems that weaken weapon systems' ability to dependably deliver all of their designed performance that could be essential in combat. These missing characteristics include situations in which:

- The pilot sees a symptom of a fault but does not report it to maintenance.
- The pilot reports a symptom as a discrepancy deserving the attention of maintenance technicians, but the flight line technicians do not remove a line replaceable unit (LRU) from the airplane because they could not duplicate (CND) symptoms of the fault.
- The airplane's Built-In-Test (BIT) detects a fault during a flight, but flight line technicians do not remove an LRU from the aircraft because they reran the BIT test and it failed to detect the fault, and the technicians could not duplicate symptoms of the fault.
- Flight line technicians remove an LRU from an airplane and send it to the avionics shop, but the shop technicians find that the LRU bench checks serviceable (BCS) when they test it because their tests failed to detect symptoms of the fault.
- Shop technicians remove a shop replaceable unit (SRU) from an LRU and send it to the depot repair center, but the depot technicians find that the SRU retests OK (RETOK) when they test it because their tests failed to detect symptoms of the fault.

By failing to reflect such situations, the traditional view of R&M limits management's awareness of the overall R&M picture. Such partial awareness results in insufficient capabilities to fully support the designed capabilities of mission-essential equipment.

Although the complexities of mission-essential military equipment have long defied the simplifying assumptions upon which the traditional view has stood, the processes for acquiring, improving, and supporting complex systems continue to be driven by a set of measures[1] that reinforces a traditional view of R&M. For highly visible failures—for example, total failure of a major subsystem—such measures have been very meaningful. However, the complexities of modern equipment have caused visible symptoms of failure to become more obscure.

DATA SOURCES

This research is based on detailed examinations of one particular aircraft weapon system, the F-16 A/B, and on in-depth examinations of two critical radars, the APG-66 on the F-16 A/B and the APG-63 on the F-15 C/D. Although this study uses data currently available from the Air Force MDC system, important aspects of the new view of R&M are more fully illustrated by data that are available at present only by special means. Such data were collected as part of the F-15/F-16 Radar R&M Improvement Program:

- Data on the F-16's APG 66 radar were collected from 150 F-16s monitored during a six-month period (June to December 1984) at Hill AFB and Hahn Air Base and covered 16,077 flights and the resulting maintenance at these bases and the depot.
- Data on the F-15's APG 63 radar were collected from 150 F-15s monitored during the same period at Langley AFB and Bitburg Air Base and covered 16,702 flights and the resulting radar maintenance at these bases and depot.

Contractor personnel interviewed pilots after maintenance debrief, documented all symptoms of faults observed by the pilot—including BIT detected symptoms—and documented maintenance on the flight line, in the shop, and at the depot. To collect these data, the radar contractors[2] and the weapon system prime contractors[3] deployed 72 people to the four air bases and the two depots for six months.

The Air Force conducted the F-15/F-16 Radar R&M Improvement Program in response to a recommendation from a RAND project that the commander of the Air Force Systems Command[4] had requested to analyze ways of improving avionics acquisition and support. That proj-

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[1]See Sec. II.

[2]Hughes Aircraft Radar Systems Group for the APG 63 and Westinghouse Defense Electronics Center for the APG 66.

[3]McDonnell Aircraft Company for the F-15 and General Dynamics for the F-16.

[4]Who then was General Alton D. Slay.

ect also helped the Air Force establish the data collection and analysis phase of that program.[5]

By continuing to assist that special Air Force program, the present project has been able to acquire crucial data and to explore specific means for implementing several methods described in this report. Such research has examined methods where implementation is most likely to be complicated by the need to alter long-established policies and procedures.

ORGANIZATION[6]

To help close the gap in the current emphasis on R&M, and to lay a basis for developing methods and a strategy for improving weapon system R&M, Sec. II presents a new approach to viewing R&M, which is used in subsequent sections to analyze the Air Force's management of weapon system R&M. Weaknesses and corresponding opportunities for improvement are found in three areas: the support process (Sec. III), the product improvement process (Sec. IV), and the acquisition process (Sec. V).[7] A comprehensive strategy is formed to strengthen the Air Force's ability to manage the R&M of its aircraft weapon systems. Section VI summarizes the recommended strategy and states our conclusions.

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[5]Gebman, Shulman, and Batten, 1988.

[6]The content and organization of this report closely parallel the project's final summary briefing presented to Air Force audiences during 1987.

[7]We take up the support process first because opportunities for improving it are important to strengthening product improvement and the acquisition process. Second, we take up the product improvement process because opportunities there are important to strengthening the acquisition process.

II. VIEWS OF RELIABILITY AND MAINTAINABILITY

The traditional view of R&M masks problems that weaken weapon systems' ability to deliver the full measure of their designed performance. To help assure the dependable delivery of mission-essential performance, we present a new approach to viewing R&M, describing why such an approach is needed, comparing the new view with the traditional view, and providing an example application. The example illustrates how the traditional incomplete picture can mask problems of potentially major consequence to the combat effectiveness of mission-essential equipment.

THE TRADITIONAL VIEW

The traditional view is a carryover from an earlier era when it may have been appropriate to assume:

- If the operators don't complain about it, it isn't broken.
- Even if they complain, if the technicians can't duplicate the alleged symptom, it isn't broken.[1]
- If it isn't broken, don't fix it.
- If it was broken, it's fixed as soon as the technicians decide that their actions have corrected the problem.[2]

This simple view assumes that the equipment is either broken or fixed and both conditions are easy to identify. Such a view leads to simple measures for characterizing R&M:

- Fully mission capable (FMC) rate: a measure of availability influenced largely by the pilot's subjective assessment of whether maintenance is needed;
- Mean time between failure (MTBF): a measure of reliability influenced mostly by whether technicians in the air base's shop find it appropriate to execute a repair action;

[1]Unless the reports persist, whereupon technicians will assume that something is broken.

[2]The technicians' judgment is questioned only if the operators (flight crews) request maintenance after one of the next three flights. Thus, if flight crews tolerate signs of degraded performance for more than three flights following a maintenance action, the current system implicitly assumes that the maintenance action was fully effective.

- Mean time to repair (MTTR): a measure of how quickly the technicians on the flight line complete their work.

Within the simple traditional view, this set of measures accounts for all possible conditions of the equipment. Unfortunately, the world of modern integrated avionics is not so simple. Some problems limit ability to detect symptoms of serious faults; and even when detected, some problems limit responses to such symptoms. These problems are masked by the limited vision of the traditional view.

Limited Capabilities to Detect Fault Symptoms

When equipment fails to deliver its full measure of designed performance, the underlying fault often causes a degradation in performance that is subtle and difficult to observe.

Many factors make it difficult for pilots and BITs to detect faults in modern avionics:

- Limited opportunities to exercise certain subsystems,
- Rare occurrences of total failures,
- Varying degrees of degradation,
- Intermittently observable symptoms,
- Incomplete and imperfect testing,
- Pilot workload.

Limited Opportunities to Exercise Certain Subsystems. Routine peacetime missions provide limited opportunities to exercise the full capabilities of certain combat-oriented subsystems, such as fire control radars, air-to-air weapon delivery systems, and electronic countermeasures (ECM) systems.

Rare Occurrences of Total Failures. Nowadays, reliability and versatility of equipment has grown to the point where equipment very rarely experiences total failure. Rather, it falls victim to faults that erode its performance superiority over potential enemy weapons. Indeed, graceful degradation of performance is the mode of failure that developers strive to achieve in their designs. However, that can be difficult for pilots to detect, especially when they cannot judge what level of performance the equipment was designed to deliver.[3]

Varying Degrees of Degradation. To further complicate matters, the degree of degradation may vary across the different

[3]A fire control radar is a classic example of equipment whose designed performance depends upon the situation of use. Target detection, for example, will occur at different ranges depending upon the target, its orientation relative to the radar, and the background clutter.

functions that a subsystem performs, with some functions rarely being executed during peacetime training missions. On such missions a pilot may see no symptoms whatsoever for combat-critical faults. Fortunately, modern subsystems have built-in tests that can monitor equipment performance and often detect symptoms of such faults. However, false alarms and other problems with some BIT systems, especially the early ones that were developed, have given BIT a spotty reputation that undermines its credibility with pilots and maintenance technicians.

Intermittently Observable Symptoms. The symptoms of degraded or failed performance may appear intermittently. Faults in sophisticated subsystems exhibit different symptoms depending on the operating mode and environment. In some, the equipment may function properly; in others, it may deliver only part of its designed performance; in yet others, it may totally fail.

Some faults manifest different symptoms in different operating environments. Equipments that rely on sensors (such as the antenna in a radar) for their primary source of information are designed to perform more or less well depending on the background environment in which the object is sensed and on the object's movement within that environment. If a fault has degraded the equipment's performance capabilities, it may fail to detect a target in a highly cluttered environment, whereas it might do fine in an uncluttered environment.

The operating environment can have another effect as well. Symptoms of some faults (such as mechanical flaws in connections) are triggered by such environmental changes as temperature, vibration, and deflection under high flight loads (e.g., pulling nine gs). A loosely soldered wire may manifest symptoms that the pilot can observe only while the aircraft is executing a high g maneuver. (Worse, maintenance technicians may not be able to observe its symptoms because of lack of an environmental test chamber.) To further complicate matters, the pilot may not know or remember all environmental conditions that may have influenced the manifestation of the fault's symptoms.

Testing Is Incomplete and Imperfect. Because of problems with relying only on pilot observation and judgment, maintenance technicians are depending more and more on BITs of circuits, not only in fire control radars but also in such subsystems as Electronic Countermeasure Equipment in which certain modes are used irregularly. Though technicians are becoming critically dependent on these tests of circuits, the tests have limitations: They are not comprehensive, many of them are not continuous, and most do not indicate the severity of a problem. Moreover, the symptoms of many faults occur intermittently or only in certain situations or environments, so the BITs can yield irregular indications of serious faults.

Neither BIT indications nor pilot observations provide the kind of accurate information that maintenance should have, *but both together are better than either alone.* Consequently, during peacetime it is necessary to consider all indications of problems, whether they be pilot observations or BIT indications.

Pilot Work Load. Although the pilot directly controls some functions by activating switches on the control panel, the throttle, and the stick, computers directly control other functions. In addition, the pilot often rapidly executes a series of functions (such as search, acquire, track, weapon release) while coping with a high workload and—in the case of fighter pilots—a physically exhausting series of maneuvers. Thus when symptoms of a fault arise, the pilot may not know the precise operating mode. Even if he does, he probably cannot subsequently identify the precise settings of all switches at the time the symptoms were observed.

Fire control systems offer further examples of equipment that presents special difficulties for maintenance technicians in detecting faults. For instance, pilots have no direct means of assessing whether the fire control radar is delivering the full range of its capability. Pilots do not use all of the radar's functions in every mission. The performance they do see is also a function of many factors, including where the pilot is looking and what he is looking at.

Limited Responses to Fault Symptoms

Uncertainty about the extent of performance degradations causes pilots and maintenance technicians to have problems determining their responses to symptoms of a fault. If a pilot lacks strong corroborating evidence that a subsystem is broken, he is reluctant to tell maintenance about BIT detected symptoms. He might also hesitate to share information about pilot-perceived symptoms unless there are strong signs that the equipment is broken. Such practices are part of a *pilot tradition that you don't ask maintenance technicians to fix something unless you are sure that it is broken.*

Similarly, technicians have been forced to adopt a *maintenance tradition* that *you don't replace an item of equipment unless you are sure that it is broken.* Technicians become certain that an item of equipment is broken only if it fails to pass one of the tests that they apply to it. For example, if the pilot reports that the equipment failed a BIT during a flight, the flight line technicians will run the BIT again on the ground to try to duplicate the BIT-detected symptom. If they can not duplicate (CND) a symptom on the flight line, or detect any other symptom(s) they usually will not replace any equipment. Likewise, shop technicians at an air base will not replace parts in a unit they are testing if the unit bench checks serviceable (BCS); that is, no symptoms of a fault were found. And at a depot, technicians will not replace parts in a unit if it retests OK (RETOK) when they run their tests.

Both the pilot and maintenance traditions have reasonable foundations. First, spare parts often are expensive and not always readily available. Second, even in the best of circumstances, the process of replacing an item of equipment may induce damage that is far worse than the original problem. These realities and traditions create pressures not only to discount but to dismiss information that indicates a fault whenever subsequent observations or tests fail to find symptoms.

Modern equipment, however, have been plagued by high CND, BCS, and RETOK rates, even though the equipment often has otherwise excellent scores in terms of the traditional measures of R&M: FMC, MTBF, and MTTR.[4] Although high rates for CND, BCS, and RETOK reflect much fruitless maintenance activity, the more serious concern is the combat preparedness of weapon systems that carry hard to fix faults for prolonged periods.

THE NEW VIEW

For complex military equipment that provides combat-essential functions, we believe that the primary objective of R&M needs to be the full and dependable delivery of the equipment's designed capabilities.[5]

Currently, the main threat to this objective comes from the type of performance-eroding fault that manifests symptoms only in certain situations. Faults with such nonstationary observability are what we

[4]Gebman, Shulman, and Batten, 1988. Unfortunately, faults have lingered in equipment for weeks and even months before finally being isolated and corrected. The F-15/F-16 Radar R&M Improvement Program documented this phenomenon with both the APG 63 and the APG 66.

[5]A contrary view holds that it is unreasonable to expect equipment to continue delivering designed levels of performance long after it has been introduced into service. However, the whole support process (including BIT and tests at air bases and depots) is based on the premise that it is reasonable to expect the support process to maintain designed levels of capability through the equipment's service life. An exception to this sometimes occurs, as with aircraft engines that may have limits placed on operational performance to prolong periods of operational service between maintenance. In the event of such derating, a fault would be defined relative to the derated level of performance rather than the designed level.

term *Type B* faults. A *Type A* fault is one where symptoms are observable no matter when or where the faulty item of equipment is operated or tested. Faults with such stationary observability have the kind of visibility that is needed for the traditional measures of R&M to be meaningful. Special data collection efforts suggest that the acquisition, product improvement, and support processes have come a long way in addressing Type A faults. Indeed, much of the current emphasis on improving weapon system R&M should contribute further to improving the situation with Type A faults. However, equipments frequently afflicted with Type B faults also need to be addressed, requiring a whole new approach to how we view R&M.

The new approach must deal with both Type A and Type B faults and it must provide full visibility of the two fundamental phenomena that determine R&M:

- Fault initiation,
- Fault removal.

To do this, we propose a view of R&M based upon a pair of considerations:

- The frequency with which new faults initiate within equipment, thereby degrading the equipment's ability to dependably deliver the full measure of its designed performance.
- The efficiency with which maintenance technicians remove faults, thereby restoring the equipment's full measure of designed performance.

To apply such considerations to an assessment of the R&M situation for a particular subsystem, the Air Force must be able to detect degradations in its performance. In many instances, however, the Air Force cannot do this in the environment of routine operations. Instead it must rely on indications gleaned from *both* pilot observations and BIT-detected symptoms. Although an indication of difficulty from a single flight may not provide satisfactory evidence of a fault, it nonetheless needs to be documented and interpreted in the context of any related indications for important patterns to be recognized.

When a pattern develops, it must be stopped as early as possible even though that may require extraordinary actions[6] by the support process. To minimize the cost and disruptions created by special actions, repetition of such patterns must be minimized by focusing the

[6]One example of extraordinary action is testing a unit on a special test bench (called a system bench or hot mock-up). Another example is enclosing a unit in an environmental chamber during testing.

product improvement process on rectifying their root causes. Likewise, to minimize the cost of product improvement efforts, the need for such improvements need to be minimized by actions during the acquisition process that cause new equipment and its support process to be designed to decrease susceptibility to repeated patterns of degraded performance.

TRADITIONAL AND NEW VIEWS COMPARED

The value of information added by the new view is illustrated by a set of six-month case histories compiled from the 1984 data collection phase of the F-15/F-16 Radar R&M Improvement Program. The case histories illustrate the radar R&M situation from several perspectives:

- For a radar subsystem,
  - Force-level view of subsystem experience,
  - Aircraft-level view of subsystem experience for a problem-plagued aircraft,
- For the most troublesome type of LRU in a radar subsystem,
  - Squadron-level view of experience with that type of LRU,
  - Aircraft-level view of experience with problem plagued LRUs of that type.

Views of Radar Subsystem Experience

Force-Level View. From a force-level perspective, Figs. 1 and 2 provide two views of R&M for each of two radars. Figure 1 summarizes radar experience for 150 aircraft assigned to two representative wings of F-15 C/D aircraft.[7] Figure 2 provides a similar summary for 150 aircraft assigned to two representative wings of F-16 A/B aircraft.[8]

The top bar in each figure portrays a traditional view based upon contractor calculated estimates for MTBF. The estimates, derived from the Air Force's standard MDC system, portray only part of the R&M situation. A richer view of the situation is depicted by the bottom three bars in each figure.

Although the mean flight hours between units failing shop tests is fairly close to the MTBF estimates, the average flying-hour intervals between pilot requests for maintenance were much shorter than those between failure of shop tests. The difference is caused by two kinds of problems: shortcomings in fault isolation efficiency and ill-founded

[7]The 1st TFW at Langley Air Force Base, Virginia, and the 36th TFW at Bitburg Air Base, FRG.

[8]The 50th TFW at Hahn Air Base, FRG, and the 388th TFW at Hill AFB, Utah.

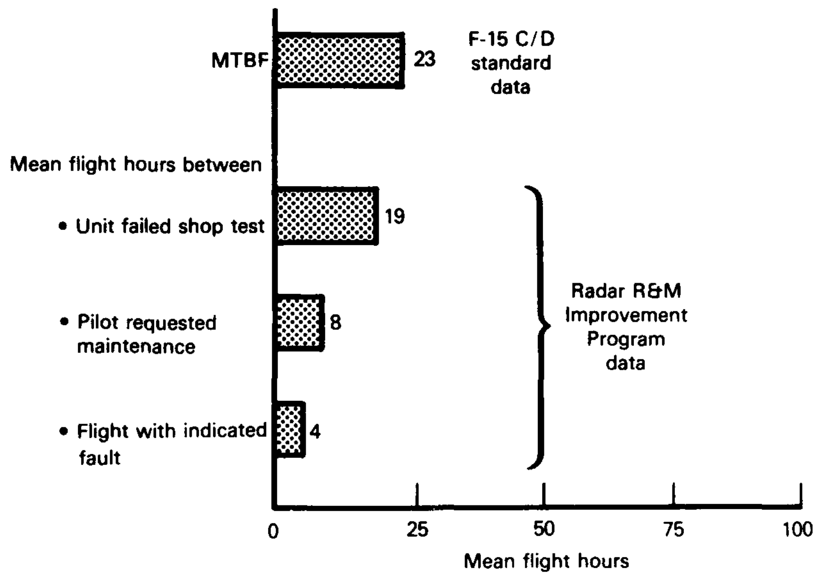

Fig. 1—Standard F-15 C/D data show a partial picture of radar R&M

requests for maintenance. The F-15/F-16 Radar R&M Improvement Program data collection and engineering analysis demonstrated that the dominant problem is fault isolation efficiency rather than pilot's demanding maintenance without a proper basis.[9] Indeed, as the bottom bars in Figs. 1 and 2 show, pilots are encountering flights with indications of faulty radar operation at average flying-hour intervals much shorter than the intervals between requests for maintenance. Pilots may be too tolerant of radar subsystems that are manifesting signs of performance less than the full designed capabilities of the equipment. A view from the aircraft level sheds some light on this possibility.

Aircraft-Level View. Figure 3 summarizes nearly two months of radar experience for an F-16A aircraft (number 0577) that had persisting radar problems throughout the six-month case history period. The portrayed experience includes pilot observed reports from the BIT-detected faults (col. 2) as well as the pilot's own independent observations and assessment of radar performance (col. 3). Column 4 ("radar op.") shows the pilot's net assessment of radar capability, as reported to the contractor data collectors, and col. 5 ("radar code") shows the

[9]See Gebman, Shulman, and Batten, 1988 for details.

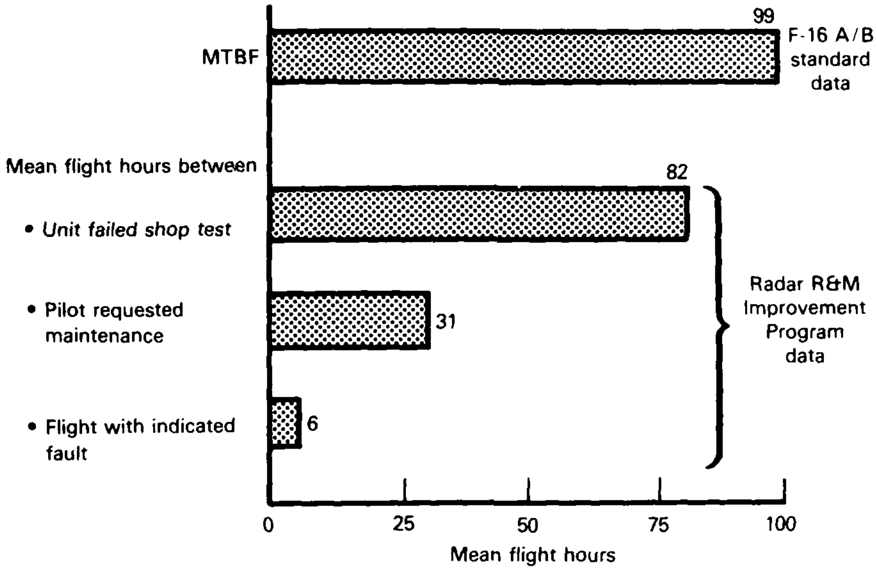

Fig. 2—Standard F-16 A/B data show a partial picture of radar R&M

equipment status code that the pilot reported to the maintenance debriefer. When a status code of 1 is reported, maintenance assumes that the subsystem does not need maintenance. A code 2 or a code 3 constitutes a pilot request for maintenance, with code 3 indicating a greater degree of urgency (fix before next flight).

This figure raises three major points:

1. Pilots do not request maintenance for every indication of a fault in the radar. A request for maintenance is influenced by many considerations including:
   - What does the airplane need to do on its next training flight?
   - Would the indicated fault affect the training value of the next flight?
   - What are the chances that the indicated fault was caused by microwave signals generated by something external to the aircraft?
   - What is the likelihood that technicians can duplicate the fault on the ground?
   - If the fault is duplicated, what are the chances that a replacement spare is available?

2. Standard data systems miss many indications of degraded radar performance because information about performance degradations is collected only when a pilot requests maintenance (flights in which returning pilots assign a Code 2 or Code 3 to the radar's performance). However, a history of degraded performance may be developing even when pilots are not requesting maintenance (Code 1).
3. Although the F-16's BITs are very reliable[10] compared with those of the F-15,[11] they nevertheless often fail to detect faults, especially Type B faults. Numbers in the second column of Fig. 3 refer to the specific BITs that the radar failed. Some faults—such as ones causing false targets and lock problems—may not be caught by BITs. Others—such as a faulty transmitter—are only sometimes caught by BITs. In Fig. 3, for example, the first BIT indication of a fault in the transmitter occurred on June 25, when tests 032 and 035 failed. Although the pilot also observed indications of a problem with false targets, he did not request maintenance. BIT indications of a fault in the transmitter occurred again on the next day, and the pilot requested maintenance. However, the radar specialist Could Not Duplicate the BIT failures reported by the pilot, and the technician did not remove the radar transmitter. The first flight the following day yielded no reports of any BIT failures, but the next flight did, and the BIT failures again pointed to a faulty transmitter. Moreover, the pilot assigned a Code 3 to the radar. Maintenance then removed the transmitter (XMTR) and sent it to the shop for different (and more detailed) testing and repair. The replacement transmitter appears to have operated as it should for the remaining five months because the BIT indicated no subsequent faults with the transmitter.

Unfortunately, F-16 number 0577 had experiences like those indicated in Fig. 3 during the entire six-month data collection effort. This airplane had more than its share of false target and target-lock-on difficulties. As Fig. 3 illustrates, there were many flights after which the pilot reported status code 1 even though there were signs of faulty

[10]This was determined by tracking the movement of LRUs from airplane to shop to airplane and monitoring BIT-detected faults. When the shop failed to fix a BIT-detectable fault, the trail of faults would follow the LRU to the next airplane. When the contractors subjected faults to special tests, they found faults. From this we conclude that when the F-16 radar's BIT detects a fault, it is a reliable indication that the system has a fault.

[11]Gebman, Shulman, and Batten, 1988, Sec. IV.

Date	BIT	Pilot Comments	Radar		LRU Removed
			Op.	Code	
June 20		Med PRF false targets in Air Mode		1	
25	032 035	MFL then screen flooded with false targets – Recycled and worked OK MFL at touchdown	OK	1	
26	057 035 032 048		Inpp	2	(CND)
27		Very few returns/would not lock on to any tgts use mostly A/A. No returns in AGR.	OK	1	
27	035 032 340 048	RDR inop – no returns. Failed 5 min. after T.O. only used A/A mode	Inop	3	XMTR 0763
28		False targets	Degrd	2	(CND)
July 10		ECM pods used. –lot of false tgts and chevrons. ACM and slewable trouble locking	Degrd	1	
10		False tgts and chevrons. Radar good	OK	1	
11	055		OK	1	
13		False targets/would not hold lock. O band noise bar missing	Degrd	2	(CND)
13		Numerous false targets			
24		Radar slow to lock on – had some false targets and chevrons	Degrd	1	
29		Rdr w/n lock until 17-18 miles-m/then break, relock and worked OK	OK	1	
30		Had lots of false targets	Degrd	1	
31		Numerous false tgts throughout flight	Degrd	1	
2		Radar cursors were stuck on	OK	3	
2		Numerous false targets	Degrd	1	
6	001		OK	1	

Fig. 3—Performance of radar in F-16 number 0577, June 20 through August 6, 1984

operation and even though, at times, the pilot's net assessment was that the radar subsystem was degraded (col. 4). This degraded condition remains essentially invisible to the measures used to support the traditional view of R&M because the only event in Fig. 3 that the traditional view could recognize would be the replacement of the transmitter on June 27. The new view strives to portray the full situation: The radar was struggling to deliver its designed capabilities for more than two months of operations. However, these problems were rarely brought to the attention of maintenance. Moreover, the radar contractor would never have known about these problems if its personnel had not been present to debrief the pilots.

Because these problems often cannot be duplicated on the ground, maintenance technicians will often assign a "CND" to the problem and wait to see what the next pilot does. The data show that the next pilot often chooses not to request maintenance, and maintenance personnel therefore often do not realize that the radar is still experiencing problems.

The pilot's net assessments in Fig. 3 are not without shortcomings, however. A major limitation is that the pilot cannot keep an eye on all aspects of radar operation all of the time. The ability of BIT to test and monitor the performance of a radar subsystem and the individual LRUs in that subsystem is an important source of further information about the status of equipment. It is a key source of information for the new view, as the following examples illustrate.

Views of Experience with a Troublesome Type of LRU

The LRU, the low power radio frequency (LPRF) unit, was found to be the dominant R&M problem for the radar on the F-16 A/B.[12]

Squadron-Level View. Figure 4 illustrates a typical squadron's experience with this type of LRU in the 28 aircraft that the squadron operated during the six-month case history period.[13] Each aircraft's flight experience is represented by a horizontal bar that starts (and ends) on the date the aircraft first (and last) flew during the case history period. For 12 of the aircraft the figure portrays a completely clear bar signifying that the BIT detected zero faults in the LPRF during the six-month case history period. For the remaining 16 aircraft, one or more segments of each aircraft's bar is darkened to signify multiple-flight episodes during which the BIT was reporting to the pilot that it had detected a fault in the LPRF LRU. On average, approximately one-third of the aircraft at any given time were experiencing an episode where the BIT was detecting faults in the LPRF. The darkened portions of the bars are long because pilots waited to request maintenance and maintenance technicians encountered so much difficulty, first to verify fault existence and second to determine the precise location of faults. These problems may be fully depicted with a look at individual aircraft's experience.

Aircraft-Level View. A particularly rich and interesting example is provided by F-16A aircraft number 0752, which had problems caused by LPRF LRUs throughout the six-month period and beyond until the

[12]See Sec. IV and for further details see the discussion of the F-15/F-16 Radar R&M Improvement Program in Gebman, Shulman, and Batten, 1988.

[13]The 10th Tactical Fighter Squadron in the 388th TFW.

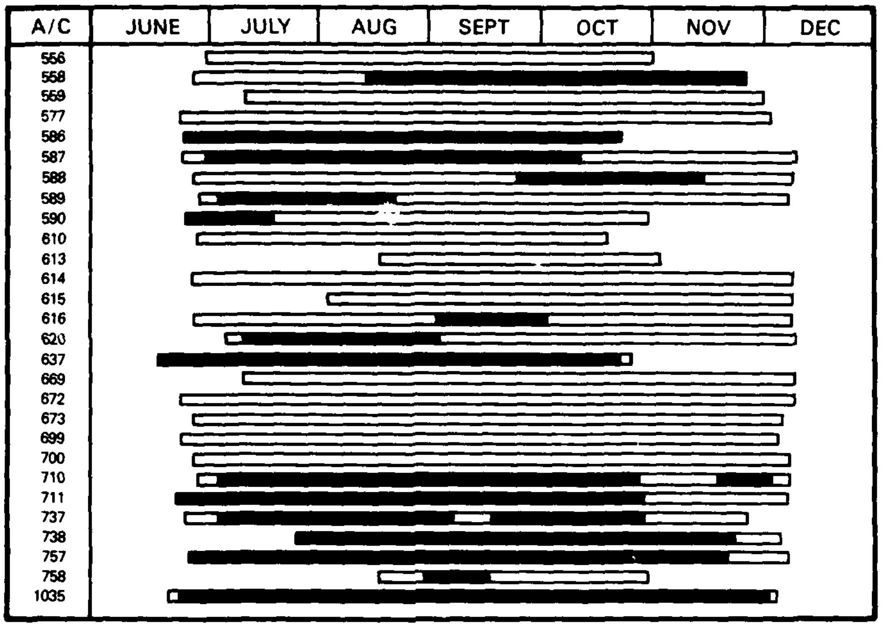

Fig. 4—LPRF BIT failure episodes: 10th TFS, June through December 1984

radar contractor helped the Air Force resolve the problem during a special follow-up effort. Evidence of the LPRF-caused problems is detailed in Figs. 5 and 6.

This aircraft encountered two serious episodes where there were clear patterns of faulty operation with its radar during 1984. Figure 5 shows many flights where the BIT detected symptoms of the faults; it also shows many flights where it did not. This illustrates the imperfect nature of BIT. Unfortunately, BIT indications have many omissions, and faults may exist in a unit but the BIT may not always detect their symptoms. However, when the BIT in the F-16 A/B radar does detect a fault, it is trustworthy, even if it fails to detect a symptom on the next flight.[14]

Arrowheads in the top row of Fig. 5 represent flights in which the BIT detected no symptoms of faults in the LPRF. Arrowheads in the second row represent flights in which the BIT did detect symptoms. The number in each arrowhead represents a set of consecutive flights.

[14]Gebman, Shulman, and Batten, 1988.

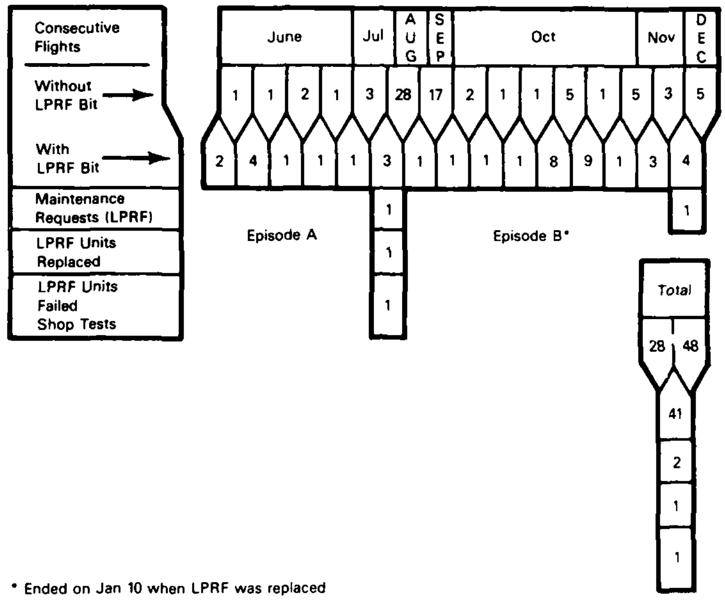

Fig. 5—History of LPRF BIT indications of degraded performance: F-16 number 0752, June through December 1984

The figure shows that the BIT would detect symptoms of faults during some flights but not during others.

Figure 5 shows an irregular pattern: Two consecutive flights occur with BIT-detected symptoms, one without, four with, one without, and so on. Here we have an illustration of one or more faults with irregular symptoms, typical of Type B faults. Except for a 28-flight respite during August, patterns persisted throughout the six-month data collection period. The 28-flight respite occurred after a pilot requested maintenance and radar technicians replaced the LPRF.

The replacement happened on July 19, 1984, after the fault had deteriorated to the point where a circuit board in the LPRF unit started generating smoke that entered the cockpit. Smelling the smoke, the pilot aborted the flight before takeoff. Unfortunately, analysis of these and other data obtained after the radar contractor and the Air Force had finally installed another LPRF (during January 1985) revealed that on July 19, 1984 maintenance technicians probably had replaced the smoking LPRF unit with another that was also defective. Although from the perspective of the BIT there were 28 flights in a row without any indications of a fault, Fig. 6 illustrates the degraded performance observed by the pilot and compares them with BIT indications on the same flight. A BIT indication of "no" means the BIT found no fault, while a "yes" indicates a fault. On eight occasions when the BIT indicated no fault, the pilot observed a problem with the radar. Even on most of the occasions when the pilot observed a problem, the flight received an equipment status code of 1 (maintenance not needed) rather than a 2 (maintenance needed but may be postponed) or a 3 (maintenance required before next flight).

Because maintenance technicians were being apprised of neither BIT-detected faults from code 1 flights nor pilot comments noted in Fig. 6, the technicians had no way of knowing that they had installed a faulty LRU on July 19 until the code 3 request for maintenance over three months later on October 26.

The example of aircraft 0752 is particularly rich because it also illustrates how depriving technicians of BIT information from code 1 flights can hinder their maintenance efforts once maintenance finally

Flight	FMC Code	BIT	Pilot Observation
	EPISODE A: June 15, 1984 - July 19, 1984		
July 17	1	no	Lock-on problems
July 19	3	yes	Smoke in cockpit, ground abort
	EPISODE B: July 19, 1984 - January 10, 1985		
July 23	1	yes	Lock-on problems
July 26	1	no	Could not paint tanker until 25 miles away
July 26	1	no	Degraded performance
Aug 10	1	no	Could not lock until RO-8
Aug 13	1	yes	Lots of false targets
Sept 10	1	no	False targets positioned randomly in corners
Sept 11	1	no	Numerous false targets
Oct 15	1	yes	Lots of false targets/no targets detected
Oct 16	1	yes	Weak radar/false targets/slow to lock-on
Oct 26	3	no	Radar flooded with false targets
Nov 26	3	yes	Degraded performance
Jan 10	1	no	Degraded performance

Fig. 6—History of LPRF pilot indications of degraded performance: F-16 number 0752, June through December 1984

is requested.[15] For example, on October 26, even though the BIT failed to detect a fault during the flight that day, the pilot gave the flight a status code 3 because the radar was flooded with false targets. Maintenance technicians, unaware of the history of BIT-detected faults on flights throughout the month, placed total reliance on their execution of the BIT on the ground, which failed to find any faults. Moreover, because faults in any one of several different LRUs, as well as external phenomena, can cause excessive false targets, the technicians decided to take no further action and instead waited to see if the pilots asked for maintenance again.

A month later, on November 26, after many more flights with BIT-detected faults (Fig. 6), a pilot asked for maintenance following a flight where he witnessed degraded performance and the BIT detected faulty operation as well. Maintenance technicians had no knowledge of the other flights where the BIT detected faults. All they had to work with was the pilot's report, the BIT report from the one flight on November 26, and the results of their own execution of the BIT, which found no faults. Because the latest evidence (their execution of the BIT) revealed no faults, they took no further action and instead chose to wait and see if the pilots would repeat their request for maintenance. Pilots chose not to request maintenance, even though the pattern of flights with and without BIT-detected faults continued into January.

Although Air Force maintenance technicians where unaware of the patterns depicted in Figs. 5 and 6, the radar contractor's engineering personnel had developed a high level of interest in such patterns that were afflicting about one-third of the aircraft at a given time. Anxious to show the Air Force that the patterns could be terminated simply by installing a healthy LPRF, the radar contractor persuaded the Air Force to direct the removal of the faulty LPRF from aircraft 0752 and a few other aircraft during January 1985. Subsequent tracking of these aircraft for an additional 30 days validated the contractor's proposed remedy.

The example of aircraft 0752 illustrates the problems of dealing with a Type B fault that is more easily found in the air by observation than by the BIT on the ground. If maintenance had seen the history of unarguable evidence presented in Figs. 5 and 6, the LPRF unit would have been removed back in October, if not sooner. Maintenance needs this kind of composite history to better guide its actions. In Sec. III we

[15]This reveals a shortcoming of the traditional view of R&M that tends to weight the last observation most heavily, if not exclusively. The idea has been that the only symptoms that matter are those from the last flight, or the last test. The new view suggests that all of the evidence be accumulated and considered.

discuss an experimental prototype of a system designed to collect and provide such useful information.

Figures 5 and 6 also demonstrate that these fault symptoms are not only intermittent from flight to flight, but their impact varies over time as well.

With the measurements operative under the traditional view of R&M, the data from aircraft 0752 yield a 99.9 percent FMC rate, an MTBF of 94 hours, and an MTTR of 2 hours (Fig. 7).[16] This FMC is a very good rate for the reliability of a fire control radar and, indeed, is close to representative of the F-16 radar. From the vantage point of our new view of R&M, the aircraft and pilot endured seven months of

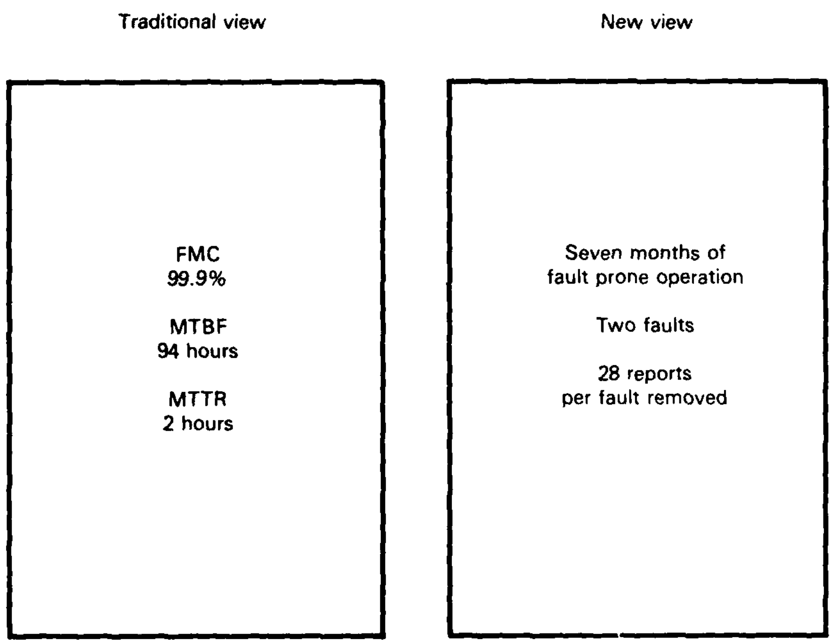

Fig. 7—Traditional view of R&M versus the new view, F-16A number 0752 radar

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[16]MTTR is more correctly understood as "mean time to complete a repair" than simply "mean time to repair." *In many instances* "repairing" is only a matter of removing one LRU and replacing it with another. Actual repair of the LRU takes place at the shop or depot.

fault-prone operation when the full designed capability of the radar was not available, all because of of two faulty units.

Throughout this period there were only two requests for maintenance and only one LRU removed. Even during the one period of 28 flights without BIT indications of faults, the pilot observed faults that the BIT finally picked up; so it is reasonable to assume that there were one or more faults in the replacement LPRF. It is also reasonable to believe that during the other 89 flights there were one or more faults in the LPRF that could inhibit the radar from delivering its full designed capability. Although only 41 flights yielded BIT indications of faults, twice that number of flights were apparently flown with one or more faults present in the LPRF.

General Observations About the New View

The new view provides a framework for recognizing and addressing problems that heretofore have been masked by a view that is sensitive to only part of the R&M landscape. It offers the potential of a better basis from which the Air Force could strengthen its ability to manage R&M.

III. THE SUPPORT PROCESS

From the perspective of the new view, R&M is determined by two fundamental characteristics:

- Fault initiation,
- Fault removal.

The first characteristic is established completely by events within the acquisition process and the product improvement process. The second characteristic, however, is also influenced by the effectiveness of the support process. Indeed, a primary purpose of the support process is the removal of faults. Thus, an assessment of R&M-related weaknesses in the support process needs to start with an examination of how effectively that process is performing in terms of removing faults.

Strengthening the support process fault removal capability offers the Air Force the most immediate opportunities to strengthen its overall ability to manage weapon system R&M. Moreover, because current R&M related deficiencies in the support process result largely from lack of information, better information will highlight support deficiencies that need to be addressed by both the product improvement and the acquisition process.

WEAKNESSES IN THE WEAPON SYSTEM SUPPORT PROCESS

The weaknesses in the support process obscure the Air Force's ability to see difficult problems that seriously degrade the ability of maintenance technicians to remove faults from important equipment. Although the Air Force has struggled with the symptoms of these problems for a long time, progress at identifying the root causes has been hampered. Weapon system program managers and the senior leadership of the Air Force have lacked a methodology for providing good visibility of fault removal effectiveness.

Assessment of Fault Removal Effectiveness

We developed and applied two methods for assessing how effectively the support process removes faults from subsystems that make up an aircraft weapon system. The Air Force could use each method to improve its ability to track and manage its capability to remove faults.

The first method provides a rough estimate that is based on data routinely collected by the Air Force. The second method provides a more complete estimate, but it requires a special data collection effort. That effort, however, can provide engineers the data they need to identify the root causes of fault removal difficulties.

Assessing Fault Removal Effectiveness with Currently Available Data. This method uses information in the Air Force's MDC system to examine the worldwide experience of an aircraft weapon system. For our analysis, we applied the methodology to an example database for calendar year 1985 for the F-16 A/B force.[1] Based on our research involving other weapon systems,[2] we believe these results are representative of the experiences of a broad class of contemporary tactical aircraft.

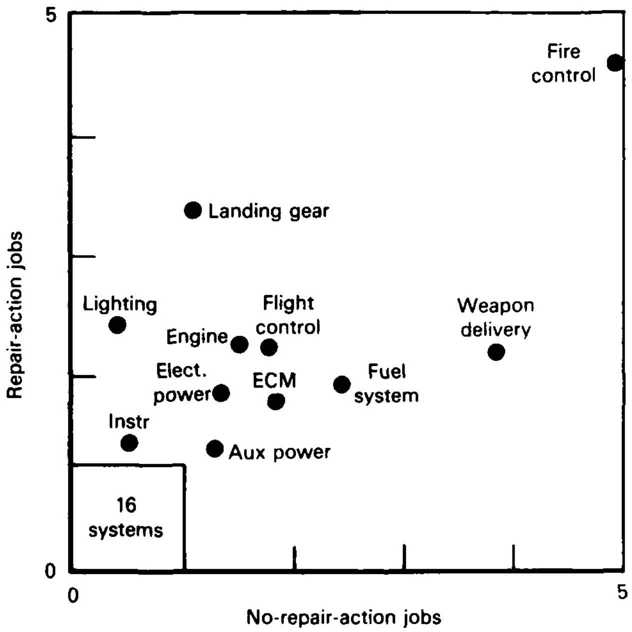

Fig. 8—Flight line repair action jobs on the F-16 A/B weapon system, per 100 flights, USAF MDC system, 1985

[1] Petruschell, Smith, and Kirkwood, 1987.

[2] See Gebman, Shulman, and Batten, 1988 for the F-15; McIver, 1974 for the F-111 series; Nelson 1974 for the A-7D; and Robinson 1967 and 1972 for the F-4.

The methodology has three main parts: (1) organization of the data by maintenance jobs, (2) classification of maintenance jobs according to whether a repair was accomplished, and (3) counting the number of jobs in each of two classifications:

- Repair-action jobs,
- No-repair-action jobs,

for each major subsystem constituting a weapon system. For the purposes of this methodology, we define a maintenance job to include all of the flight line maintenance actions that are part of the maintenance organization's response to a discrepancy that is reported against a specific subsystem.

Application of the methodology to the example database yields the results portrayed in Fig. 8. The vertical axis represents the number of repair-action jobs per 100 flights for each type of subsystem in the F-16 A/B weapon system. The horizontal axis represents the number of no-repair-action jobs per 100 flights. The figure presents a data point for each of the 11 subsystems that had the most jobs per 100 flights. Sixteen subsystems had less than one repair action job and less than one no-repair-action job per 100 flights. These subsystems account only for a small portion of the total maintenance jobs.

This figure identifies the subsystems that account for the most maintenance jobs and highlights the subsystems accounting for most of the no-repair-action jobs. For example, the fire control system had, on average, five maintenance jobs per 100 flights in which there actually was a repair. There were also about five requests for maintenance action that did not result in any repair; maintenance would find nothing to repair because the BIT did not duplicate the fault on the ground that it found in the air, or the technicians could not stimulate symptoms or duplicate the problem reported by the pilot.

The traditional view of R&M has been to discount requests for maintenance that resulted in no repair action because, it was reasoned, the BIT might have given a false alarm or the pilot may not have been really sure of what he saw, and so on. The new view, however, proposes that:

- All requests for maintenance are to be presumed valid.

Special tests conducted by contractor personnel support this fault-existence presumption. An even stronger proposal is that:

- All indications of the existence of a fault are to be presumed valid until the tracking of system performance over time proves otherwise.

Application of either presumption to the data in Fig. 8 allows one to estimate the fault removal efficiencies displayed in Fig. 9. About half the time when there was a fault in the fire control system, maintenance technicians were able to find something to repair on the ground, suggesting a fault isolation efficiency of about 0.5—that is, 50 percent. In contrast, the lighting system had averaged 2.25 repair-action jobs per 100 flights and only 0.45 no repair-action jobs per 100 flights, suggesting a fault isolation efficiency of 83 percent.[3] A burnt-out light bulb does not present the maintenance problems of fire control, ECM, or weapon delivery. The pilot sees the bulb is out, maintenance confirms this easily on the ground, and it replaces the bulb. The other systems are more likely to have problems that will manifest clear symptoms in the air to the pilots and the BITs, but not to maintenance personnel on the ground.

A system with many maintenance jobs per 100 flights and a low fault isolation efficiency warrants further investigation. To illustrate

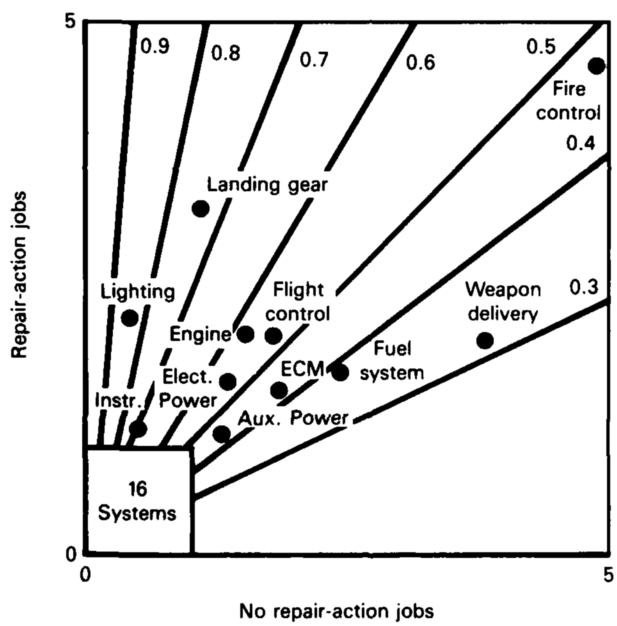

Fig. 9—Flight line fault isolation efficiency on the F-16 A/B weapon system, per 100 flights, USAF MDC system, 1985

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[3] 2.25/(2.25 + 0.45) = 0.83.

this, we go back to the fire control system and examine its constituent subsystems using the same methodology and display format. The results in Fig. 10 show that the fire control system's fault isolation efficiency is dominated by the fault isolation efficiencies for the radar and the inertial navigation system (INS).

Using data currently available to the Air Force, our methodology has identified two of the seven subsystems constituting the fire control system as the dominant sources of trouble with the F-16 A/B weapon system's fault isolation efficiency. However, the data have not identified the causes of the problems. That requires a special data collection effort.

Assessing Fault Removal Effectiveness with Special Data. For the radar, a special data collection effort took place during 1984 as part of the F-16 A/B Radar R&M Improvement Program. Such data can be used to estimate the fault removal efficiency for the radar, as well as to determine the causes of fault isolation problems.

Figure 11 shows us the fault isolation efficiency not only on the flight line, but also at the shop and depot levels of maintenance. The first bar (the flight line) corroborates the MDC system data used in the

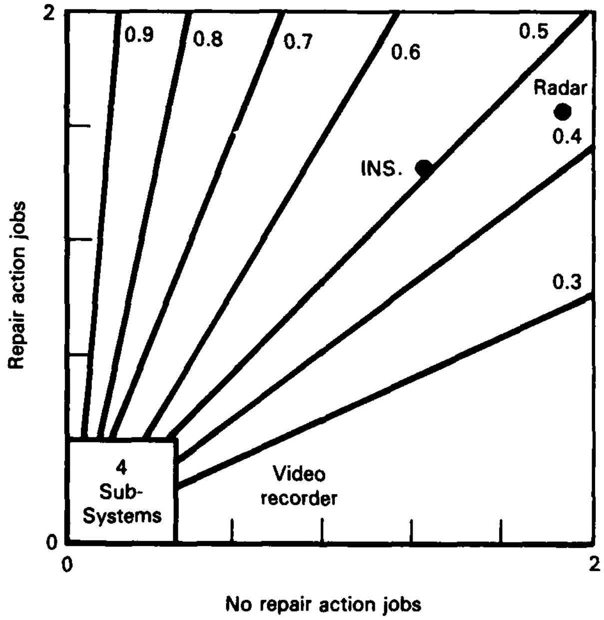


Fig. 10—Flight line fault isolation efficiency in the F-16 A/B fire control system, per 100 flights, USAF MDC system, 1985

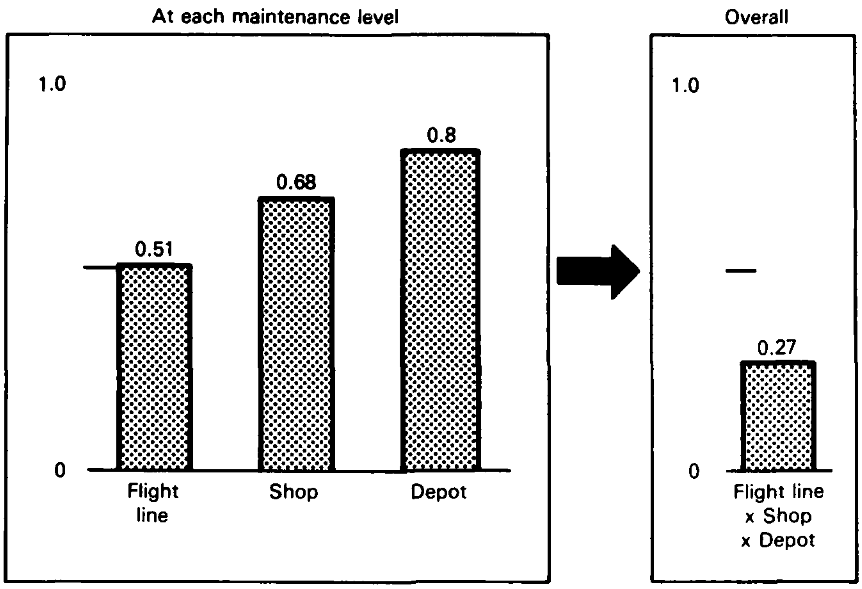


Fig. 11—Overall fault isolation efficiency for the F-16 A/B radar, 16,000 flights, special data collection, 1984–1985

previous figures: Fault isolation efficiency on the flight line is about 50 percent for the radar. However, that efficiency in the shop was also imperfect, though better than on the flight line. When an LRU from the radar was sent to the shop, 68 percent of the time the shop executed a repair action. When the shop pulled a shop replaceable unit (SRU) and sent it to the depot, the depot was able to execute a repair action about 80 percent of the time.

The special data collection and associated engineering analysis effort verified that:

- Nearly all of the pilot reported discrepancies were valid observations, *even though flight line technicians could not duplicate the pilot observed symptoms* for half of the pilot reports.
- Nearly all of the LRUs sent to the shop were faulty, even though the shop could find faults in only 68 percent of the LRUs.

At first glance, the track of improving efficiency in Fig. 11 might look good. However, the product of the efficiencies at each maintenance level is not very good. The flight line efficiency times the shop efficiency times the depot efficiency yields an overall fault isolation efficiency of 27 percent. That is, for every four requests for maintenance, the support process takes about one repair action.

We also need to examine fault *removal* efficiency. Figure 12 shows that fault removal efficiency is a function of both maintenance requests per faulty flight and fault isolation efficiency. Although the fault isolation efficiency is still one in four, the special data collection effort found that the pilots were asking for maintenance at the rate of once every five flights in which they saw an indication of a problem. In other words, for every hundred times a pilot saw a difficulty with the radar subsystem, such as in aircraft number 0752 discussed in the previous section (see Figs. 1 and 2), he would request maintenance 20 times. So the fault removal efficiency for the entire subsystem is the product of the rate of these maintenance requests and the overall fault isolation efficiency. For the F-16 A/B radar subsystem, this efficiency is 5 percent.

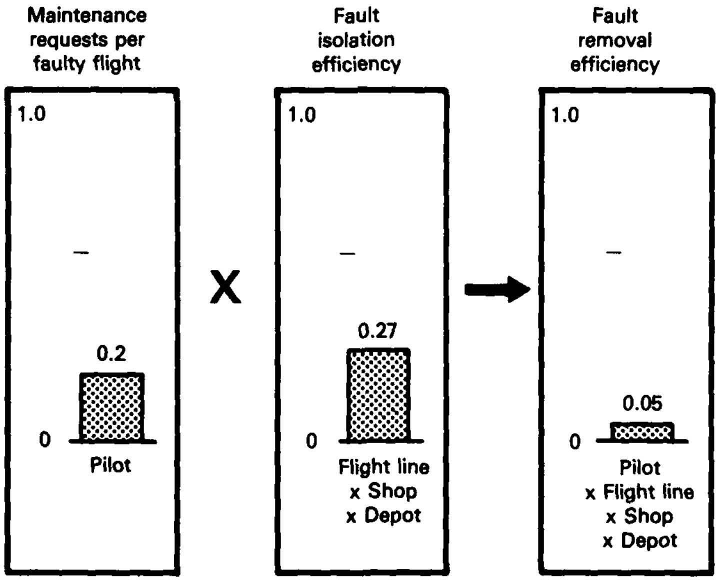


Fig. 12—Fault removal efficiency for the F-16 A/B radar, special data collection, 1984–1985

Investigation revealed that the problem with the F-16 A/B radar lies primarily with the Low Power RF unit, one of the main boxes in the radar. Over half of the units (58 out of 98 LPRFs) going back into the airplanes within 15 flights after their release from the shop were again failing the BITs in the air. This rate is about one-tenth the reliability of that LPRF unit, so it is highly unlikely that very many of the faults are new ones. About half the time the shop looks at an LPRF unit, it cannot find anything to fix.

Evidence that the units were faulty came from two sources: tracking the faulty performance of units when they returned to aircraft following their shop visits, and a special test for 30 units that continuously failed BIT while in various aircraft, only to pass the shop's tests.

The 30 units that could not be fixed in the shop were put through a special test program. The LRUs were subjected to a more challenging thermal environment and certain tests were repeated more often than would normally occur in the shop. These special procedures discovered faults in 20 of the 30 units. Unfortunately, the special test program did not have the capability to impose a vibration environment. We do not know, therefore, whether vibration may have elicited symptoms of faults in the remaining 10 units.

Low fault removal efficiency is not a problem peculiar to the F-16 A/B radar. A parallel collection of special engineering data was made on the F-15 C/D radar over a six-month period at two bases. Here, too, researchers found serious deficiencies in the shop's ability to fix units: 32 units were sent to the shop five or more times; seven of these units were sent eight or more times.[4] Such patterns are due to limitations in the shop's ability to find the faults that are causing in-flight problems. Symptoms of these limitations are reflected in the following statistics:

- In 37 percent of all LRUs sent to the shop, the shop found no fault.
- In 20 percent of all LRUs sent to the shop, the shop detected faults and implemented repair actions, but subsequent engineering analysis revealed that all of the repair actions were unrelated to the faults that occurred in flight.

In the latter case, the shop technicians found something to do, perhaps an adjustment or a minor repair; but whatever it was, it was irrelevant to the fault condition detected in flight. The technicians, lacking

[4]Over this period, these units would be expected to make one visit to the shop. Even allowing for any kind of reasonable random distribution (such as a Poisson distribution), five or more visits is clearly excessive.

necessary engineering data to know otherwise, had no idea that their efforts were irrelevant.

Figure 13 illustrates the consequences of inefficient fault removal in the radars of the F-15 C/D and F-16 A/B. In the case of the F-15 C/D radar, faults were indicated in 33 out of every 100 flights during the special data collection effort; of these, 85 percent experienced faults that had been indicated in previous flights. In the case of the F-16 A/B radar, the situation looks better: Only 22 flights out of 100 had some indication of difficulty; but 95 percent of those with fault indications are old faults.

Figure 13 analyzes consequences from the operator's point of view. From the R&M engineering management point of view, Fig. 14 carries the same basic message but it addresses the basic characteristics that determine R&M and ultimately drive the consequences observed by the operators.

Figure 14 illustrates current fault removal capabilities in the context of the overall R&M situation for the F-15 C/D radar and the F-16 A/B radar. This type of display illustrates how the R&M of such subsystems could be improved and implements the new view of R&M.

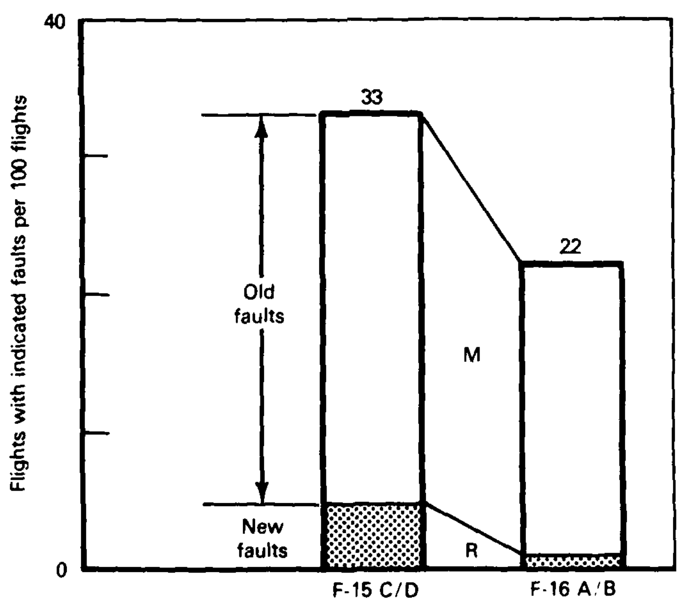


Fig. 13—Consequence of inefficient fault removal in the F-15 C/D radar and F-16 A/B radar, per 100 flights, special data collection, 1984–1985

Along the vertical axis we show the mean time between shop confirmed failure to indicate reliability. To complete the R&M picture, we propose a measure of fault removal efficiency to indicate maintainability.

As Figure 14 shows, the F-16 A/B radar is far better than the F-15 C/D radar in MTBF, but its fault removal efficiency is worse. In both cases the fault removal efficiency is still very low, confusing the difference between reliability and maintainability. This composite way of viewing R&M is therefore intended as a first-order management tool rather than a contractual device.

When a system or subsystem registers a low percentage for fault removal efficiency, the Air Force needs to examine ways to improve the fault removal capability of the support process. The Air Force may want to enlist the help of equipment contractor engineers in analyzing causes of fault removal problems. For instance, they may find that the LPRF unit alone is causing the problem, as in the case of the F-16 A/B radar, or that the BIT in several LRUs are causing problems, as in the case of the F-15 C/D radar.

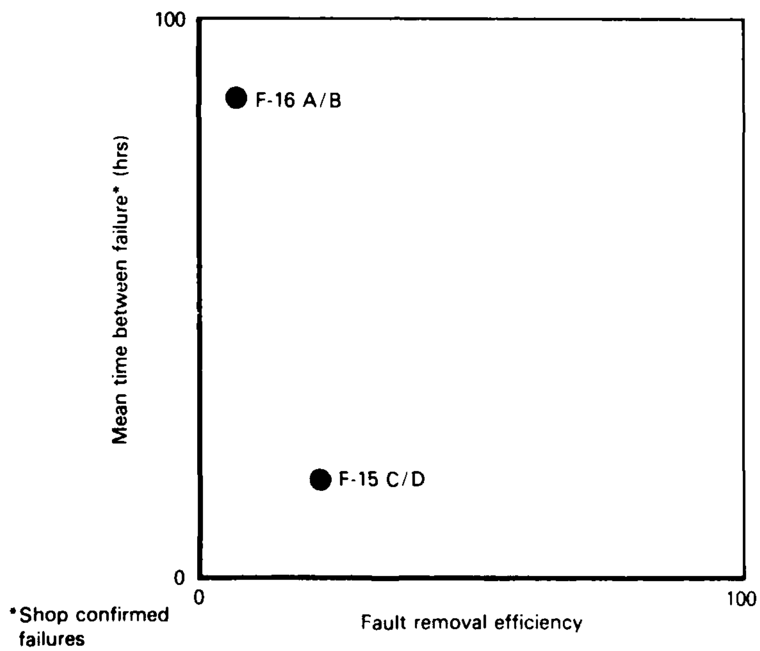


Fig. 14—A new view of R&M for fighter radars: F-15 C/D radar and F-16 A/B radar, special data collection, 1984–1985

Support Weaknesses Contributing to Fault Removal Problems

Beyond equipment-specific difficulties, the following deficiencies in the support process are strong contributors to poor fault removal performance. The current process

- *Provides inadequate information about avionics equipment performance during routine training flights.* Indeed, pilot-observed indications of faults often go unreported to technicians even when the BIT corroborates degradation in the equipment's performance.
- *Fails to track avionics equipment performance by serial number.* This procedure could facilitate the identification of faulty units that repeatedly circulate between shops and airplanes.
- *Inadequately integrates maintenance efforts and fault information across maintenance levels.* Even though avionics technicians use different tests and different pass/fail criteria at each maintenance level (flight line, shop, and depot), technicians lack test dictionaries that would enable them to translate test results from one level to another.
- *Provides inadequate capabilities and procedures for fixing bad actor equipment.* Not only do technicians lack equipment to represent aspects of the flight environment, but they also lack capabilities to repeat certain tests and initiate other tests before thermal equilibrium is achieved. Such capabilities would decrease maintenance time and lead to the more accurate identification of thermally sensitive faults.

STRATEGY FOR IMPROVING THE SUPPORT PROCESS

To strengthen the fault-removal capability of the support process we propose a four-part strategy that includes debriefing pilots for indications of faults, tracking avionics subsystems by serial number, integrating repair levels, and fixing "bad actors" before they recirculate.

Debrief Pilots for All Indications of Faults

Pilots need to share with maintenance all the indications of difficulties with the complex weapons system equipment that they perceive, large or small. They do not necessarily have to request maintenance every time they notice a problem, but they need to help maintenance track the history of difficult subsystems.

To improve the quality of information received at postflight debriefing, the Air Force could develop an interactive system to help question a flight crew about airplane malfunctions. Such an automated system could employ data transfer units to capture information from the BIT[5] and personal computers to record information interactively from pilots. The growing complexity of avionics equipment and avionics faults makes it increasingly difficult to obtain a thorough characterization of symptoms and operating conditions from pilots during debrief.

Track Performance of Avionics by Equipment Serial Number

The tracking of problematic subsystems that begins with pilot debriefs should continue with tracking of the components of the subsystems by serial number. Maintenance needs to keep accurate and updated records of which units and subunits are being circulated between the flight line and the shop and depot. This step is essential in helping the shop and the depot track and locate units they are having difficulty fixing. The tracking of units helps identify the bad actors that need special attention.

Share Information About Fault Symptoms Across Maintenance Levels

Because the support process must use different tests and pass/fail criteria at each maintenance level,[6] sharing of information is especially important to rectify the hard to fix Type B faults. One beneficial way to improve information sharing would be to provide *test translation dictionaries* that would enable avionics technicians at one maintenance level to translate test results from another maintenance level into terms they would find useful for isolating and correcting faults and identifying bad actors.[7] Technicians must use information from the previous level to confirm that they are correcting failures discovered at

[5]A data transfer unit is a data recording device that pilots use to transfer mission data from digital computers in their operations facility to the digital computers in their aircraft just before a mission. Many modern combat aircraft not only have such devices, but they also use these devices during a mission to record faults detected in flight. When used in such a manner, a data transfer unit is a painless mechanism for obtaining a thorough and accurate record of BIT-detected faults.

[6]The tests on the aircraft are different from the tests run in the shop, which in turn are different from tests run on circuit boards at the depot. Unfortunately, these differences are necessary.

[7]A dictionary could relate tests from one level to another. For example, each BIT at the airplane level would be related to a block of tests at the next higher maintenance level (the shop). For example, BIT X in the aircraft is related to the block of Tests A, B, C, and D in the LRU, but it does not indicate which of those four should be run in the shop. Test A in the LRU, for instance, is likewise related to the block of Tests 1, 2, 3, and 4 in the SRU but does not indicate which one of those four should be run at the depot.

the previous level. If tests at different levels produce different results, the unit may be a bad actor and thus require special surveillance by pilots and flight line personnel. And if the unit's anomalous behavior persists, it should be sent to the depot for special testing and analysis.

Fix Bad Actor Equipment

The test translation dictionary is only an aid for improving fault-isolation and identifying bad actor equipment. The next key element of the strategy is to repair the problem units or components so that they do not circulate between the support process and aircraft in degraded condition. To improve the efficiency of repairing bad actors, we recommend improved fault-isolation capabilities based upon those measures that contributed to the F-15/F-16 Radar R&M Improvement Program. These include:

- *Direct entry into test sequences for specific sections of lengthy ground avionics tests at both the base and the depot* so technicians could avoid having to run tests in an invariable predetermined sequence. Technicians would have improved ability especially to find Type B faults that are sensitive to time-varying thermal conditions.
- *Loop testing for specific tests at both the base and the depot* would enable technicians to run the same test repeatedly, thereby improving the prospects of catching Type B faults.
- *Special environmental and system bench capabilities for depots* would enable test equipment to better replicate operational modes (such as air-to-ground mode) and environmental settings (such as extreme temperatures) that especially influence Type B faults.

AN EXPLORATORY APPROACH TO IMPLEMENTING TWO CRITICAL PROPOSITIONS

The whole strategy for strengthening the fault removal capability of the support process depends upon two critical propositions: improved debriefing of pilots and serial number tracking of equipment. Neither proposition is new. The challenge is to devise an approach to implementation that leads to a bearable burden. Recent developments in computer science technology may provide an opportunity. To explore this possibility we have worked with Aeronautical Systems Division Strike System Program Office (SPO) to develop a prototype to support fuller debriefing and serial number tracking of equipment at the air base.

The prototype capability was designed to lighten the workload of pilots and maintenance technicians alike by identifying bad actor equipment and moving it from the air base to the depot. This maintenance aide has been named PORTER, which stands for *P*erformance *O*riented *T*racking of *E*quipment *R*epair. The principal aim of PORTER is to restore aircraft and their subsystems to their full design capability as quickly as possible. Currently, the PORTER prototype is implemented on a set of PCs.

Rationale for a PORTER Capability

Even with the best engineering efforts—including a formal process aimed at maturing reliability and maintainability—some avionics faults will still evade detection and correction at various points in the support process. Consequently, avionics technicians need special information to track down such faults, correct them, and document deficiencies in the support process that allowed these faults to escape detection.

Flaws in avionics equipment can escape detection for several reasons. The narrow confines of the aircraft and the limitations of the BITs make it impossible to test all equipment thoroughly when the aircraft is in the air. Similarly, the inability to replicate airborne stresses makes it impossible to conduct a fully realistic test of all equipment when the aircraft is on the ground. Moreover, when equipment is removed from the aircraft and taken to shops and depots for more exhaustive testing, both the nature of the tests and their pass/fail criteria change.

Because test equipment is often inadequate to assess deficiencies in complex avionics equipment, omissions occur in covering certain failure modes. Consequently, faulty equipment circulates through the support system until either the fault develops into a more serious problem (such as an open circuit) or maintenance personnel take extraordinary measures to isolate the problem. Faulty equipment recirculates all too frequently with sophisticated airborne electronics equipment.

Items of equipment that circulate in this fashion are commonly labeled "bad actors," and they deny pilots regular and dependable access to the equipment's full designed capability. Fixing them places great demands on the support process, consuming time and resources spent on personnel, spare parts, and test equipment. The air base shop repeatedly tests the equipment; the depot needs to use special environmental tests and test benches. It is especially critical that these extraordinary efforts focus on solving only the most serious problems. The efficient identification of such equipment is at the heart of the PORTER concept.

Unfortunately, the Air Force's standard data systems do not gather sufficient information from flight-to-flight performance to enable maintenance personnel to identify and diagnose ineffectual maintenance and evolving problems with sophisticated avionics. PORTER strives to fill this gap.

Once a particularly hard-to-fix fault has been cured, when it occurred in a different unit, mainetenance could go directly to the solution. After several successes, it becomes a "well-known problem," which is a candidate for a more permanent cure through the product improvement process. Institutionalization of PORTER would create such a situation.

Functional Description of a PORTER Capability

Figure 15 shows how maintenance information currently flows, and Fig. 16 shows how it ideally would flow after instituting a PORTER capability.[8]

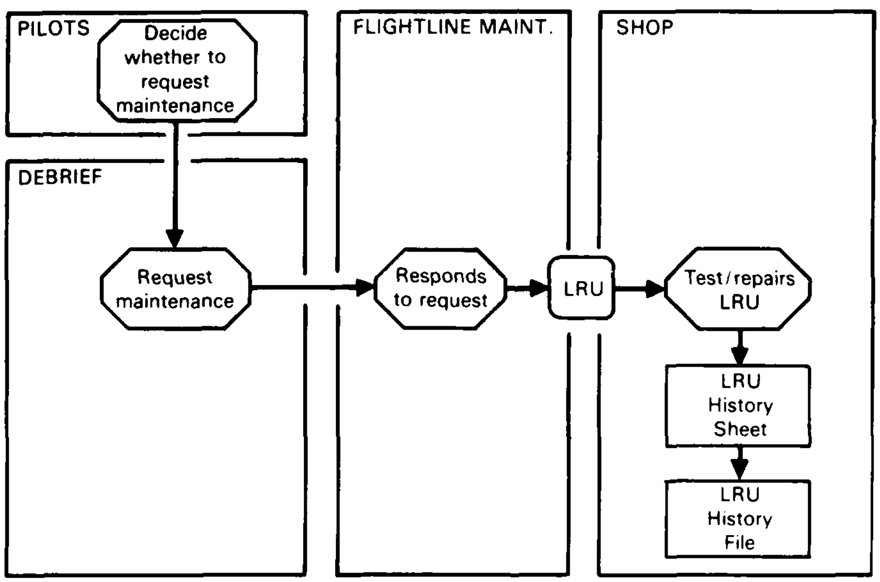
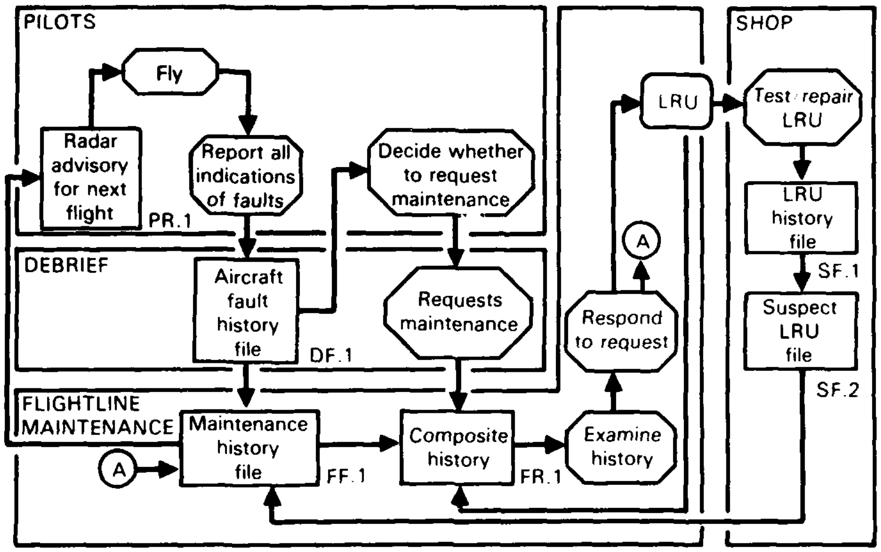


Fig. 15—Current maintenance information flow

[8]See Gebman, Shulman, and Batten, 1988, for a fuller description of PORTER.



NOTES: DF.1, FF.1, SF.1 and SF.2 are computer files.
PR.1 and FR.1 are printed reports

Fig. 16—Maintenance information flow after instituting PORTER

PORTER starts with a full debrief from the pilot that includes descriptions of all indications of potential faults—even though the pilot may not ask for maintenance.[9] All such indications are tracked over time along with descriptions of all maintenance actions. This integrated tracking provides the basis for rapid identification of bad actor equipment. It also provides a better information base for engineering R&M improvements to both the airborne and the ground-based support equipment.[10]

However, because PORTER's primary purpose is as a maintenance aid, its mechanization must be tailored and synchronized to events in the maintenance process. An operational wing has assisted not only in

[9]Eventually it would be best to have a computer aided interactive debriefing session where questions put to the pilot would be tailored in response to his previous answers. Initially, though, it would be a substantial improvement just to gather all pilot observations concerning potential problems.

[10]PORTER can contribute to improved engineering, first by providing a more complete view of difficult maintenance problems and second by providing a baseline data collection system that can be expanded upon to support special field data collection efforts such as the ones that were part of the F-15/F-16 Radar R&M Improvement Programs.

testing and demonstrating PORTER, but also in defining and experimenting with its functional specifications.[11]

Less than one year after concept formulation, an austere PORTER capability was in a demonstration and evaluation phase at Bitburg. Based upon a favorable reception of even the austere capability, RAND and the Air Force are working on integration of a PORTER capability into the Air Force's Core Automated Maintenance System so as to eliminate any duplication of data entry tasks.

SUMMARY

Improving the flow of information within the support process is the first essential action to improve fault removal and thereby strengthen the Air Force's capability to manage the R&M of already fielded equipment. Such improved information flow needs to present a balanced view of R&M that highlights problems with both fault initiation and fault removal. Only with such a view will the Air Force fully identify the major deficiencies in the capability of the support process to remove faults. Such identification is also key to improving the product improvement process and the acquisition process.

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[11]This interactive development of PORTER's experimental prototype has occurred on PCs at the 36th TFW at Bitburg Air Base. The Strike SPO at the Aeronautical Systems Division provided on-site support through a contract with Support Systems Associates, Inc. The RAND Corporation, as the architect of PORTER, helped coordinate the technical development and demonstration of the prototype.

IV. THE PRODUCT IMPROVEMENT PROCESS

Each of the Air Force's product improvement programs has one or more of four goals:

1. Improve safety of flight,
2. Increase functional performance,
3. Lower costs of operations and support,
4. Raise readiness and sustainability.

Achievement of each of these goals requires attention to

- Fault initiation rates,
- Capability of the support process to remove faults effectively.

Because such attention is especially critical to the third and fourth goals, we use these goals to focus our assessment of R&M-related weaknesses in the product improvement process.

WEAKNESSES IN THE WEAPON SYSTEM PRODUCT IMPROVEMENT PROCESS

To determine how effective the current product improvement process is at applying resources to reduce fault initiation rates and to increase the capability of the support process to remove faults efficiently we need to know something about where the dominant problems lie, their extent, and their influence on costs, readiness, and sustainability. Knowledge of such considerations is at best incomplete. This is in itself reason for concern about the effectiveness of the current product improvement process.

Lack of such knowledge is one of two major weaknesses addressed in this section. The second is a lack of timely implementation for the most critically needed improvements.

Inadequate Information About Dominant R&M Problems

Although symptoms of the dominant problems may be known, the product improvement process lacks full knowledge of the connection between the root causes and the symptoms. Moreover, a single problem often manifests a diverse set of symptoms, giving the impression that there are a lot of lesser problems and contributing to fragmentation of efforts to improve the situation.

To illustrate these points we compare the state of knowledge about the dominant R&M problems with two subsystems before and after special field data collection and engineering analysis efforts. Each of these special efforts was far more intensive than any other field data collection effort that occurs in the normal execution of the product improvement process. The subsystems that were the objects of these special efforts are the F-15 C/D radar and the F-16 A/B radar. The data collection and field analysis efforts occurred during 1984 and 1985 as part of the F-15/F-16 Radar R&M Improvement Programs. In the case of each radar, perceptions of the dominant R&M difficulties were changed considerably when the radar contractors presented the results of their special efforts.[1]

To illustrate this point, we next discuss the dominant R&M problems for the F-15 C/D radar and the F-16 A/B radar. What are they? What was known about them before the special efforts? Why had the normal conduct of the product improvement process not revealed the important findings of the special efforts?

Dominant Radar R&M Problems for the F-15 C/D and the F-16. The special data collection and engineering analysis efforts revealed that the major R&M problems

- For the F-15 C/D radar lie in the design of the BIT,
- For the F-16 A/B radar lie in the design of the Low Power Radio Frequency (LPRF) LRU.

In the F-15 case, the radar contractor concluded that the three dominant design problems are

- Errors in BIT logic that cause false indications of problems and give maintenance erroneous reports on the location of faults,
- Too few test points to resolve ambiguities about the location of faults,
- Inadequate data processing capacity to accommodate BIT software.

In the F-16 case the radar contractor concluded that the two dominant design problems are

- A circuit board that is prone to development of flight sensitive faults,
- An internal packaging of the LRU that makes it difficult to maintain the integrity of delicate radio frequency connections.

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[1]Gebman, Shulman, and Batten, 1988, Sec. IV.

The subject circuit board (an SRU) has a large number of sites where faults are developing because of molecular migration. At these sites, gold connector ribbons are joined with an indium solder. Unfortunately, a chemical process is taking place whereby molecules in the connectors are being drawn steadily into the solder. Eventually, enough molecules migrate in this fashion to degrade the quality of the electrical connection. Over time, the quality of the connection will degrade and eventually the connector ribbon will separate from the solder. Such an open circuit is far easier for shop and depot tests to detect than is an intact yet degraded connection.

Inside the LRU, many delicate radio frequency connections are located in hard to service areas and require precise alignment and torque to function properly. These connections, many of which must be opened when the LRU receives maintenance, may manifest no problems on the ground during shop tests. However, if the connection is not within tolerances, it may encounter difficulties when subjected to dynamic flight loads.

Knowledge Before Special Efforts. The Air Force's maintenance data collection system was the main source of information for the product improvement process. It revealed virtually no direct evidence of the BIT problems with the F-15 radar. In the case of the F-16 radar, this source led to the assessment of symptoms summarized in Fig. 17, which summarizes the state of knowledge and the contractor's proposed improvement plan before the special efforts in 1984–1985. The story summarized in Fig. 17 is that data in the MDC system located a problem with either the LPRF unit or the support process for that unit. According to the MDC system data, the flight line technicians were sending many LPRF units to the shop that shop technicians could find no faults in.

Before the special data collection and analysis effort, the root causes of the problems with the LPRF (or its support process) were masked by several factors. For one thing, a radar with a 99-hour MTBF does not draw much attention,[2] especially when it is not known that there are only six flying hours between indicated faults (80 percent of which were by the BIT). Moreover, false targets, target tracking problems, and the like can often result from factors external to the aircraft. Furthermore, the extent of flight-sensitive failure modes in the LPRF was not generally known. Many of the faults detected by the BIT were thought finally to result from a grounding problem that could be corrected by a new shim that would provide a tighter electrical path for grounding the radar equipment to the airframe.

[2]The F-4's radar has less than a 9-hour MTBF.

	LPRF	Antenna
1979 - 1983 Symptoms 1983 Plan	• BIT reports LPRF faulty, but shop finds no fault • Replace grounding shim	• Harness wearout causing antennas to go to depot • Improve harness reliability
1985 Assessment	• LPRF responsible • Many flights affected • LPRF redesign needed	• Harness can be redesigned for field replacement • Redesign also lessens wear

Fig. 17—Knowledge of R&M needs for the F-16 A/B radar

This hypothesis was rigorously tested during 1984 as part of the F-16 Radar R&M Improvement Program. Special tests in which this new shim was installed showed that it would not correct problems the BIT was attributing to the LPRF: Of 20 aircraft that received new shims, 19 were still found to have faulty LPRF units that caused the BIT fault indications.[3]

In part, problems with the LPRF resulted from squeezing a capable and versatile radar into a very small volume with a tight weight limitation and a limited amount of environmental cooling. Advances in technology have now created an opportunity to develop a more maintainable LPRF

[3]The units were determined to be faulty as a consequence of two considerations. First, the units left a trail of BIT-detected faults that followed the subject units from airplane to airplane. Second, although the units had histories of the shops failing to find any faults, the contractor engineers and technicians participating in the special program were able to subject the units to special tests that revealed faults not being detected by the shop's normal testing procedures.

that should be less prone to the kinds of connection problems that plague the current design.[4]

Knowledge Limitations of the Current Product Improvement Process. The dominant R&M problems with the radars in the F-15 C/D and the F-16 A/B were identified and documented through the special data collection effort in the F-16 A/B Radar R&M Improvement Program. The extent and severity of the R&M problems with the F-15's BIT and the F-16's LPRF were determined and validated by a four-step process that started with a special data collection, that then guided engineering tests, engineering analysis, and independent review.

The current product improvement process lacks such special and intensive data collection efforts. Figure 3 helps show why that is a serious weakness.

The lack of a continuing record on how individual radars perform creates two major problems:

- Maintenance resources cannot be applied to the radars with the greatest need.
- Engineering resources cannot be applied to those radar R&M problems[5] that cause the greatest potential degradation in performance.

As with the radar and other modern avionics on contemporary fighter aircraft, the LPRF unit rarely experiences a complete failure that renders it totally incapable of supporting the airplane's mission. Its most common failure modes have two characteristics:

- They degrade the available level of performance by reducing detection ranges, introducing target tracking problems, and/or creating false targets.
- They manifest themselves mainly when the radar is exposed to thermal and dynamic stresses from the airplane's operational environment. Thus the BIT will frequently catch a fault during flight but later fail to duplicate it when the airplane is on the ground.

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[4]To explore this idea, the Radar R&M Improvement Program commissioned Westinghouse to develop a conceptual design for a new LPRF drawing on technologies that Westinghouse is currently incorporating in its contemporary radars. This new design enables more circuitry to be packaged into a smaller volume. Such packaging is more modular and facilitates disassembly. With connections on the back of each module, shop technicians would no longer have to disrupt so many delicate radio frequency circuits to remove a module.

[5]The root causes of which may lie in the radar or its support process.

To further illustrate the need for a special data collection and engineering analysis to sort out dominant factors, we now turn briefly to the second example in Fig. 17. Here, the Air Force's MDC system data reported that the antenna's harness was wearing out. It simply was not lasting very long, and when it wore out maintenance had to send the antennas to the depot. During 1983 the Air Force's plan called for improving the reliability of the harness.

The additional engineering data and the general review of the radar's R&M situation that was part of the F-16 A/B Radar R&M Improvement Program led to a different perspective. The dominant R&M problem was not reliability, it was maintainability. The harness, it was discovered, could be redesigned for replacement in the field so that, when it does wear out, maintenance would not have to send the whole LRU to the depot. Moreover, it turned out that such a redesigned and reconstructed harness would also wear out less often. However, the rapidly scanning antenna will always cause severe wear.

The F-15's BIT, the F-16's antenna, and its LPRF all are examples that illustrate a general lack of knowledge in the product improvement process concerning the root causes for dominant R&M problems. Knowledge is lacking in the normal process because equipment contractors are not involved in special data collection efforts; and lacking contractor supplied engineering analyses, the Air Force does not have a sound position from which it can view a weapon system's R&M posture in the context of underlying causes of problems.[6]

Lack Timely Implementation of Most Important Improvements

Timely implementation of the most important R&M improvements is hindered by lacks in four areas:

- No mechanism for initiating special data collection,
- No consensus about root causes of dominant problems,
- Lack of continuity in weapon system program management responsibility,
- Poor coordination of management of weapon system after PMRT.

Lack of a Mechanism for Initiating a Special Data Collection. When a large and complex system that is built from many leading edge

[6]A PORTER capability would help improve the Air Force's position and it would help contractors carry out special data collection efforts. It would not, however, provide an adequate alternative to the kind of contractor involvement needed for engineering analysis.

technologies reaches its initial operational capability (IOC) date, it is reasonable to expect shortfalls in R&M characteristics. This is when the process of maturing and improving the product can begin in earnest. At present, however, the Air Force lacks a mechanism for initiating the kind of special data collection and corollary engineering analysis that is essential to an effective maturation program.

The need for a formal mechanism is illustrated by the tedious and time-consuming process that was required to establish the special efforts for the F-15 and F-16 radars.

Figure 18 illustrates the current timetable for R&M maturation of the F-16 A/B radar. The F-16 A/B Radar Maturational Development Demonstration, which yielded the information for a F-16 A/B radar improvement package (presented below), was first discussed in September 1980, formally proposed at the beginning of 1981, and approved six months later. From the date of approval, it took three years for the Program Management Directive to come through and for all the contracting to be completed. Theoretically, the Data Collection and Analysis phase of the demonstration began in 1981 when the proposal

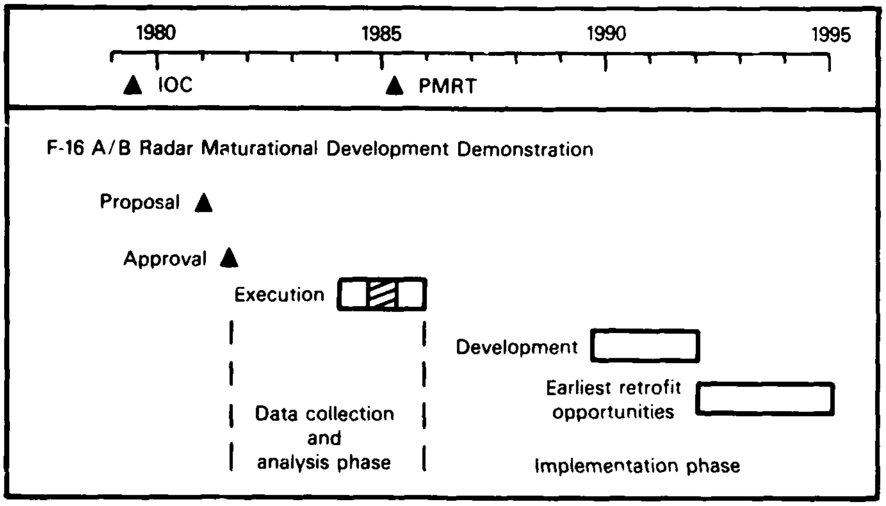

Fig. 18—Pace of R&M maturation for the F-16 A/B radar

was approved; but in fact, execution of that phase did not begin till 1984 when the contract was let. It was midway through 1984 before data collection and engineering analysis began (see cross-hatched area on "Execution" phase). When that stage was completed in mid-1985, the recommendations in the improvement package were fully assembled. At that point, the engineers knew what needed to be done to mature R&M *for* F-16 A/B radar and its support process.

If such a special effort had been launched three to four years sooner (shortly after IOC), we believe that the major results would have been the same, because the problems with both the LPRF and the antenna were known at that time. What was lacking at that point was knowledge of the extent of these problems in relation to other problems. A thorough data collection and engineering analysis and independent review at that time would have shed much light on the identity of the dominant R&M problems and their root causes.

Lack of Consensus About Root Causes of Dominant Problems. Essential to timely implementation of improvements is a consensus about three things:

- The relative importance of the problem,
- Its cause(s),
- The most cost-beneficial remedy.

To build a consensus on such matters, the Air Force needs four elements: (1) contractor involvement in engineering analysis, (2) systems analysis of alternative courses of action, (3) independent review to assure objectivity, and (4) active participation of the organizations that must contribute to the consensus and accomplish implementation. The results of the first three elements for the F-15/F-16 Radar R&M Improvement Program reveal some important things about the necessary scope and conduct of such special efforts. To lay the foundation for these points we review the results for the F-16 A/B radar and then we turn to the F-15 C/D radar.

Redesign of the LPRF would serve as the cornerstone in implementing an R&M maturation program for F-16's radar. A complete package of R&M improvements for the F-16's radar would include the items listed in Table 1. The improvements fall into three priority classifications based on subjective assessments of their potential benefits.[7] Priority 2 improvements for the F-16 consist of

[7]In spite of these classifications, we recommended that the Air Force pursue all the identified improvements.

Table 1

A MATURATIONAL DEVELOPMENT IMPLEMENTATION PACKAGE FOR THE F-16's RADAR

	Priority 1	Priority 2	Priority 3
F-16 Specific	LPRF	Antenna cable Radio frequency test station Depot environmental testing for LPRF	Technical orders Shop software
Generic	Tracking equipment by serial number Test translation dictionaries	Direct entry testing Loop testing	Material deficiency reporting Technical Orders feedback Interactive pilot debrief

1. Redesigning and re-routing the *antenna cable* to allow replacement at the AIS and thus avoid having to send the entire antenna to the depot for cable replacement
2. Using recently developed technologies to improve the maintainability of the *radio frequency station*, currently the most difficult station to maintain in the AIS
3. Instituting *environmental testing* at the depot to improve repair of the current LPRF and other bad-actor equipment.

Priority 3 improvements for the F-16 consist of

1. Changing *Technical Orders* to make them more consistent, compact, accurate, and useful for maintenance personnel
2. Correcting deficiencies in *shop software* that allow certain faults to escape detection.

Such a total development package could triple the mean time between indicated faults (from six hours to 19 hours) and also reduce the maintenance workload by 35 percent. The total development package (excluding Priority 3 items) would cost $250 million, although some of this cost would be offset by the decreased need for maintenance.

Most of the F-16 money must go to retrofitting the LPRF unit. The principal benefit to be derived from the complete package is a substantial increase in fault removal efficiency from about 7 percent to nearly 55 percent (see Fig. 19). The dimension of MTBF offers less benefit.

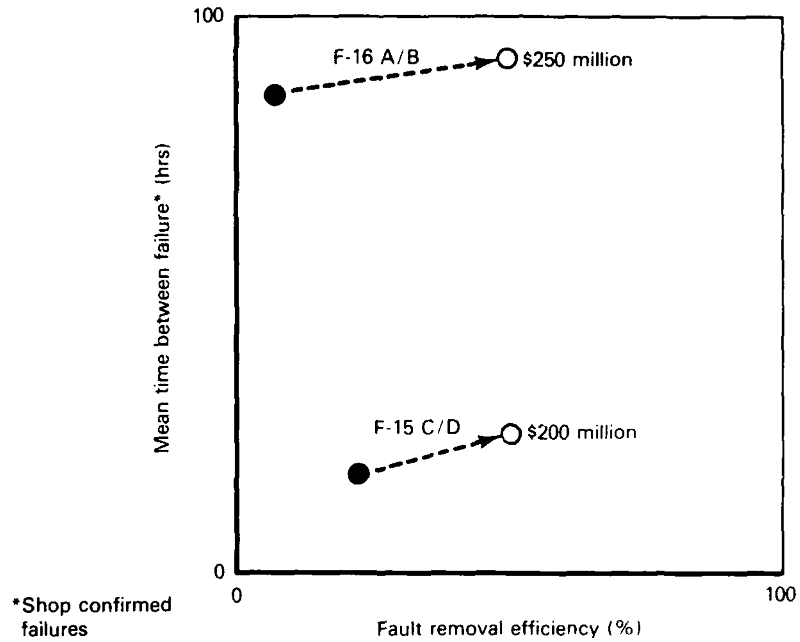

Fig. 19—Opportunities for benefiting from R&M maturation

The large increase in fault removal efficiency, however, would yield a subtantial increase in the number of fault-free flights. Although the precise magnitude of the increase is unclear, because we don't know how many flights were flown with faults that generated no symptoms, we can estimate the potential magnitude by assuming a ratio for the total number of faulty flights to the number of flights with symptoms. Figures 5 and 6 present an example where there were two fault episodes that affected at least 89 flights (48 + 41), although the BIT detected faults on only 41 of the flights. This experience suggests that the number of fault-plagued flights may be as much as double the number with faults indicated by the BIT. On that assumption, the incorporation of the improvement package would increase fault-free flights from 56 to 86 percent.[8]

The dominant problem with the F-15 C/D radar is the BIT itself, which one-third of the time incorrectly indicates a fault when there is none. Moreover, even when there is a real fault present, one-third of the time it indicates the wrong LRU as the location for the fault.

To deal with the F-15's BIT problems, the special data collection and analysis effort of the Radar R&M Improvement Program identified three kinds of needed improvements:

1. *Improvements to the BIT Software.* Although new tactical software is developed and tested each year, the BIT—which is interleaved with this tactical software—is not retested. During the Radar R&M Improvement Program, Hughes engineers found ten situations in which the BIT, because it is interleaved with the tactical software, falsely detects faults.
2. *Additions to the BIT Hardware.* During the data collection and engineering analysis stage, the Warner-Robins ALC sponsored a program to develop special ground support equipment that could augment the BIT function. This equipment necessarily requires up to three hours for use, so it is not designed to support the quick turnarounds required in wartime. Even so, it could still be used during the night when the demands for quick turnarounds are lessened. Moreover, it could be available in about two years.
3. *Improvements to the BIT Hardware.* Adding memory and test points to the BIT hardware will provide more of the capabilities that are being incorporated in the ground support equipment and will allow quick turns without further ground support equipment.

Because the F-15 radar first entered operational service in 1975, it is reasonable to enquire why the BIT deficiencies had not been resolved much sooner. A major factor is that the Radar R&M Improvement Program provided the radar contractor the first opportunity to make an in-depth, first-hand engineering examination of what was happening in the field. Although the radar contractor had had technical representatives assigned to various bases over the years, these representatives could not begin to collect the kinds of data needed to define the specific engineering deficiencies with the current BIT.

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[8]An alternative assumption of 1.5 faulty flights for each flight with a fault indicated means that the incorporation of the improvement package would increase fault-free flights from 67 to 90 percent.

Improvements to the BIT's software and hardware would be the cornerstone in implementing maturational development improvements for the F-15's radar. A complete package of maturational development improvements for the F-15's radar would include the items listed in Table 2. The improvements fall into three priority classifications based on subjective assessments of their potential benefits.[9] Priority 2 improvements for the F-15 consist of

1. Undertaking *LRU fixes* for the radar's exciter, transmitter, receiver, antenna, analog processor, programmable signal processor, and power supply
2. Adding dynamic test and fault-isolation capabilities for the *Antenna A Test Station* in the AIS
3. Instituting environmental testing and adding a complete radar test bench to the *depot equipment*[10]
4. Undertaking research, evaluation, and selection of a replacement for *Coolanol*, which is prone to contamination.

Table 2

A MATURATIONAL DEVELOPMENT IMPLEMENTATION PACKAGE FOR THE F-15's RADAR

	Priority 1	Priority 2	Priority 3
F-15 Specific	BIT software and hardware	LRU fixes Antenna A Test Station Depot equipment Replacement of Coolanol	Technical orders Shop software Reseat problems
Generic	Tracking equipment by serial number Test translation dictionaries	Direct entry testing Loop testing	Material deficiency reporting Technical Orders feedback Interactive pilot debrief

[9]In spite of these classifications, we recommend that the Air Force pursue all the identified improvements.

[10]The test bench allows testing of any radar LRU as part of the overall radar subsystem.

Priority 3 improvements for the F-15 consist of

1. Changing *Technical Orders* to make them more consistent, compact, accurate, and useful for maintenance personnel
2. Correcting deficiencies in *shop software* that allow certain faults to escape detection
3. Identifying reasons why problems with SRU connections seem to disappear when maintenance personnel *reseat* the SRU in the LRU.

Such a total development package could triple the mean time between indicated faults (from four hours to 13 hours) and also reduce the maintenance workload by 50 percent. In total, this development package (excluding Priority 3 items) would cost $200 million, but it is estimated that much of this cost could be offset by the decreased need for maintenance.

Table 3 summarizes the benefits and costs of implementing recommended improvements for both the F-15 and F-16 radars.

Table 3

BENEFITS AND COSTS OF IMPLEMENTING RECOMMENDED PRIORITY 1 AND PRIORITY 2 IMPROVEMENTS

Radar	Mean Time Between confirmed Failure[a] (hours)	Fault Removal Efficiency[b] (%)	Additional Cost (million 1984 $)
APG 63 on the F-15 C/D			
Observed during 1984	19	21	
Projected with improvements	25	50	200
APG 66 on the F-16 A/B			
Observed during 1984	82	7	
Projected with improvements	100	55	250

[a]Mean Time Between confirmed Failure (MTBF) is based on shop confirmation of failure.

[b]A fault removal efficiency of 21 percent means that 21 percent of the flights with a radar fault indicated ended up with the support process removing faulty equipment from the airplane.

The benefits to be gained in spending the $200 million to improve the F-15 C/D radar also appear to be a substantial rise in fault removal efficiency, from a current rate of about 20 percent to an improved rate of around 50 percent.

This increase in fault removal efficiency, combined with a lower MTBF than the F-16 radar, would yield a major increase in the number of fault-free flights. Although the precise magnitude of the increase is unclear, again because we don't know how many flights were flown with faults that generated no symptoms, we can again estimate the potential magnitude by assuming a ratio for the total number of faulty flights to the number of flights with symptoms. Assuming that the number of fault-plagued flights is double the number with indicated faults, then the incorporation of the improvement package would increase fault-free flights from 34 to 79 percent.[11]

From the specific R&M improvement packages for the F-15 and F-16 radars, we next turn to lessons that these packages suggest. Each has a bearing on building the consensus needed to support timely implementation of important improvements.

- Important benefits to be derived from improved R&M include matters other than reduction in costs of operations and support. Principal among these are increased availability of the full measure of the equipment's designed capabilities. Although the true economic benefit of such improvement is difficult to gauge in quantitative terms, understanding of such benefit is crucial to making sound choices about product improvement.
- A key to such increased availability is increased efficiency in fault removal.
- Increasing fault removal for an already fielded system can be very costly when hardware must be retrofitted.
- Causes of R&M problems may lie in many places: the airborne equipment, its built-in tests, its support equipment, its support procedures, and/or debriefing practices of flight crews.
- A cohesive program to mature weapon system R&M may require implementation actions by many organizations within the Air Force.

Building a consensus for necessary and timely action on R&M improvements requires not only sound information, but also a special kind of cooperation by involved organizations.

[11]An assumption of 1.5 faulty flights for each flight with a fault indicated means that the incorporation of the improvement package would increase fault-free flights from 50 to 85 percent.

No Continuity in Weapon System Program Management Responsibility. Achieving such cooperation is complicated by the practice of transferring program management responsibility (PMRT).

In the case of avionics, engineering management responsibilities are transferred from the SPO to the Air Force Logistics Command (AFLC) long before R&M maturation has occurred. This generally occurs during the equipment's early operational life, when engineers assigned to the SPO are only beginning to have an opportunity to identify the equipment's strengths and weaknesses.

Once the AFLC System Program Manager assumes responsibility, a new and much smaller group of Air Force engineers becomes responsible for the equipment's further maturation. These engineers must produce entirely new contracting documents to begin any redesign work. This contracting procedure is far more burdensome than the one that the SPO follows to do the same sorts of design changes before PMRT. Thus, any improvements in equipment maturation slow considerably after PMRT. With an impending transfer of R&M engineering responsibilities, it is also difficult to keep the development organization interested in improving R&M, especially when routinely collected statistics reveal no great need for such improvements.

To illustrate the effect of these difficulties, consider the case of the LPRF. In part because PMRT has occurred, and in part because a consensus has been slow to materialize, the contract for the development of a new LPRF unit cannot be let until late 1989. Figure 18 shows that this is almost four years after engineering efforts analyzed the problem and recommended redesigning the LPRF unit.

Poor Coordination of Management of Weapon System after PMRT. Following PMRT, there is another complication. Entirely different Air Logistics Centers may be responsible for the airborne equipment and the support equipment. Although in theory these organizations work together, in practice the weapon system no longer enjoys the single source of management attention that the SPO once could devote to it. Such splitting of management attention after PMRT poses special challenges to a timely implementation of a cohesive program of improvements such as the ones illustrated in Tables 1 and 2.

STRENGTHENING THE PRODUCT IMPROVEMENT PROCESS

To strengthen the responsiveness of the product improvement process to the causes of a weapon system's dominant R&M problems we propose a three-part strategy that includes improving the flow of information from the field, increasing field engineering, and expediting important improvements.

Improving Information from the Field

By applying the proposed new view of R&M to data already being acquired by the Air Force's existing MDC system, the Air Force can better identify areas where further R&M investigation is most needed.[12] Monitoring and analyzing information from the previously proposed tracking of avionics performance by equipment serial number and determining why the routine support process fails to correct problems, would make the product improvement process more aware of the dominant R&M problems being experienced in the field.

Increasing Field Engineering

A rational approach to R&M management must include arrangements for addressing the reality that following IOC more work will have to be done on any system—especially sophisticated systems such as radars—to raise the maturity of their R&M characteristics to an acceptable level. One way to do this is to get equipment contractor engineers more involved in understanding R&M from the viewpoint of the operators and the maintainers in the field. A capability to do performance-oriented tracking of equipment after repairs have been completed will help, but an actual presence in the field will be required to identify the causes of major problems in the more complex subsystems. This will require more special data collection activities such as the one that emphasized the F-15 and F-16 radars.

Expediting Important Improvements

Effective product improvement must also be timely product improvement. Special data collection and analysis efforts should be scheduled to begin immediately after the Air Force has a few squadrons at IOC. That change alone would have saved about four years from the time line in Fig. 18.

The actual development of the most critically needed improvements should begin right after the data collection and analysis phase. In the F-16 radar case that would have saved an additional four years. To do this, the Air Force would need to preprovision funding so that the implementing improvements phase can be scheduled immediately

[12] Petruschell, Smith, and Kirkwood, 1987.

following analyses and decisions about recommended improvements. The Air Force would also need to establish policies and procedures for arriving at consensus to expedite important improvements. If such funding and programmatic provisions had been made for the F-16 A/B Radar R&M Improvement Program, the retrofitting of a new LPRF would already be completed, instead of having to wait till 1994. But even more, there would be fewer items to retrofit in the F-16 radar because the development effort would have broken into the production line before production was concluded on the LPRF LRU.

By adopting such immediate data collection and development for critical improvements, the Air Force could initiate much of the most important R&M maturation work before PMRT, thus avoiding further delays.

SUMMARY

By improving the amount and source of field information with better collection efforts and in-depth field engineering investigation, the Air Force gains a very different and extremely useful perspective on the R&M needs of weapon systems. Knowledge of the most serious R&M problems with vital equipment and associated support resources increases immensely. Better knowledge coupled with improved procedures for building a consensus on what needs to be done for specific weapon systems should lead to wiser and more beneficial investments in product improvement, thus enhancing vital R&M characteristics.

V. THE ACQUISITION PROCESS

The new view of weapon system R&M emphasizes two R&M characteristics:

- Fault initiation,
- Fault removal.

Although the first is determined exclusively by the airborne equipment,[1] the second is influenced by a combination of that equipment and the associated array of ground support equipment used by technicians on the flight line, in the air base shops, and at the depot's repair facilities. Thus, to fulfill responsibilities for both characteristics, the weapon system acquisition process needs to research, develop, and procure

1. *Airborne equipment* that will dependably deliver the Air Force's specified levels of performance when that equipment is operated and maintained by people of normal skill and in accordance with Air Force approved technical data,
2. Weapon-system-peculiar *ground support equipment* needed for routine support of the designed capabilities of the airborne equipment,
3. *Technical data and any special equipment* needed to support the correction of any faults not resolved by the routine support process.[2]

Such a broad view of weapon system acquisition responsibilities is key to the notion that weapon system maintainability needs to reflect the ease with which the complete support process (from flight line through depot) can restore the designed capabilities of airborne equipment.

WEAKNESSES IN THE WEAPON SYSTEM ACQUISITION PROCESS

Our review of the ability of the current acquisition process to provide for both R&M characteristics has identified three weaknesses:

[1]We always use the term *equipment* to refer to hardware and any associated software.

[2]Recall the need for test translation dictionaries and special equipment for the depot repair facilities to fix bad actor equipment (Sec. III).

- Failure to use a meaningful set of management measures for R&M,
- Lack of a process for setting rationally based R&M goals for future equipment,
- No strong assurances that needed levels of R&M will be delivered.

Failure to Use a Meaningful Set of Management Measures for R&M

Especially within the acquisition process, the traditional view of R&M assumes that equipment is broken or it's fixed and it's easy to identify when it is broken. Such a view leads to relatively simple management measures for characterizing R&M: mean time between failure (MTBF), mean time to repair (MTTR), and fully mission capable (FMC) rate. Such a set of measures provides only a partial picture of the R&M situation. The lack of situational awareness greatly weakens the ability of the acquisition process to respond fully to R&M needs.

An effort to improve R&M situational awareness must cope with two challenges. First, R&M is a quality that has many dimensions. Second, precise characterization of this quality becomes more difficult as the complexity of the equipment and its support process grows. Each of these realities is especially applicable to modern military avionics.

For such equipment the two main dimensions of interest are the mean time between initiation of new faults and the efficiency of the maintenance process in removing faults. The usual practice is to estimate MTBF by calculating the mean time between shop confirmed failures; that usually provides a plausible estimate for the mean time between initiation of new faults.[3] To complement the MTBF parameter, the Air Force needs a parameter that reflects the efficiency of maintenance technicians in fully restoring the designed performance of a system once a fault has developed. Lacking such a measure, the acquisition process is failing to attract management attention to the more serious maintainability problems.

Lack of a Process for Setting Rationally Based R&M Goals

Even with the measures currently used in the acquisition process, the Air Force lacks a rationally based process for setting R&M goals for future equipment. Although broad goals, such as direction to

[3]This assumes that the equipment and its support process have achieved a state of equilibrium where the rate at which the shop is confirming (and removing) faults exactly matches the rate at which new faults are being generated.

double weapon system reliability and halve maintenance, convey a message that the Air Force is serious about reliability and reduced maintenance, more specific guidance needs to be established for equipment developers.

Consider the idea of simply doubling the reliability of everything in the weapon system. First, reliability is not a free good; it is achieved through investment of time and resources. Moreover, with most equipment and parts the cost of increasing reliability becomes more expensive as the level of reliability rises. Second, the achieved level of reliability is much like the strength of a chain; it is determined by the strength of its weakest link.

In many cases, a weapon system's overall reliability will be dominated by the reliability of about one-fourth or fewer of its subsystems. Each subsystem likewise has a reliability that may be dominated by perhaps only one-fourth of its major assemblies. Each such major assembly's reliability may be dominated by only about one-fourth of its subassemblies. And finally, each such subassembly's reliability may be dominated by only about one-fourth of its parts. Thus, reliability of a weapon system will be dominated by a very, very small portion of its total parts. In our hypothetical example, there would be only about four parts in one thousand[4] that would dominate overall R&M. The challenge for the acquisition process is to direct attention to those areas that provide the greatest leverage in terms of cost beneficial improvements to R&M.

Reliability goals, at all levels of assembly, need to be carefully established in view of not only the prospective contribution to overall weapon system reliability, but also the differential costs of achieving reliability goals for different types of equipment. A rationally based goal setting process also needs to address the differential nature of the benefits to be derived from alternative levels of reliability for specific types of equipment. Consider an analysis of what improved reliability of the F-16 A/B weapon system could have yielded in several dimensions of different benefit:[5]

- Reductions in base-level maintenance manpower
- Reductions in certain engine and spares costs
- Improvements in squadron deployment flexibility.

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[4] $.25 \times .25 \times .25 \times .25 = .004$.

[5] For a full description of this potential benefit analysis, see Abell, Kirkwood, and Petruschell, 1988. Although the actual amount of estimated benefits is substantial, it was beyond the scope of the analysis to estimate the costs or other resources that would have been required to achieve the postulated reliability improvements.

To simplify the calculations, we assumed that the mean time between maintenance request (MTBMR) would also quadruple, as would the mean time between demand (MTBD) for parts. These assumptions are reasonable approximations to the extent that maintainability characteristics do not change to any appreciable extent.[6]

Maintenance Manning. A twofold improvement in the overall reliability of the aircraft—i.e., a 50 percent reduction in the rate of maintenance actions on all components of the aircraft—could reduce maintenance manpower requirements an estimated 9 percent, given the same level of wartime flying activity.[7]

The manpower savings occur almost entirely in the component repair squadron. The requirements for avionics technicians could be reduced by about a fourth and for propulsion technicians by about a third, accompanied by more modest reductions in other skills. Including training costs, these reductions would represent an annual savings of about $5 million per 72-PAA wing.

Spares Cost. The effects of improved reliability (as reflected by component removal rates) on the investment costs of spare engines and engine modules, and the procurement, depot-level repair, and condemnation costs of recoverable aircraft spares for the F-16 A/B program were also estimated in this work. A twofold reliability improvement in fire-control and propulsion system components alone (as reflected by a 50 percent reduction in component removal rates), given a constant 80 percent aircraft availability goal, would have yielded an estimated cost avoidance of $1.2 billion in constant, undiscounted FY84 dollars in these resource categories over the 13-year period from 1978 through 1990.

Deployability. Improving reliability also decreases the number of personnel and the tonnage of spares and equipment required to support tactical deployments. The postulated twofold reliability improvement for a 24-PAA F-16 A/B squadron would reduce its burden of bare-base deployment support during the first 30 days of a deployment by an estimated 40 tons. Although seemingly large in absolute terms, it is only about 5 percent of the total tonnage required, much of which comprises tractors, trailers, and loaders for handling munitions and towing aircraft. Thus, reliability does not dramatically effect

[6]In the previous section we addressed the possibility of major changes in maintainability that also could cause substantial changes in both MTBMR and MTBD. However, regardless of what mixture of maintainability advances and reliability improvements were to achieve a fourfold improvement in MTBMR and MTBD, the derived benefits would remain the same.

[7]Alternatively, the reduction in maintenance manning described could be traded for an estimated 17 percent increase in wartime sortie generation capability with current manning levels.

deployment support requirements.[8] Figure 20 summarizes the benefits for two cases:

- A doubling in reliability (results designated by the "2x"),
- A quadrupling in reliability (results designated by the "2x").

The results designated by the "1x" reflect the weapon system's current level of reliability. The findings reported in Abell, 1988, have been adjusted to 630 aircraft, four wings deployed, a 15-year life cycle, and 1986 dollars.

In percentages, the manpower (air base maintenance) benefits may not look striking—a fourfold improvement in mean time between maintenance requests yields about a 15 percent reduction in manpower. But consider that much of these savings of about 2,000 people worldwide would be in high-skilled avionics and propulsion specialties.

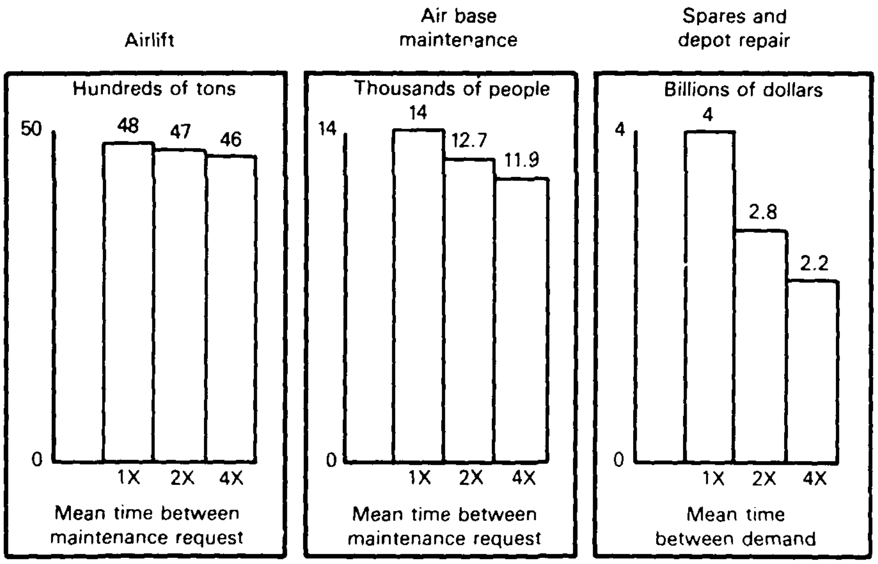

Fig. 20—Summary of benefits from study of improved reliability on F-16 A/B weapon systems

[8]The airlift (deployment) benefit for the F-16 is modest because during the first 30 days of a deployment the F-16 does not deploy an Avionics Intermediate Shop (AIS). A similar case study for the F-15, whose AIS is deployed with the aircraft, would yield a much greater airlift savings.

Evidently the area of the greatest benefits from improved reliability is the costs of spares and depot repair (excluding base level maintenance repair cost). Doubling the reliability (in terms of mean time between demand for parts) yields a $1.2 billion savings over the 15-year life cycle of the systems. A fourfold improvement yields yet another $600 million in reductions. Because the results show a diminishing return to further increases in reliability, no more than a fourfold improvement in the overall mean time between demand for parts for the next fighter airplane may be a reasonable requirement.

Individual analyses for each subsystem would need to establish precise goals for individual types of subsystems. Such analyses must consider the prospective cost of achieving alternative levels of reliability. Because such costs depend on many factors peculiar to the technologies used in a design, as well as the design itself and conditions of equipment use, we can not make a general forecast of tl :ost of alternative levels of reliability.

Appropriate R&M management measure(s) for maintainability need to be addressed in addition to reliability.

No Strong Assurances that Needed Levels of R&M Will Be Delivered

Once appropriate R&M goals are established, the next challenge for the acquisition process is to provide strong assurance that the needed reliability *and* maintainability characteristics will be delivered. Because of the complexity of aircraft weapon systems and their associated support systems and the urgency normally associated with their development and initial fielding, it is only prudent to base our approach to acquisition on the view that:

> **Following initial introduction to operation, some significant amount of product improvement will be required to mature R&M characteristics to needed levels.**

The Air Force's ability to assure that needed levels of R&M will be delivered is determined by the strength of the product improvement efforts that can be brought to bear in areas of deficiencies. Needed product improvement activity is lacking in the aircraft weapon system acquisition process, notwithstanding two classes of efforts by the Air Force:

1. Warranties and
2. Government funded R&M improvement programs.

Warranties.[9] Although warranties have long been a common part of commercial business practice, often as an element of price competition, until recently they were applied only occasionally to military equipment, mainly avionics and other subsystems. The services expressed satisfaction with some applications and cited problems with others. Then in 1983 Congress passed the Defense Appropriations Act for 1984, since modified by the Defense Authorization Act of 1985, requiring the armed services to obtain warranties on all major buys of weapon systems.

The Congressional intent seems to be a combination of desires based upon pragmatic considerations about the acquisition process. Major aircraft weapon system acquisition programs usually contain large elements of uncertainty and urgency,[10] once started they are difficult to abandon, and major weapon deliveries, even if very short of certain specifications, are difficult to reject. Newly developed weapon systems generally represent such substantial advances on the equipment they are to replace that the government is ill-disposed to writing off years of development by rejecting delivery. The services recognize, moreover, that the road to fuller compliance with the mission-essential aspects of the performance specifications often requires working with the contractor's engineering staff rather than becoming embroiled in legal disputes.

The Congress, growing impatient with recent acquisition program outcomes, seems to want a better track record in terms of the match between the performance specifications promised during the bidding process and the performance eventually measured in the field. Warranties seem to offer an opportunity for remedies that can be tied proportionally to the shortfalls in essential performance. Congress seems to see requiring warranties as a way to instill more discipline in the relationships between the services and their contractors.

Some view warranties as providing an opportunity to insure acquisition program outcomes because the contractor is obliged to accept prescribed risks that empower the government to assess blame and extract damages in a predetermined and agreed upon manner. Major concerns about such a strong view include some specific to R&M in addition to some of a general nature:

- First, pragmatic considerations still limit the economic value of the maximum damages that the government can extract, no matter how great the economic cost of the damage.

[9]For a more detailed discussion see Stucker and Smith, 1987.

[10]Most of the major weapons bought by the military are very advanced, complex, risky products that do not have counterparts in the commercial world.

- Second, there are serious questions about the extent to which the government can totally shift risk to the contractor. The government shares a role in approving design and setting forth specifications[11] that subsequently may prove either beyond the state of the art or vulnerable to some other supervening impossibility[12] that interferes with the contractor's ability to discharge his responsibilities. Either event lays grounds for legal disputes about the validity of a contract.
- Third, even if pragmatic and legal considerations do not interfere, economists will caution that it is rarely to the government's advantage to buy insurance from a private firm.[13] Most analysts believe the government should usually self-insure: It has more resources than any firm and a better ability to survive losses, it has more projects under way at any given time and can better spread large risks, and it is less risk-averse than typical profit-motivated firms.

These general concerns flow from the inescapable reality that major weapon systems differ from commercial products in fundamental ways that will effect the manner in which warranties should be applied to military equipment. For example, the *primary objective* of a *weapon system* warranty, as distinct from a commercial warranty, should be

> **To mature the weapon system to a point where there is an acceptable probability that the system will deliver the full measure of its designed capability whenever called upon in combat.**

When a fighter pilot is assigned an aircraft to take into combat, what he needs is confidence that his afterburner, radar, and other essential equipment are prepared to deliver the full measure of their designed capabilities during combat.

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[11]The design and development of most major military acquisitions are typically supervised and controlled by the services: The product is not uniquely the responsibility of the firm that develops and produces it; and that firm is usually not in a position to take full responsibility for the design.

[12]For example, military products are frequently ordered into production long before their test programs are completed, and certainly long before their R&M characteristics can be fully validated.

[13]Although it may be appropriate to view warranties for commercial products as a form of insurance, there are many different views of warranties in the government/contractor context. One view holds that it is naive to think of warranties in this context as insurance when the main purpose of the warranty is to try to get the contractor to bid honestly.

To see whether warranties might provide assurance for achieving such an objective, we examined two sets of warranties:

- One set written before the new laws were passed
- The second set written since January 1, 1985.

Although our examination of the older warranties was limited by a dearth of available information, reading of program documents and discussions with government and industry officials suggest that four factors may be important to the ability of such warranties to contribute to R&M objectives:[14]

- Specific, measurable, pertinent objectives,
- Explicit, unambiguous remedies,
- Explicit duties for the contractor and government,
- Reasonable prices and expectations.

At this time we cannot say that these factors insure favorable outcomes, or even that they are usually associated with them. But they were important to warranty programs that people have viewed favorably, and their absence was frequently mentioned as a problem on the more troublesome programs.

Examination of the set written to comply with the 1985 law revealed some interesting contrasts with the earlier warranties. In particular, two major attributes that contributed to the success of earlier warranties are missing from many of the newer ones: the simple definition of measurable objectives and the precise, prespecified remedies expected of the contractor.[15] We are concerned that such nonspecificity can easily lead to misunderstandings and possibly to threats of nonperformance and litigation.

Because warranties are being applied in so many diverse forms, the systematic acquisition of information about these different experiences is essential to building a body of knowledge upon which future warranties might more fruitfully be framed and applied in areas where they have the most cost beneficial effect. Unfortunately, we find that the services are spending a lot of money and effort specifying, negotiating, implementing, and enforcing warranties, without much information on whether it is all worthwhile. Meanwhile, although data and contractual language are being gathered sporadically by various agencies, a systematic and coordinated process has not yet been established for acquiring data essential to evaluate the effectiveness of individual warranty programs.

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[14]See Stucker and Smith, 1987, Sec. III.

[15]Stucker and Smith, 1987.

Lacking solid evidence of a sufficient connection between warranties and achieved levels of R&M, we would be imprudent to rely solely on warranties to mature a complex aircraft weapon system to a point where there is an acceptable probability that the system will deliver the full measure of its designed capability whenever called upon in combat.

Government Funded Product Improvement Programs. Not only have warranties fallen short of providing strong assurances that development programs will deliver needed levels of R&M, but the usual government funded product improvement programs have also fallen short. Even the special F-15/F-16 Radar R&M Improvement Program has yielded, at best, a slow response to the most needed improvements.

STRATEGY FOR IMPROVING THE WEAPON SYSTEM ACQUISITION PROCESS

To strengthen the ability of the acquisition process to meet its responsibilities to deliver weapon systems with needed R&M characteristics, we propose a strategy that includes expanding awareness of R&M deficiencies, emphasizing fault removal efficiency, accelerating maturation of avionics, and reorganizing avionics development.

Expanding Awareness of R&M Deficiencies

To improve the R&M record of the acquisition process, the government and industry organizations that are responsible for the development of new equipment need to expand their awareness of the dominant R&M deficiencies in currently fielded equipment. Implementation of the proposals to strengthen the support process and the product improvement process will highlight such deficiencies and their root causes. Thus, efforts to improve the acquisition process will benefit from improvements to these other processes. An improved acquisition process will in turn lighten the burdens that now must be borne by these other processes.

Emphasizing Fault Removal Efficiency

Improved awareness of the dominant problems is only an initial step that needs to be followed by a greater emphasis on fault removal efficiency in new developments. We propose that the Air Force adopt fault removal efficiency in conjunction with the MTBF parameter to provide a comprehensive capability to view the overall R&M situation for complex subsystems in aircraft weapon systems.

We base this proposal on the following goals:

- Provide a comprehensive overview of the R&M situation at the subsystem level,
- Reflect the full range of problems that arise in identifying faults and isolating their causes,
- Account for all flights with indications of faulty subsystem operation.

To achieve such thorough accounting, pilots and technicians need to report all indications of situations where either they or the BIT perceive a subsystem's performance departing from designed capabilities. Such full reporting of symptoms is absolutely essential.[16] Such thorough accounting for all perceived indications of faulty operations is a complete change from the comfortable traditional view that a problem not found on the ground did not exist in the air.[17]

Approach to Estimation. The following method for estimating fault removal efficiency is consistent with the noted goals:

$$\text{Fault Removal Efficiency} = \frac{\text{MTBI}}{\text{MTBF}} \times 100\%$$

where

MTBI = Mean flight time between flights with indication(s) of faulty operation of the avionics subsystem.

MTBF = Mean flight time between flights that resulted in shop confirmation of a failure of the avionics subsystem.

Critical Concerns. To arrive at a meaningful MTBI, pilcts not only need to report all indications of suspected faults, but maintenance personnel need to maintain a historical record of such pilot reports for the critical subsystems on each aircraft.[18]

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[16]It also depends upon the pilot's ability to recognize degradations in performance. Such ability can be enhanced by making pilots aware of criteria that they should apply and special tactics they can employ to verify the performance of their equipment.

[17]Such a philosophy becomes increasingly inappropriate as the nature of avionics faults shifts toward ones where symptoms are situation-dependent. Some symptoms appear only under flight stresses, while others depend upon the mode of equipment use.

[18]As noted in Sec. III, such serial number tracking of aircraft is also essential to improving the capability of maintenance technicians to identify units of equipment (both LRUs and SRUs) having faults that are evading detection by the standard tests used by shop and depot technicians.

To productively achieve its full potential, thorough reporting of symptoms for suspected faults will require a new mind set for pilots, technicians, maintenance supervisors, and maintenance managers. Pilots and technicians need an environment where they can feel comfortable in documenting and discussing symptoms. For example, rather than penalize squadrons and wings for the quantity of symptoms reported, incentives need to be created to encourage dialogue between pilots and maintenance.

The end goal of unit evaluations should be based on the achieved condition of the unit's equipment rather than intermediate measures of how the unit achieves such an end goal. Indeed, the wing with the highest rate of reported symptoms may have its equipment in the highest state of readiness in terms of ability to deliver the full measure of designed capabilities. And the wing with the fewest reported symptoms could be in the opposite position if the reason for the low reporting rate is simply a greater toleration of degraded performance.

Incentives must encourage a free flow of such information between pilots and maintenance. One way to avoid problems in this respect would be to refrain from comparing units based upon their fault removal efficiency for specific subsystems. Such comparisons could make it awkward for units to document symptoms. However, those involved in the acquiring and improving of avionics should understand which subsystems pose the greatest burdens in terms of fault removal efficiency. One way to deal with such information would be to aggregate it so as to preclude the identification of specific units.

Application to Existing Subsystems. An example can show the utility of this indicator. Suppose a subsystem averages 82 flight hours between flights with a failure confirmed by the shop (MTBF = 82 hours) and averages six flight hours between flights with an indication of one or more faults (MTBI = 6 hours). Although the MTBF indicates very good reliability for a technologically sophisticated subsystem in a modern combat aircraft, the comparatively lower MTBI raises a flag about the subsystem's maintainability, as does the following estimate for the fault removal efficiency:

$$\begin{array}{c}\text{Fault}\\ \text{Removal}\\ \text{Efficiency}\end{array} = \frac{6 \text{ hours}}{82 \text{ hours}} \times 100\% = 7\%$$

This result means that maintenance personnel could find a shop-confirmed fault in this subsystem for only 7 percent of the flights where symptoms were indicated for one or more faults, ensuring that a high reliability indicator does not obscure a subsystem's poor maintainability.

Such a low fault isolation efficiency should draw acquisition management attention to the possibility of problems in one or more of such areas as the timeliness of requests for maintenance, the avionics subsystem itself, the BIT, the shop equipment and tests, the depot equipment and tests, the Technical Orders, and training of maintenance personnel. To identify the specific problems that are the dominant causes of such low performance usually will require the subsystem's developers to field a special engineering data collection and analysis effort.

Figure 21 shows how using MTBF and fault removal efficiency in concert can provide a composite view of the R&M of a system. As the figure shows, the F-16 A/B is far better than the F-15 C/D radar in MTBF, but its fault removal efficiency is actually worse. Nevertheless, in both cases the fault removal efficiency is still very low, which can actually confuse the difference between reliability and maintainability, especially when irrelevant repairs occur in the shop. (Recall that MTBF is based upon shop-confirmed failures.) This is one reason why a composite view (as in Fig. 21) is needed to provide a complete view of

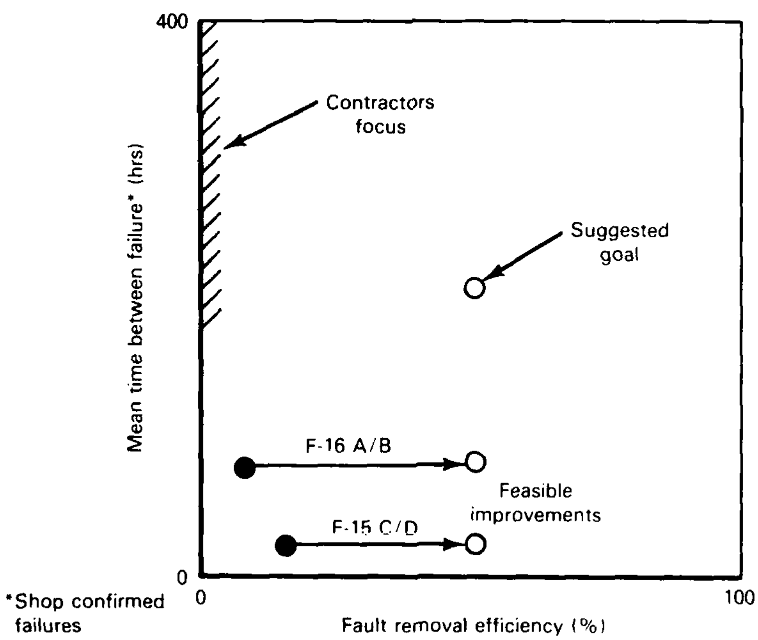

Fig. 21—Radar R&M goals for 1990s fighter aircraft

R&M. Such a perspective would also direct attention to the linkage between the ability of weapon systems to deliver their designed capabilities and the increasingly critical roles of BIT, fault reporting and recording, shop test equipment, and depot test equipment.

Application to Future Acquisition Programs. Figure 21 shows how fault removal efficiency and MTBF could be used to provide joint guidance on R&M for the development of a new subsystem. This figure is similar to Figs. 14 and 19, but now the scale has changed on the vertical axis to make room for more information. For the 1990s, contractors are estimating that they can provide a new fighter radar with an MTBF in the ball park of 200 to 400 hours. At one point, one leading radar manufacturer was estimating an MTBF of about 400 hours. Senior engineers for another leading radar manufacturer have expressed the belief that an MTBF of about 200 hours would be ambitious, but achievable if some new technologies mature rapidly enough. Realistically and practically, estimates at this stage of R&D often exceed eventual field experience by a factor of two, sometimes by a factor of ten. At this point, striving for a goal of about 200 hours (actual field experience) seems reasonable and is consistent with the notion of an overall quadrupling of weapon system reliability.[19]

In the fault removal efficiency dimension, there is little historical information upon which one can base a goal, other than the F-15/F-16 Radar R&M Improvement Programs. Targets for improved fault removal efficiency rates, given the investments identified in Sec. IV, are at about the 50 percent level. These are substantial improvements over the 7 percent fault removal efficiency rate for the F-16 radar and the 20 percent rate for the F-15 radar.

Because there are always going to be some R&M problems with such complex equipment as fire control radars, we need to set realistic goals. Rather than ask for perfection, which cannot be achieved, we instead propose something that appears technically reasonable by virtue of the aforementioned radar R&M improvement programs. Accordingly, we suggest that R&M management strive for a combination of

- The 50 percent fault removal efficiency goal that appears achievable for existing radars,
- A 200 hour MTBF (as eventually measured from field experience).

[19]The F-15/F-16 Radar R&M Improvement Program data from 1984 yielded an MTBF of 19 hours for the F-15 C/D radar and 82 hours for the simpler F-16 C/D radar. A fourfold improvement on these experiences would yield an MTBF in the ball park of 76 to 328 hours. Because the sophistication of the next generation fighter radar will probably be pushing the then available state of the art, as the F-15 radar did more so than the F-16 radar, a goal for the next generation radar needs to be cognizant of the F-15 radar experience in addition to that of the F-16.

The important aspect of this suggestion is not the precise numbers but rather the illustration of a process for establishing balanced goals. Balance is essential to direct appropriate attention and resources to each of the important dimensions of R&M.

Accelerating Maturation of Avionics

This element of the strategy for strengthening the acquisition process aims at more timely and fuller achievement of R&M goals. Although it focuses on aviation electronics (avionics)[20] because this class of equipment currently presents the greatest R&M challenges, the general concept of maturation is applicable generally to the development of very complex systems.

General Concept of Maturation. Our general concept of maturation is based on viewing the research and development of a very complex weapon system as a process that has six basic phases:

I. Technology development
II. Critical component development
III. Subassembly development
IV. Assembly/unit development
V. Subsystem development
VI. Weapon system integration development.[21]

An orderly and efficient development program will invest just the right amount of time and resources in each phase; and while phases will overlap, they will be neither initiated nor terminated too soon.

During each basic phase, we use the concept of maturity as a qualitative gauge of the status of development efforts. We say that a phase has reached *maturity* when both the *state of knowledge* and the *level of performance (including R&M characteristics)* indicate that it is reasonable to initiate the next phase. The term *full maturity* designates the situation where knowledge and performance have advanced to where it is reasonable to terminate the development work within that phase.

Our general concept of maturation holds that whether we are deciding to initiate or to terminate a phase, the decision should be based on scientifically accumulated evidence of progress and an objective

[20]Including airborne electronic warfare equipment.

[21]In the case of an aircraft weapon system, recall that we define the weapon system to include the system-peculiar ground support equipment in addition to whatever other data and equipment are required to fully restore the capabilities of the airborne equipment. Such equipment goes through the development phases just as does the airborne equipment. Phase VI is then responsible for integrating all of these elements of the weapon system.

assessment of the likelihood that lingering difficulties can be resolved before efforts in the next phase get too far along. Within this framework, the soundness of the basis for decisions can be examined in terms of the extent to which phases preceding a decision have systematically explored possibilities and alternatives using the scientific method of:

1. Observing
2. Questioning
3. Forming hypotheses
4. Testing hypotheses by
   a. Measuring
   b. Organizing and recording data
5. Interpreting data
6. Drawing conclusions.

From the vantage point of our general concept of maturation, when development efforts fail to fulfill their technical potential, it often can be viewed as a consequence of one or more of three basic types of development problems:

- Type 1. Flawed application of the scientific method,
- Type 2. Premature initiation of a basic phase of development,
- Type 3. Premature conclusion of a basic phase of development.

For avionics, such problems can be observed during each basic phase of development; and although development programs may survive, R&M characteristics often suffer. To reduce the occurrence and the influence of such R&M-degrading problems, RAND's current research on avionics R&M has emphasized strengthening the acquisition process during during Phase V (subsystem development) and Phase VI (weapon system integration development).[22]

Particular Concept of Maturational Development. For these phases, we have proposed a particular form of the general concept of maturation that we call maturational development. Because the development of avionics subsystems and associated support equipment often proceeds so quickly, little of the systematic maturation advocated by the general concept takes place. To correct this situation, we have proposed that the Air Force institute a formal period in the acquisition process for which development programs would be required to set aside time[23] and resources:

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[22]Gebman, Shulman, and Batten, 1988.

[23]The acquisition process must resist overemphasizing speed of development because an undue emphasis on speed can lead to failure to (1) collect accurate and relevant data concerning potential problems with maintaining the full measure of designed perfor-

- Measuring operational experience, organizing and recording R&M-related data, interpreting the data, and drawing conclusions about the root causes of the dominant R&M problems that are responsible for any shortfalls in needed R&M characteristics.[24]
- Correcting R&M deficiencies, preferably before PMRT.

This particular concept is based on the thinking that a design for a very complex subsystem and its associated support equipment[25] should be viewed much like a set of hypotheses until rigorous testing and operational experience demonstrate that the design delivers the needed levels of performance (including R&M). The prudence of such thinking is supported by the recurring observation that

> **Until they have had detailed data about actual operational experience, developers have failed to identify the root causes of the most serious problems that have plagued their equipment's operation.**

Design methods and tools cannot predict all causes and modes of degraded performance. During the design process, designers lack complete information about new materials and processes needed to manufacture avionics subsystems with advanced technology. Moreover, they cannot foresee all environments in which the avionics subsystems will perform, nor all complex interrelations among them because of the the multiple functions of most subsystems, the multiple operating states for many functions, and the complex integrations among subsystems.

mance, and (2) redesign portions of the weapon system and its support system to avoid these problems. When fielding new weapon systems, we need to watch not only the time to IOC but, more important, the largely ignored time to a fully matured operational capability. The latter can take much longer, as can be seen in the time needed to introduce radar R&M improvements for the F-15 and F-16. This maturation time would be shortened considerably if the Air Force scheduled a formal maturation process into the overall acquisition process.

[24]Gebman, Shulman, and Batten, 1988, refers to such a set of actions as *Stage 1: Data Collection and Analysis*. This stage collects data based on operational experience to determine where, how, how often, and why combat-essential avionics subsystems may fail to deliver their full designed capability. *Stage 2: Implementation of Further Development* involves a further development effort aimed exclusively at reducing the frequency of failure and degraded performance and at increasing maintainability. Using the data and analyses from Stage 1, the developer may have to change materials, derate certain components, and redesign others. He may also have to impose tighter quality control on certain materials and production methods. To improve maintainability, the developer may have to change the BIT circuitry and programs, the system partitionings, and the test points. He may have to add test points and capture more information about the airplane's mode of use at the time of degraded performance.

[25]Including software and Technical Orders governing its operation and maintenance.

Consequently, designers need at least one development effort, including an opportunity to gather information from field operations, to understand the dominant R&M problems and their causes. The government likewise needs such an operational evaluation to gauge status and understand the magnitude of the further development efforts needed to achieve its R&M goals. For particularly advanced and complex equipment, such a pattern of iterative development, illustrated in Fig. 22, may require several efforts to achieve needed goals.

Proposed Applications for Maturational Development. We recommend a formal maturational development phase for three classes of complex combat-essential avionics subsystems:

- New subsystems that are just beginning development,
- Existing subsystems that are being modified to improve their functional performance,
- Existing subsystems where improvements in reliability and maintainability would substantially narrow the gap between designed performance and operationally available performance.

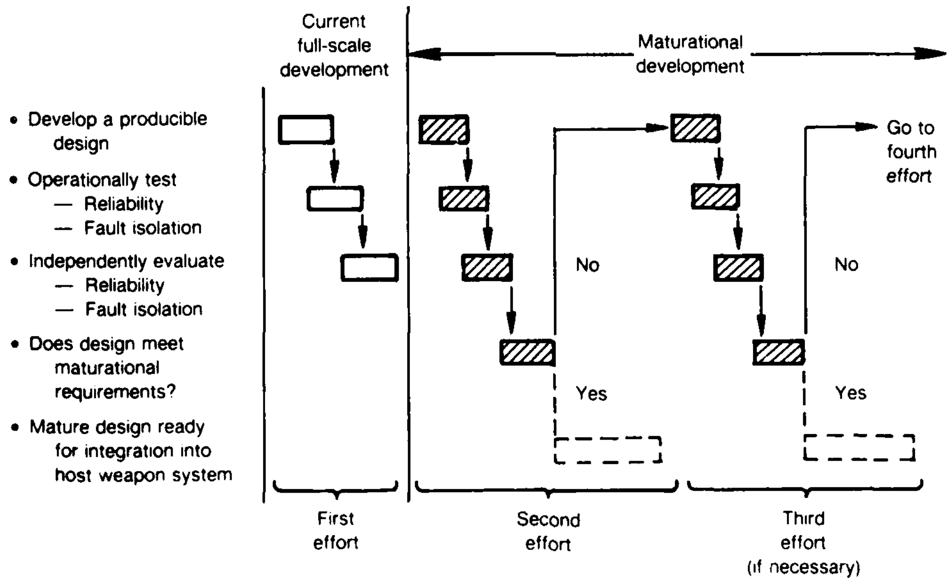

Fig. 22—Maturational development: A multiple phase process

Maturational development can achieve the largest benefit-to-cost ratio when aimed at developing selected new avionics subsystems that are just beginning development (Phase V of the development of a weapon system). In such cases, it should occur *before high-rate production* to avoid the high costs of retrofitting hardware. For this class of equipment, the Air Force might most profitably begin with new avionics for the new Advanced Tactical Fighter (ATF).

A maturational development phase can greatly improve selected existing avionics equipment particularly when improvements

- Involve large changes,
- Affect the weapon system's overall design,
- Increase the airplane's modes of operation,
- Substantially raise performance specifications for existing modes,
- Make a large proportion of its components no longer interchangeable with those of the previous model.

Furthermore, already fielded equipment can also benefit. In these respects the Air Force should consider instituting maturational development for

- Fire control radars such as the APG 68 for the F-16 C/D, APG 70 for the F-15 E, APQ 164 for the B-1B;
- Electronic countermeasures equipment such as the internal countermeasures set for the F-15, the threat warning system for the F-16, the advanced self-protection jamming system for the F-16, and the jamming pods with application to numerous weapon systems;
- Weapon delivery systems for the F-15 and F-16;
- Low altitude night targeting infrared (LANTIRN) navigation and targeting pods.

Although each of these programs has an ad hoc plan for maturing R&M, we believe that each would benefit from taking the further step of committing to a formalized process where funds, time, and responsibility would be established in accordance with a standardized format and reviewed accordingly. Lacking such commitment and oversight, the time and funds for R&M maturation are constantly at risk as development programs suffer through the growing pains of achieving needed levels of functional performance.

Reorganizing Avionics Development

This final element of the strategy for strengthening the acquisition process aims at reducing the R&M-related development problems that occur throughout the process of developing a weapon system. To this end, we propose a reorganization that aims at two goals:

- Institutionalize maturational development during Phase V (subsystem development) and Phase VI (weapon system integration development),
- Expedite the maturation and application of new technologies by better focusing both government and industry sponsored R&D during Phase II (critical component development) and Phase III (subassembly development).

Institutionalizing Maturational Development. Ideally, subsystem development (Phase V) would start far enough ahead of weapon system integration development (Phase VI) to allow a maturational development effort to be underway before Phase VI begins. Although such a Phase V application of maturational development would have to see the subsystem hosted on a different weapon system for the gathering of operational experience,[26] the advantage of such long lead development of critical subsystems is that design improvements can be incorporated before high rate production for the new host weapon system.

Currently, avionics subsystems usually start full-scale engineering development (FSED) last, even though they are probably the most complex areas of the airplane. This is because the avionics contractors and subcontractors are often not chosen until after the prime contract has been let. The engine, however, typically starts FSED many years ahead of the combat avionics,[27] and the airframe anywhere from six months to a year before many avionics subcontractors even receive their contracts. For example, Fig. 23 shows the major milestones in the acquisition and development of the F-15. Concept formulation for the F-15 began in June 1967, and FSED for the airframe began in January 1970. While initial development for the engine began roughly 16 months before FSED for the airframe, FSED for the avionics

[26]This is an incomplete environment for identifying subsystem integration problems, but it does provide an operational opportunity to exercise the subsystem in an airborne environment that is a close approximation to the intended operational setting. Moreover, with complex subsystems, it is beneficial to iron out most of the subsystem problems before attempting integration.

[27]Recognizing the sophisticated and *flight-essential* nature of turbine engines, the Air Force usually (1) contracts directly for their development; (2) starts this development long before that of the airframe; and (3) precedes this with many years of development, testing, and redevelopment of the engine's more critical components.

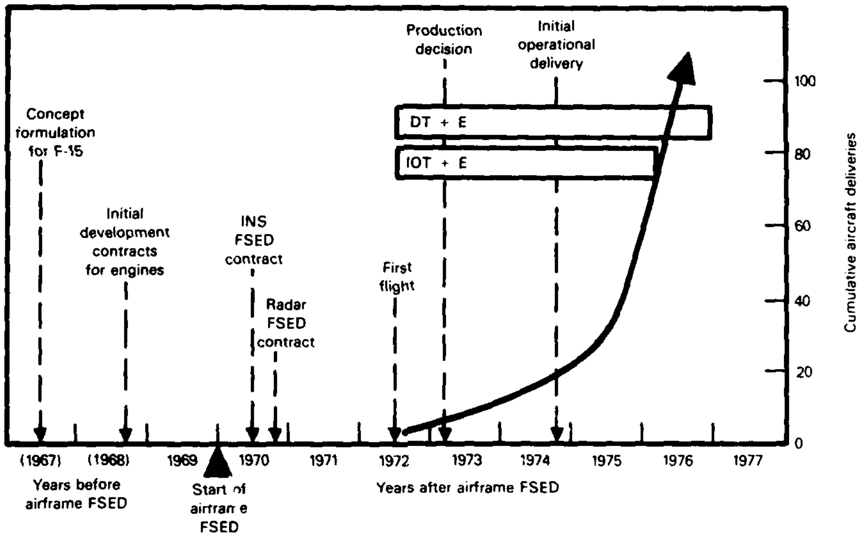

Fig. 23—Major milestones in the acquisition and development of the F-15

systems began considerably later. Indeed, FSED for the inertial navigation system began roughly eight months later, and FSED for the fire control radar system began roughly 11 months later.

Because of such tight scheduling, avionics developers typically lack adequate time to design and mature their equipment before it is delivered to operational squadrons.[28] Moreover, shortly after fielding the initial squadron, developers lose touch with many of the operational realities in which their designs must survive. This means, for instance, that they lack engineering data on how temperatures, vibrations, and flight loads may be punishing the more fragile parts of their design. The problems such programs have faced are that

[28]The authors, over a period of 20 years, have personally witnessed the development and fielding of four generations of avionics equipment that is now being used by the F-111s, the F-15s, the F-16s, and the B-1B. In every case, one or more crucial avionics subsystems failed to meet the original development schedule because the size of the necessary engineering effort was larger than possible within the time allocated. In such situations, equipment was fielded before all of the functional performance specifications had been satisfied. Subsequent modifications, necessary to satisfy the performance needs, would alter the equipment configuration and delay the point at which configurations had stabilized to a point where R&M characteristics could be fully demonstrated and assessed.

- Inadequate time has been allotted in the product improvement and acquisition processes; and
- Insufficient funding has been provided to pay for data collection, analysis, and implementation of improvements.

Such patterns, while damaging to the R&M characteristics of contemporary avionics subsystems, portend potentially more serious consequences for forthcoming avionics developments.

Improve Focus of Developments During Phases II and III. Reorganization of avionics development also needs to streamline efforts in such areas as

- The development of critical components (Phase II)—for example, active elements for an active phased array antenna,[29]
- The development of subassemblies (Phase III)—for example, common modules for integrated communication, navigation, and IFF (identify friend or foe) equipment.

Current interests in the development of common avionics modules is sparked by desires to reduce

- The need for air base avionics shops,
- The amount of new avionics equipment that must be developed for each new weapon system.

This technology allows a group of common modules to be used both *within* a subsystem and *across* several subsystems.

Common modules also aim at developing smaller and cheaper LRUs, which in turn would negate the need for an AIS. Current LRUs are so costly, removed so often, and in such short supply that each air base generally needs its own avionics shop. Because many LRUs cost between $100,000 and $500,000, the avionics shop uses large sets of test equipment to identify faulty SRUs within these LRUs. The shops then send these less expensive SRUs to the depot for repair, reducing the time and the value of assets tied up in the repair pipeline.

To eliminate this need for avionics shops on air bases, the avionics industry and various Air Force organizations are examining the concept of more modular avionics.[30] Rather than building a radar with less than nine LRUS, one would aim at building a radar with 50, 100, or more modules. Like LRUs, these modules could be removed at the

[29]See Gebman, Shulman, and Batten, 1988, for details.

[30]These efforts include an Air Force Avionics Laboratory program known as PAVE PILLAR, an Air Force Air Staff effort known as Modular Avionics System Architecture, and various industry efforts known as Line Replaceable Modules.

flight line; like SRUs, these modules would be cheap and could be sent to the depot for repair.

Figure 24 illustrates the laboratory development of an advanced design for a digital processor. It includes so many modules that it takes up two boxes. Each section is a different circuit board or module. The shadings indicate four module types. Thus, within this one design there are several different applications of each module type. If this kind of multiple application of a single module proved to be the design of the future, it would increase incentives to invest in maturing these units.

Most important, the improvements in modular avionics go beyond the unit level shown in Fig. 24 to the subsystem level shown in Fig. 25. Here a set of 34 different modules have been used like a set of standard building blocks to lay out designs for three very different subsystems: (1) an army ground-based application, (2) a helicopter, and (3) an upgrade for a fighter aircraft. With these kinds of multiple applications of avionics equipment to other weapon systems, the possibilities increase for justifying resources to mature the modules. The potential

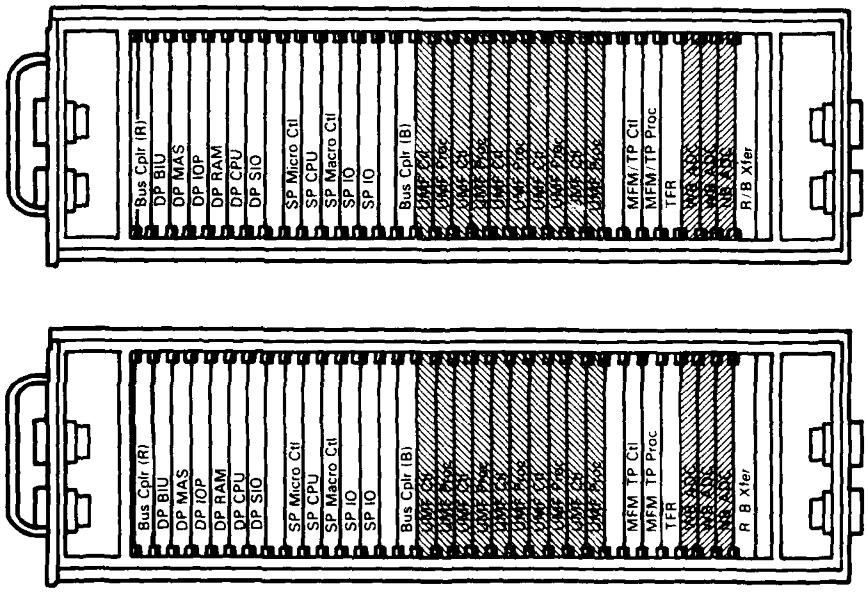

Fig. 24—Example of a digital processor designed with standard modules

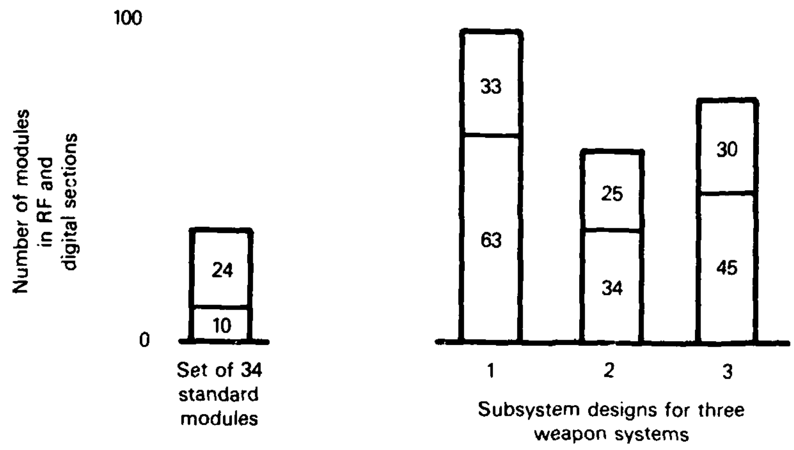

Fig. 25—Three designs built for communication, navigation, and identification equipment from one standard set of modules

broad applicability of the ten most utilized types of modules from the set of 34 is illustrated in Fig. 25. Subsystem number 1 would need 63 modules from this top ten set. Subsystem number 2 would use 34 from this top ten set. Well over half of each of the three subsystems would be built from modules from this top ten set. This top ten set clearly presents a very broad opportunity for benefiting from investments in R&M maturation, as do the 24 remaining modules.

While the adoption of common modules has many attractive features, it also presents some R&M-related challenges for the acquisition process. Administrative challenges include

- Establishing a modular avionics architecture that has sufficient flexibility to support high levels of maintainability,
- Orchestrating adequate time and resources to mature R&M characteristics.

Technical challenges include

- Designing sufficient fault isolation capabilities into individual modules and integrated sets of modules,
- Designing interconnections between modules that are reliable and easy to fault isolate, even though the number of

interconnections between modules seems to be increasing with greater miniaturization of electronics.

SUMMARY

The major weaknesses in the acquisition process are the absence of meaningful measures of R&M, such as an indicator of fault removal efficiency, lack of a process for setting rationally based and balanced R&M goals for future equipment, and weak assurances that needed levels of R&M will be delivered.

Strengthening the acquisition process to deal with these weaknesses must start by expanding designer awareness of R&M deficiencies, especially of problems with current avionics equipment. Although there is a lot of emphasis on reliability and some people believe that levels of 2000 hours MTBF are attainable, there is no comparable enthusiasm for maintainability. This study suggests fault removal efficiency as a way to stimulate such emphasis. Maturational development is one way to assure delivery of specified levels of R&M on complex avionics equipment.

Strengthening the acquisition process also calls for accelerating the maturation of avionics equipment currently in the field. Because future avionics will account for 40 percent or more of the fly away costs for future fighters, more attention must be paid to maturing it quickly to avoid high costs of spares and retrofitting improvements.

Finally, all the above strategies may depend ultimately on reorganizing avionics development. This may prove necessary to begin maturational development's first stage (data collection and analysis) early in the development of new subsystems. It may also be necessary to timely implementation of the second stage (implementation of further developments). By scheduling a formal maturational development process into the development of complex subsystems, and by providing the necessary funds and time to accomplish maturation, the Air Force can go a long way toward assuring that needed R&M levels are actually delivered.

VI. RECOMMENDATIONS AND CONCLUSION

Although the traditional view of R&M may deal adequately with problems that are consistent show stoppers, a new view of R&M is needed to deal effectively with faults that only degrade performance and/or manifest situation-dependent symptoms. Because many of the R&M problems with modern avionics are of the latter category, we have proposed a new approach to viewing R&M that emphasizes the two most fundamental R&M characteristics:

- Fault initiation and
- Fault removal.

Managers need a minimum set of indicators that provide a comprehensive characterization of how a system or subsystem is doing in terms of these fundamental characteristics. We have suggested two parameters for such purposes:

- Mean flight time between flights with shop confirmed failures (MTBF) and
- Fault removal efficiency.

Using such parameters to analyze contemporary field experience, we find progress in MTBF not being matched by progress in fault removal efficiency. We have proposed several actions that aim at bolstering the capability of the support process. Such improvement alone, however, will not be sufficient. Product improvement actions must examine the dominant causes of low fault removal efficiency and important improvements must be expedited to bolster the supportability of specific equipment. The high expense of such product improvement makes it far more desirable for future acquisition programs to build in high fault removal efficiency capabilities.

Strengthening the acquisition process alone is not sufficient in the near term because of the low rate of turnover in military equipment. Even with the best of improvements in acquisition programs, there will still be major needs for bolstering product improvement programs and strengthening the support process to cope with problems currently in the field. For these reasons, the last three sections have developed a strategy for strengthening the Air Force's capability to manage weapon system R&M during all phases of the weapon system life cycle.

Perhaps most obvious in the strategy summarized in Fig 26 is that at each stage—not just support, but also product improvement and acquisition—there is a critical need for better information from the field. Maintenance personnel need more complete information to deal quickly and effectively with faulty assets that escape repair, especially with the less than fully mature equipment already in the field today.

To improve the isolation and correction of faults that degrade performance, the Air Force needs to improve the quality of information received from the pilot debrief and improve the tracking and correction of R&M deficiencies. When equipment resisting repair efforts is located, the support process needs greater capabilities to fix hard problems so that faulty equipment does not circulate between shops and aircraft in degraded condition.

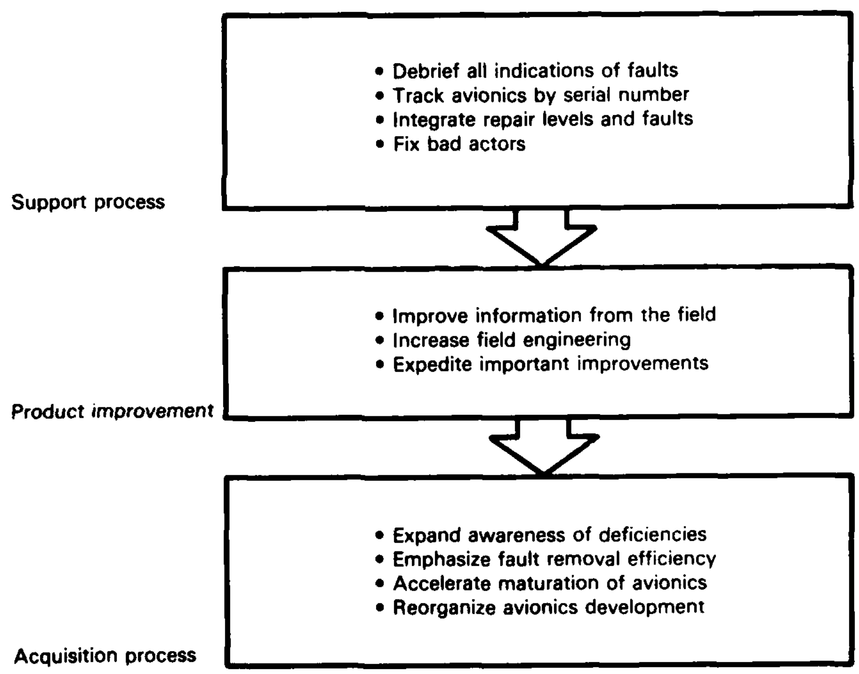

Fig. 26—A cohesive strategy for improving R&M

For enhancing the product improvement effort, we recommend improvements in the systems for gathering information and engineering data about field problems, an increase in the amount of field engineering analysis, and expediting of important improvements in products.

For improving the acquisition process we recommend expansion of the awareness of deficiencies in the process, adoption of the maintainability indicator of fault removal efficiency and of maturational development to help mature new avionics equipment, and reorganization of avionics development to better address current problems and to meet future challenges.

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