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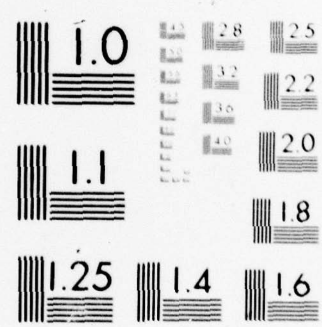

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RELIABILITY AND MAINTAINABILITY MANAGEMENT MANUAL

Anthony Coppola
Alan N. Sukert

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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This manual provides a guide to Air Force program managers, at all levels, for the planning, organizing, manning, leading and controlling of cost-effective Reliability and Maintainability programs in all phases of acquisition. It addresses both hardware and software reliability.

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PREFACE

The Air Force has always needed reliable and maintainable equipment. While this is completely obvious to logistics and operational people, and should be obvious to the research and development community, field data shows examples of equipment in operational use where reliability and maintainability fall far short of our expectations and needs. Programs are underway in both Air Force Systems Command and Air Force Logistics Command to improve those equipments, but steps must be taken to insure that deficient equipments are not deployed in the future. As top Air Force officials have emphasized, enormous life cycle cost savings can result from improved reliability and maintainability. Furthermore, military force limitations compel us to squeeze as much effectiveness out of every piece of equipment as we can, and improving reliability and maintainability is one way to do it.

Some Reliability and Maintainability (R&M) problems can be laid to technology (e.g., a jammer might require high power that can only be provided with a new tube whose reliability problems have not been resolved, and space limitations may require packaging adversely impacting maintainability). However, many R&M problems can be avoided by astute management decisions. While we will readily agree that the technical problems cannot be ignored, this report is concerned with R&M management on the premise that better management is a high-payoff, low cost approach to more reliable and maintainable equipment. The resulting management guidelines are written to fit within the scope of present regulations.

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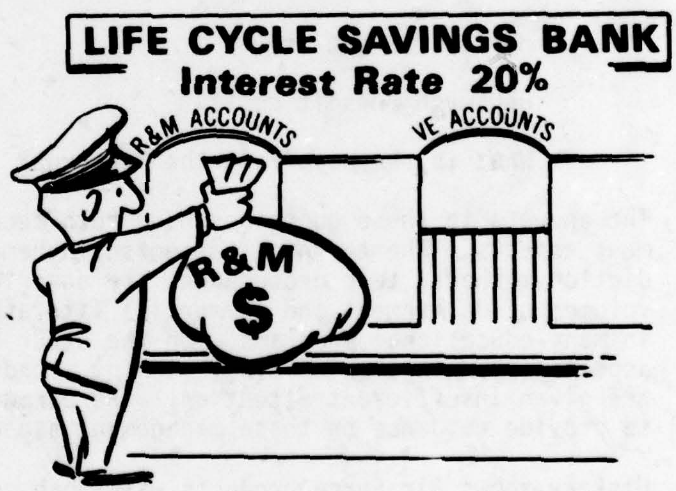
Chapter 1

INTRODUCTION

PURPOSE OF THIS GUIDE

Since World War II, the costs of buying and supporting new systems and equipment have shown alarming growth, even after discounting dollar inflation. These growing costs have been fed by the evolution of more sophisticated weapons designed for conflict in new domains of speed and space and often designed for nearly instant response. While modes of conflict over a half century old remain with us as modern threats, we have seen the addition of globe girdling aircraft, missiles, satellites, communication systems and radars; and these in turn have spawned new families of defense countermeasures and offense counter-countermeasures. Furthermore, the omen of possible nuclear destruction has motivated defense planners and engineers to build superior performance into every weapon and defense system and to apply the latest technology to the greatest extent possible. In this scene of revolutionary technical development and international competition, enormous cost growth has been unavoidable.

Costs continue to rise and projections for the future are sobering. At the same time, the buying power of the defense budget is shrinking. It is obvious that some of our ways of doing defense business must be improved.



One change which can yield savings of very substantial proportions is improved reliability and maintainability (R&M) of systems and equipments. Top defense leaders recognize that improved R&M have the potential to save billions of dollars over the next decade by avoiding unnecessary costs for spares, repairs, personnel and extra systems. At the same time, improved R&M increases the operational effectiveness of equipment by improving its chance of being in commission at the time it is needed. The dual payoffs of reduced logistics costs and improved operational effectiveness can be realized with development cost increases which are very modest when compared with lifetime savings.

To cash in on savings, Air Force managers of development and logistic support programs have been asked to take bold steps leading to more reliable and maintainable systems for our operational people. These requests for action have come from the Congress, the Secretary of Defense, the Secretary of the Air Force, the Air Force Chief of Staff and many commanders and directors. There has been no mincing of words. Everyone wants better R&M.

In response to requests for bold steps towards better R&M, many actions are underway: studies of management practice, procurement policy and hardware design; retrofit programs; data reporting improvements; action committees; revised regulations; and so on. The preparation and promotion of this R&M management guidebook is another.

While the need for reliable and mantainable military equipment appears to be obvious, what may not be so obvious in a specific project are answers to these questions:

How much R&M do we need?

How can we get it?

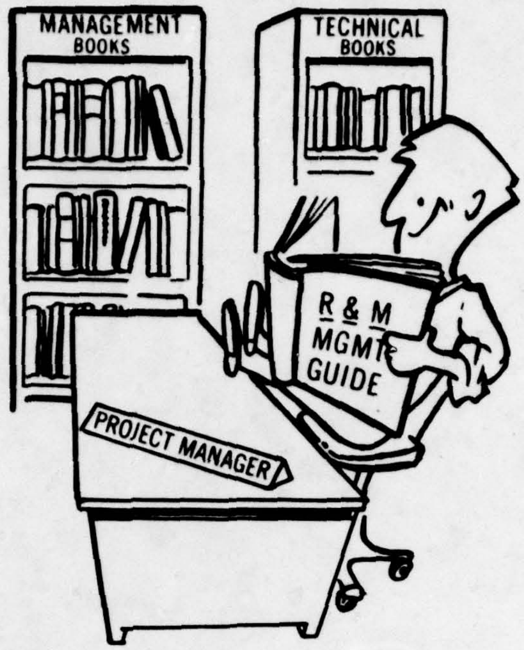
How much does it cost?

What is the payoff in the long run?

The answers to these questions have both technical and management aspects. The technical aspects (mathematical models, prediction methods, test procedures) are described in numerous volumes of Government and commercial literature and are taught in many educational programs. On the other hand, management aspects (planning, organizing, manning, leading, and controlling) are given insufficient attention. The purpose of this report is to provide guidance on these management aspects of R&M.

History shows Air Force projects with both outstanding success and embarrassing failure in achieving R&M goals. The procedures and actions recommended in this report reflect the lessons learned from the management approaches used in both the successes and failures. These recommendations are consistent with the policies and authority stated in present Air Force regulations, and are applications of management fundamentals proven valid through decades of use in countless organizations. The recommendations should be easily understood by any manager who has a general background in engineering.

This guidebook should be a useful reference for every R&M manager as well as for the System Program Director and his staff and staff personnel at other levels of system acquisition management. If it causes only a single major equipment development program to go from marginal R&M achievement to complete success, the logistics savings over the equipment life cycle can easily be tens of millions of dollars. If the principles outlined here are successfully applied during coming years in all Air Force development programs, savings in dollars and materials will be enormous.



In summary, the need for this guidebook is derived from the following observations which will be explained and substantiated in later chapters:

Growing support costs have motivated top level managers in the Department of Defense and the Air Force to call for improved R&M of all systems and equipments, and to support the management acts needed to achieve this goal.

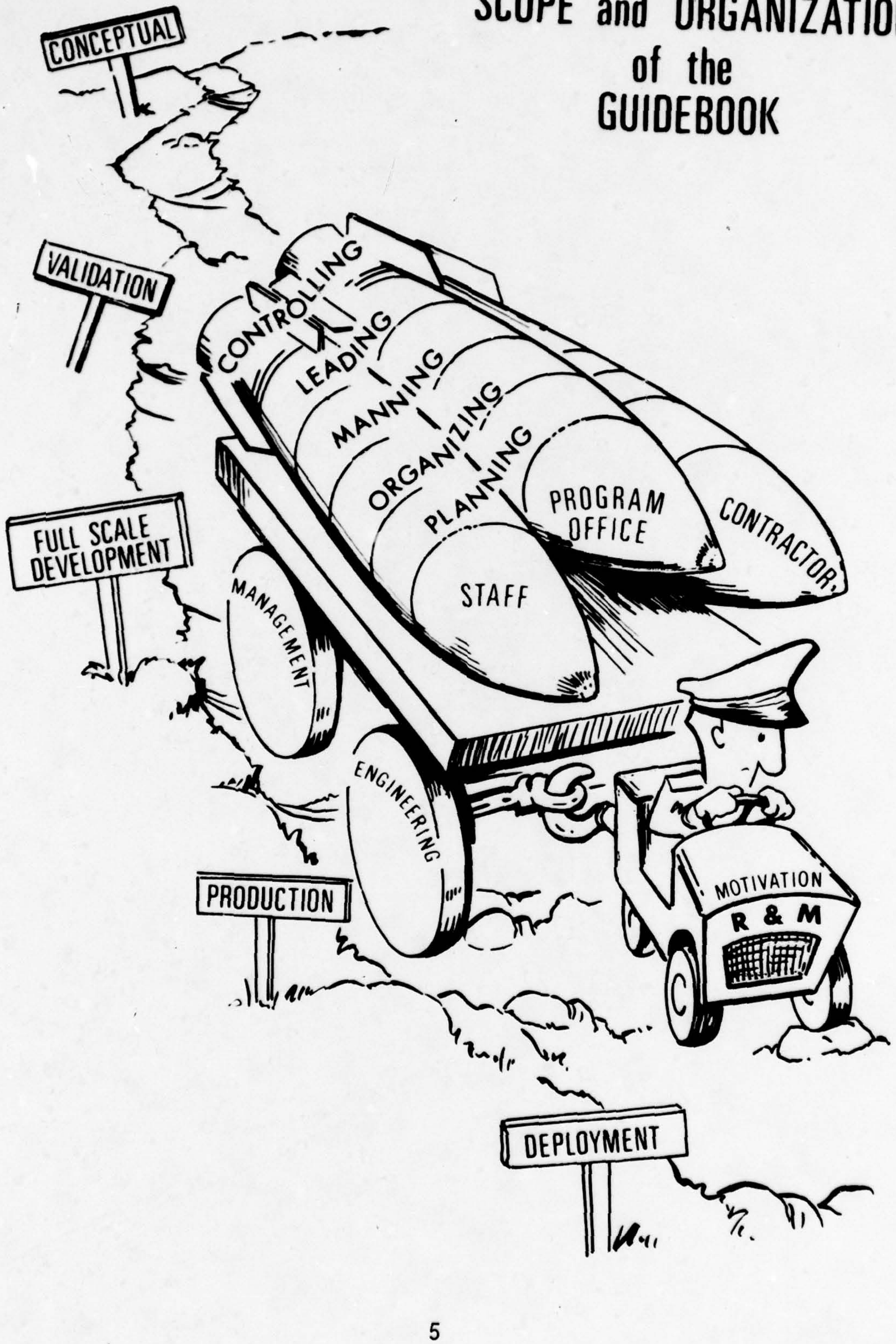
Technology is generally available, with some exceptions, to achieve the goals of improved R&M.

Many complex equipments have achieved high R&M goals, but many have not. In the deficient programs which have been observed, the program decisions which led to R&M problems were easy to recognize, relatively few in number, and generally managerial in character.

Program and project managers may lack understanding of the elements and significance of a good R&M program.

The management actions needed to insure an adequate R&M program are prescribed in current regulations and standards, are a good investment, and are easy to understand when outlined and explained in an orderly way.

SCOPE and ORGANIZATION of the GUIDEBOOK

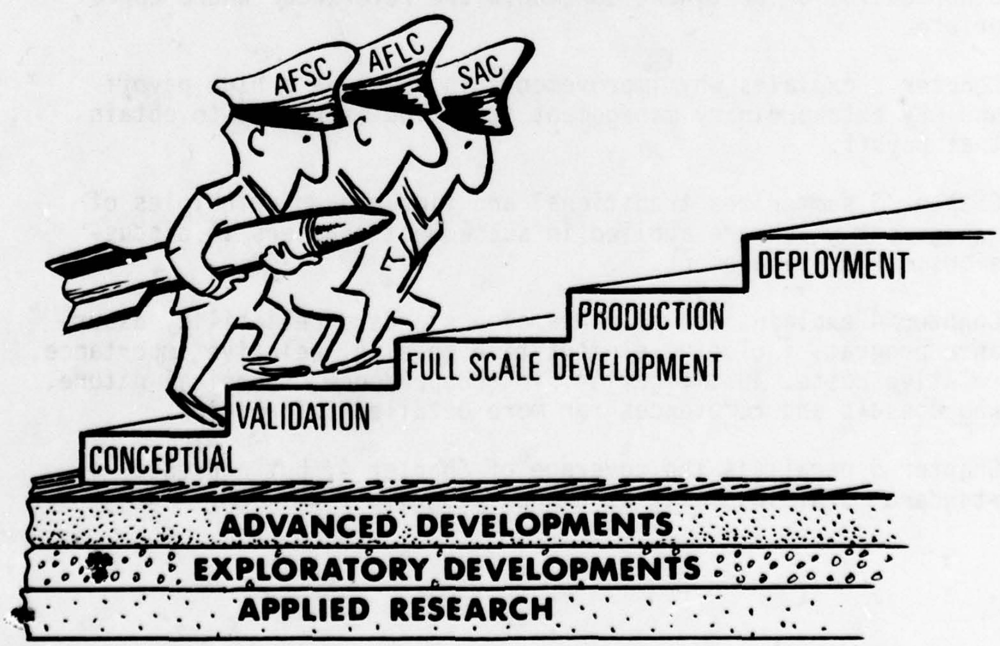


SCOPE AND ORGANIZATION

The R&M management guidelines which follow have wide application. Even though the technical approach to R&M design and demonstration may be quite different in various technologies, the R&M management issues and considerations are quite similar. Therefore, whether you are working on electronic, hydraulic, or mechanical systems, the management guidelines explained should be largely applicable to your program, even though technical details will be different.

Management activities and issues are affected by the development status of the system or equipment, and consequently, each section of the report will consider the life cycle phases from concept formulation to deployment. Anyone unfamiliar with Air Force management of acquisition programs and the phases of development, should first review AFSC Pamphlet 800-3, A Guide for Program Management, available from the Government Printing Office.

While this guidebook is principally for AFSC R&M managers, it is written with the fundamental attitude that development of new systems and equipments is a joint venture between Air Force Systems Command (AFSC), Air Force Logistics Command (AFLC), and the operational or using command. Of course, AFSC is in the driver's seat until transfer of program management responsibility to AFLC. Transfer occurs sometime during the production phase at a time mutually agreeable to AFLC and AFSC. Throughout the acquisition phase it is important that the new system is developed to be responsive to both operational needs and long range logistic support needs. At the same time, the new system is built from a technology base which is improving continuously through research, exploratory and advanced developments sponsored by Government agencies and private industry.



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This is a management guidebook, but it is not always easy to categorize a particular activity as strictly management or strictly technical. Some activities will fall in between. In every case, the management significance of the activity discussed should be clear, even if it has technical facets. While most readers will have considerable experience either managing or being managed, we recommend they read the summary of management principles in Chapter 3. The chapters which follow it are written using the terms and concepts of that summary.

This guidebook is written to aid effective implementation of three basic directives. They are:

Air Force Regulation 80-5 and AFSC Supplement 1,

Air Force Reliability and Maintainability Program

MIL-STD-785,
Reliability Program for Systems and Equipment
Development and Production

MIL-STD-470,
Maintainability Program Requirements
(for Systems and Equipments)

There are many other regulations, standards, and manuals which make reference to R&M management and engineering, but the above three are the basic ones for Air Force use, and they in turn reference other applicable documents. Throughout this book, other useful or pertinent documents are referenced where appropriate.

Chapter 2 explains why improvements in R&M have a high payoff and why extraordinary management attention is needed to obtain that payoff.

Chapter 3 summarizes traditional and time-proven principles of management which are applied in subsequent chapters to discussions of R&M management.

Chapter 4 explains the elements of a standard reliability assurance program, including element time phasing, relative importance, relative costs, justification, interdependence, technical nature, who does it and references for more detailed information.

Chapter 5 parallels the coverage of Chapter 4, but addresses a standard maintainability assurance program.

Chapter 6 summarizes the important management acts needed at headquarters staff levels, the system program office, and the contractor, to insure successful implementation of the R&M programs explained in Chapters 4 and 5.

Chapter 7 discusses the relatively new area of computer software R&M, and explains guidelines for planning an orderly program for software development that will enhance the prospects of achieving R&M goals.

Appendix A lists sources of educational opportunities in R&M.

Chapter 2

MOTIVATION FOR THE MANAGER

INTRODUCTION

This chapter shows why the R&M manager must be motivated to manage his functional activities with special care. First it shows that long range cost saving benefits can be spectacular, and that R&M engineering knowhow largely exists to achieve reasonable objectives. However, it then explains that human nature and program pressures, in both the contractor and Air Force organizations, tend to work against achievement of those objectives. Successful programs result from motivated managers who perceive the special pitfalls of R&M management and work around them. Later chapters show how they do it.

R&M ARE MATURING ENGINEERING DISCIPLINES

Although reliability and maintainability considerations under various labels have existed as long as there were machines to cause R&M problems, the genesis of R&M as an engineering discipline began in World War II when the complexity of electronic equipment reached the point where R&M became a significant concern both operationally and economically. During World War II, most reliability efforts were concerned with components, primarily vacuum tubes. In 1950 a broader attack on reliability problems was instituted with the formation of the Ad Hoc Group on Reliability of Electronics Equipment under the Department of Defense Research and Development Board, succeeded in 1952 by the Advisory Group on Reliability of Electronic Equipment (AGREE). In 1956 the first reliability design handbook, "Reliability Factors for Ground Electronic Equipment" was published by the Rome Air Development Center (RADC). In 1957 AGREE published their report, "Reliability of Military Electronic Equipment" which provided the reliability test methods still in use today. In 1958 the publication by RADC of a reliability prediction technique based on electronic parts stress data completed the set of basic tools essential to reliability engineering. At this point a practical reliability engineering discipline existed for electronic systems. In the next five years maintainability design, prediction and demonstration techniques also became available and the R&M engineering discipline was firmly established.

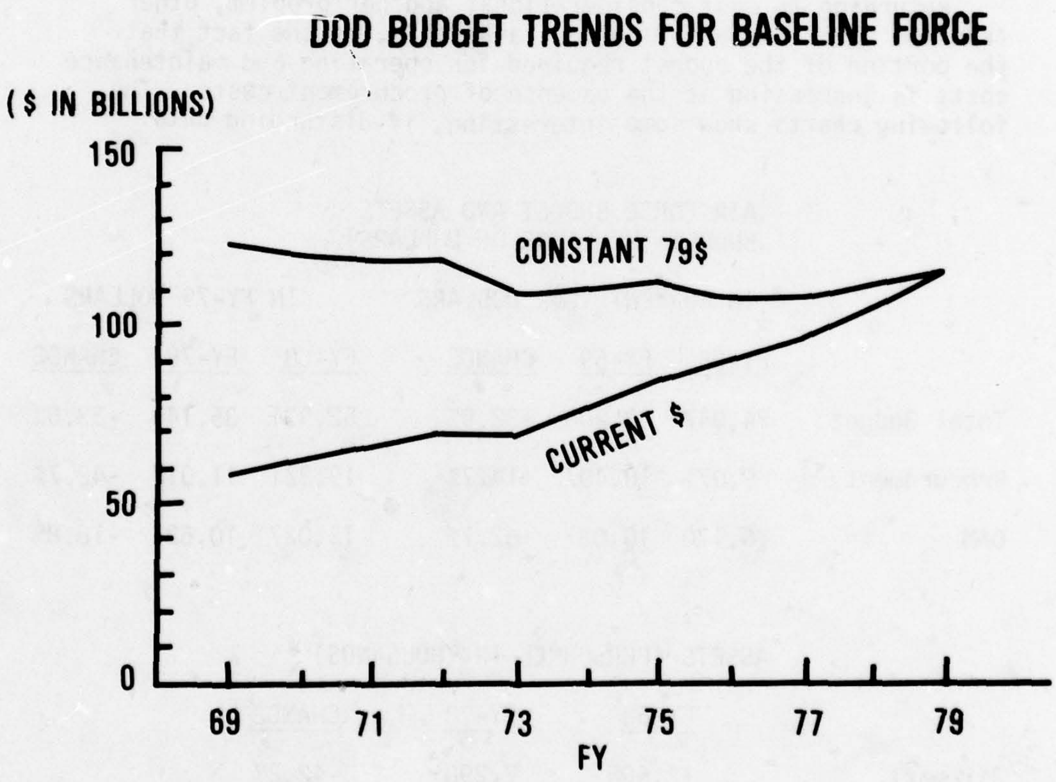
Efforts subsequent to the above have endeavored to continually improve the R&M tools in a dynamic environment of electronics development (as exemplified by the explosive development of semiconductors) and have reached even higher degrees of sophistication in attempts to reduce the cost of R&M activities, increase their efficiency, and address more subtle R&M problems still eluding satisfactory resolution. These efforts have included the development of quality assurance procedures for electronic semiconductor devices, prediction techniques for equipment in dormant conditions (i.e., a Minuteman in a silo), techniques for predicting reliability in the conceptual stage when only gross system parameters are known, more efficient statistical methods to reduce test time, designs for built-in fault indicators, methods of system design to accommodate or circumvent failures, and of course, a significant effort merely to keep up with changes in parts, manufacturing methods, and improved parts reliability. Current pioneering efforts involve development of R&M growth predictors, quantification of the effects of field environment on expected reliability, and the R&M of computer software. Software R&M is of increasing importance since all new major Air Force systems are software dependent and becoming more so as digital equipments are put into wider use. Development of tools for assuring software R&M may be the next major step forward in R&M engineering. Finally, human reliability and human factors in equipment design for reliability, while hardly a new concern, still elude satisfactory quantification.

THE PAYOFF OF RELIABILITY & MAINTAINABILITY

The greatest benefit of R&M in the current Air Force environment is its economic impact. Of course, R&M also affect safety and the probability of mission success. However, both of these factors can be forced to display satisfactory values even with equipments of relatively poor R&M if attendant penalties in cost, weight, power consumption and support effort are accepted. For example, redundant subsystems, larger force sizes, greater quantities of spares and expanded maintenance shops, can overcome poor R&M as far as mission success and safety are concerned. However, the cost penalties of these approaches while always undesirable are now intolerable. The following paragraphs describe the critical economic situation faced by the Air Force and the ways in which improved R&M can relieve that situation.

THE BUDGET CRUNCH

The economic realities facing the Air Force are illustrated in the following chart which shows the Department of Defense (DoD) budget for Baseline Forces (i.e., with additional costs of Vietnam operations removed) in terms of current dollars and constant 1979 dollars for the last 10 fiscal years.



As the chart illustrates, while the Defense budget was doubled in 10 years, the actual purchasing power in FY-79 is less than that of FY-69. The overall trend has been a constant decline in purchasing power except for the last two years when the trend reverses. This reflects the concern over a steady increase in Defense spending by the competition, which is also reflected in a request by President Carter that all NATO nations increase their budgets by 3% a year over inflation. If pursued, this policy should result in real increase in the Defense budgets of the future. However, the impact of the decline will be felt for some time. In 1968 the Air Force had 12,606 aircraft. In 1978 we had 7,290. As a result, mission success cannot be assured simply by assigning more aircraft to a job. Instead "force multipliers" are sought. These are means for improving the capability of a limited force without increasing its size. The application of R&M techniques, leading to increased sortie generation rates, is one of these multipliers.

Returning to cost considerations, another problem, other than the sheer number of dollars available, is the fact that the portion of the budget required for operating and maintenance costs is increasing at the expense of procurement costs. The following charts show some interesting, if disturbing data.

AIR FORCE BUDGET AND ASSETS
BUDGET (MILLIONS OF DOLLARS)

	IN CURRENT YEAR DOLLARS			IN FY-79 DOLLARS		
	FY-68	FY-69	CHANGE	FY-68	FY-78	CHANGE
Total Budget	24,947	33,200	+32.9%	52,931	35,145	-33.6%
Procurement	9,071	10,407	+14.7%	19,221	11,017	-42.7%
O&M	6,170	10,037	+62.7%	13,027	10,625	-18.8%

ASSETS (PERSONNEL IN THOUSANDS)

	FY-68	FY-78	CHANGE
Aircraft	12,606	7,290	-42.2%
Military Personnel	905	571	-36.9%
Civilian Personnel	342	253	-26.0%
Total Personnel	1,247	824	-33.9%

Comparing FY-68 to FY-78 in current year dollars shows the O&M costs increasing four times as fast as procurement costs. In FY-68 procurement dollars were about 50% higher than O&M, while in FY-78 they are roughly equal. In actual spending power, obtained by converting current year dollars to equivalent FY-79 dollars, the 33.6% decrease in the Air Force budget is exceeded by the decrease in procurement funds while O&M funds show a lesser drop. Put another way, in FY-78 procurement used 36.3% of the Air Force budget while O&M costs took 24.7%. Today both take about 30% of the budget. Hence, we are spending more on our current equipment and less on developing new systems. In an age of dramatically expanding military technology, this is a bad scene.

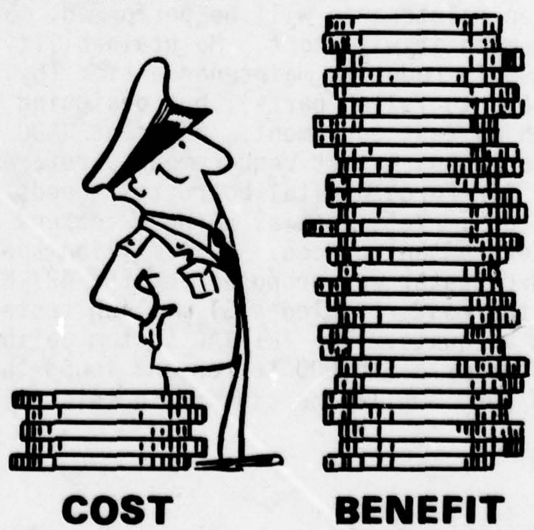
The solution is even worse when the lower half of the chart is considered. One would expect a shift of dollars from procurement to O&M if the budget declines and the capability remained constant. However, the aircraft and personnel in FY-79 were more reduced than the budget. Hence, the O&M costs are increasing faster than inflation, and if we had a budget adjusted for inflation to provide a constant purchasing power, we would still find O&M costs pulling dollars away from procurement as time passed. This trend must be checked and better R&M is one of the means for doing so.

Another factor compounding the problem is that the procurement dollar also buys less than it used to, even accounting for inflation. In 1959 the B-52 bomber cost about $10 million. The B-1 was expected to cost around $60 million. Half of the difference can be attributed to inflation. The other half was caused by greatly increased capability. This capability is provided by complex, sophisticated systems which are costly to design, produce and maintain.

By this time, one should be convinced that reduced costs are an urgent Air Force need. In the next paragraphs we will look at the role of R&M in cost reduction.

REDUCING COSTS THROUGH R&M

The impact of Reliability on O&M costs is obvious. The more failures, the more resources needed to maintain the equipment. But since there is a cost to a reliability program, it must be looked at as an investment, and shown to be worthwhile.



An analysis of reliability as a capital investment was published in a technical paper at the 1974 Annual Reliability and Maintainability Symposium (reference 1). The author of that paper studied in detail the development and performance history of three production equipments. These equipments were non-digital avionic subsystems used in high-performance aircraft, and each incorporated from 3,300 to 13,500 parts and each cost from $35,000 to $243,000 in production. He made a detailed cost analysis of a thorough reliability program that could have been followed in development and production, and then estimated the resulting reliability improvements. These reliability improvements then yielded projected reductions in maintenance costs, and reductions in acquisition costs because fewer spare parts were needed. Conservative assumptions were used throughout that tended to increase the predicted costs and diminish the predicted benefits. The following table summarizes the results:

RELIABILITY AS A CAPITAL INVESTMENT

CASE	QUANTITY	ADDITIONAL RELIABILITY PROGRAM COST	SPARE PARTS SAVINGS	INITIAL NET COST	ANNUAL MAINT. SAVINGS	10-YEAR TOTAL SAVINGS
I	564	$9.5M	$4.5M	$5.0M	$5.0M	$44.7M
II	325	$2.1M	$ .5M	$1.6M	$ .7M	$ 5.4M
III	335	$6.9M	$4.1M	$2.8M	$2.5M	$22.2M

From a businessman's point of view, the yearly returns on the investment range from 44% to 100%--returns nobody would ever pass up.

Maintainability, the other half of R&M, obviously impacts the cost of maintenance resources. While reliability dictates how often maintenance will be performed, maintainability dictates how much it will cost. Maintainability considerations include not only reducing maintenance time (by, for example, assuring access to failed parts), but designing to reduce associated costs such as test equipment. A recent RADC study of digital printed circuit board test requirements (reference 2) showed that almost all Air Force digital board test needs could be met by available testers. Yet, special purpose testers are too frequently procured, at exorbitant prices. A $4 million special digital printed circuit board tester was proposed for the 427-M system, but due consideration of the cost revealed a $1 million tester, commercially available, was adequate. The TRI-TAC system deliberated between an $800,000 tester or a $15,000 tester and found the $15,000 tester will do the job. While the savings in this case may be more of an accident than a deliberate event, it does show that design to use low cost available testers can bring significant savings.

The pay-off of R&M is also evidenced by the Air Force Producibility, Reliability, Availability and Maintainability (PRAM) Project Office. This was created in August 1975, as a combined AFLC and AFSC organization. Its function is to invest in improvements of Air Force in-service weapons systems to reduce ownership costs. As of 31 Aug 78, PRAM has invested $42 million in 379 projects with a projected five year net savings of over $795 million. Quite an impressive return.

THE CURRENT R&M REPORT CARD

Despite the impressive benefits of R&M discussed above, present programs are not taking advantage of these, according to a survey taken by AFALD. The study was completed Nov 78 and presented at the AFSC Reliability and Information Exchange Meeting, 28-30 Nov 78. The survey found that of 162 programs, 109 had satisfactory reliability provisions, 33 were marginal and 20 unsatisfactory. The major problems identified were contract reliability requirements, reliability demonstrations and parts control. Evidently, there is room for improvement in reliability.

The same conclusion could be reached from a GAO letter report, "DoD Standardization of Avionics and Other Electronics" (OSD Case #4732, PSAD 78-105) which listed in its findings "low reliability of avionics is often a factor in the readiness of operational weapon systems and could hinder effective military operation".

On maintainability, the current trend to built-in-test (BIT) as a means for rapidly detecting and evaluating failures has produced its own problems. In 1977, Maj Gen Howard W. Leaf, Commander of AFTEC, expressed concern over the BIT system for the Wild Weasle and the Central Integrated Test Subsystem (CITS) for the B-1. Lt Gen Robert T. Marsh, Commander of ESD, cited a need for a phased approach with measurable milestones for Built-in-Test development and demonstration. Lt Gen Robert C. Mathis, Vice Commander of AFSC, stated the belief that real improvements in fault detection/isolation are achievable, but that it is a major cost/management challenge.

Some of these problems are of course technical (e.g., an urgent need exists for development of techniques for demonstrating BIT capability). Some, however, are managerial. The concern expressed above resulted in an ASD program to survey and assess the BIT capability of existing systems, an RADC program to develop methods and tools for designing cost-effective fault detection and isolation subsystems, and a set of interim guidelines for program managers prepared for ESD by RADC. Clearly, maintainability engineering still requires technical and management attention.

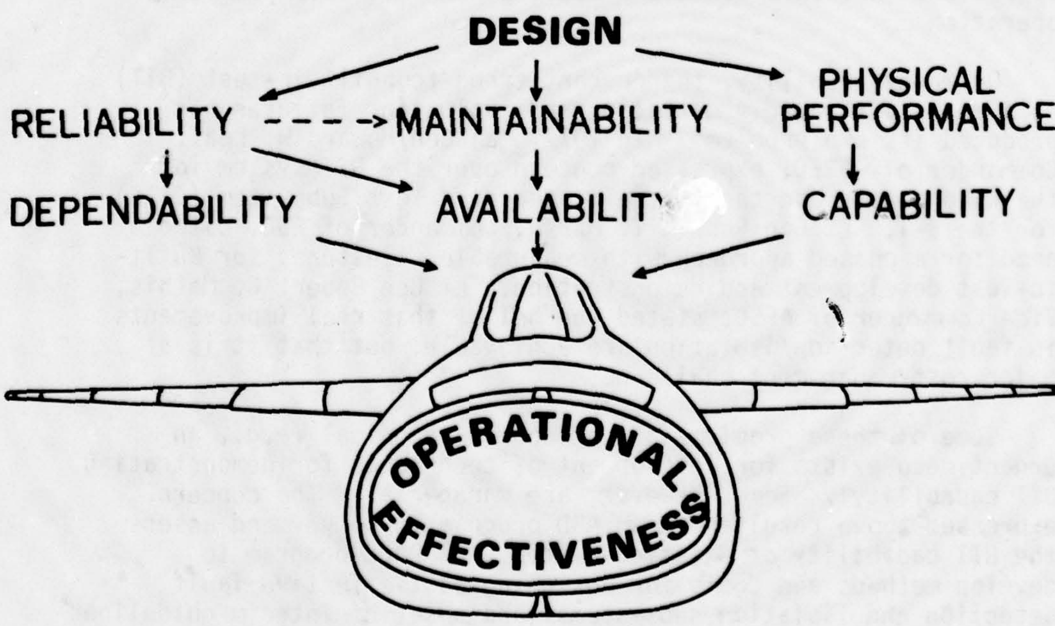
OTHER R&M BENEFITS

Mention has been made of the impact of R&M as operational readiness. The next four paragraphs will expand this to the concept of operational effectiveness and will discuss some other benefits of attention to R&M.

R&M IMPACT ON OPERATIONAL EFFECTIVENESS

Every operational commander wants reliable equipment, and if something does go wrong, he wants it fixed quickly. In other words, he knows that his operational effectiveness depends upon R&M. He wants his systems to be available, dependable, and capable for the mission.

The operational effectiveness of a system may be defined to be a function of availability (the probability that the system will be in an operating state at the start of a mission), dependability (the probability that it will remain in a satisfactory operating state for the length of the mission) and capability (the probability that, if in a satisfactory operating state, it will successfully perform the mission). Dependability is obviously derived from reliability. Both reliability and maintainability impact availability. These interrelationships are illustrated below:



The dashed line in the diagram illustrates that maintainability is analytically a function of reliability. That's because subassembly reliability affects the computed maintainability parameter, mean-time-to-repair (MTTR), of an equipment. To compute the MTTR of an equipment made up of many repairable subassemblies, the MTTR of each subassembly is weighted by a coefficient which depends on the mean-time-between-failure (MTBF) of each subassembly. During equipment design for maintainability, this dependence of equipment MTTR on subassembly MTBF is used along with logic constraints to partition the equipment into repairable subassemblies in a way that will give the best MTTR for the integrated equipment. Of course, equipment reliability is in turn affected by the maintenance concept or design because of human factors--the way people handle things.

In summary, it is clear that reliability and maintainability affect operational effectiveness, even though the more obvious effects of physical or dynamic performance tend to get much more attention. Furthermore, reliability, maintainability and physical performance are attributes which can be designed into a system or equipment, and all depend on the environment in which the equipment operates or is repaired. In short, poor R&M can cancel the superior operational effectiveness you had hoped to achieve through better physical performance.

LOGISTIC SUPPORT PLANNING NEEDS DEPENDABLE R&M DATA

Integrated Logistics Support (ILS) plans depend heavily on predictions of R&M field performance. Obviously, plans for such things as spare parts, maintenance facilities, field and depot maintenance equipment, and maintenance personnel depend directly on predicted MTBF and MTTR of the equipments and subassemblies. Without a complete R&M program, prediction of R&M field performance is largely guesswork or wishful thinking. That's because development and production contract R&M requirements will have no predictable relationship to field results if equipment R&M design is not systematically tailored to those requirements during development, and if R&M achievement is not continuously measured in development and production. This situation has been illustrated many times in the history of electronic equipment development with cases where field reliability differed from predictions used for logistics planning by factors as high as ten to twenty, usually for the worse. This, of course, leads to major disruption of support at the beginning of deployment, and subsequent delays and financial crises before reaching the system effectiveness originally predicted. On the other hand, a solid R&M program will pay off with reduced ILS planning uncertainty, and prevention of such disasterous surprises in the field. Overly optimistic R&M statements result in not operationally ready due to lack of spares (NORS) conditions, but of equal importance, pessimistic statements of R&M result in the over-buy of spares which the Air Force can ill afford.

THE FRINGE BENEFIT DURING DEVELOPMENT TESTS

Good R&M clearly benefits both the Air Force and the contractor. That is, good R&M performance during development testing will insure that tests move along smoothly and that engineers can concentrate on verifying physical performance parameters. Good reliability techniques (such as incorporating high reliability parts) should not be delayed until the qualification test articles. The more reliable the early prototypes are, the more effective and efficient the test program and the earlier the equipment reliability can be evaluated. Nothing is more aggravating during a test program than unexpected equipment failures which have nothing to do with the purpose of the test. Such failures lead to expensive program delays, or frustrating decisions on whether or not to cut short some tests to avoid these delays. In this situation, both the Air Force program office budget and the contractor's profit can be jeopardized by poor R&M. Furthermore, the reputation of both the Air Force program manager and the contractor are usually at stake during this time and a production decision may be in the balance. A well-planned and executed R&M program can pay handsome benefits in time savings, cost avoidance, profit and reputations during this critical period.

<u>WHY R&M NEEDS SPECIAL MANAGEMENT EMPHASIS</u>

With all the benefits discussed, one would think that R&M would be a high priority of all program managers. Unfortunately, this is not so. Some of the pressures acting against attention to R&M are discussed below:

PERFORMANCE IS EXCITING

First of all, America has tended to be a throw-away society with little concern for conservative use of natural resources. We buy a flashy new car or appliance, use it for several years, and when it's worn out we trade it in for a small faction of its cost or throw it away. We have not been a society where durability stood high on our scale of values, although there is some recent evidence that maybe this attitude is changing. On the other hand, dynamic and physical performance is put high on our scale of values--speed, size, acceleration, agility, flexibility, range, style, fidelity, and so on. This sense of values, developed from childhood on, probably has a subtle affect on attitudes toward durability efforts in Air Force development programs. Anyone who has worked in one of these programs will surely agree that management interest is most intense when discussing the system's acceleration, speed, range, altitude, fire-power, flexibility, load capacity, sensitivity, signal-to-noise ratio, and so forth, and its resulting effectiveness in a warfare engagement analysis. Reliability and maintainability on the other hand are often treated as just a couple of the "ilities" that the contract "boiler plate" will take care of. This attitude has been reversed, however, in certain programs where reliability is a life or death matter for the program--certain space and missile programs for example, and equipments where flight safety is a paramount consideration. In any case, unusual motivation is needed to elevate R&M to the level of attention that long range economics show they deserve.

R&M BENEFITS ARE IN THE FUTURE

Another factor which tends to diminish interest in R&M activities is the long-term nature of most of the payoffs. The benefits of these activities are not immediately visible during development and production. An R&M program costs money, but the big payoff doesn't come until years later in the form of a reduced logistics budget. The program manager on the other hand may be overwhelmed by the many short-term goals he must strive to achieve. Examples are: meeting next year's budget, meeting initial delivery and flight dates, and passing physical performance tests. Also, the program manager's performance may be judged on the basis of achievement of these easily quantified short-term goals. Consequently, the program manager must be motivated to insure that R&M gets the management emphasis that long-range Air Force interest demand, since the development and production steps may span four to eight years and the total life cycle may span 20 years or more. Long-term cost saving goals of the Air Force must be translated into short-term management goals which will successfully attract the manager's attention.

INITIAL R&M ACTIVITY IS LOW-KEY

R&M engineering is not a very flashy business, especially during initial design and fabrication. That is, the work is detailed and complex, and milestones are not very large. Progress or lack of it in the early and very important phases is not easy to measure. Consequently, management may give it only casual notice. An intermediate period activity which may arouse some management interest is nonstandard parts approval requests from the contractor. Here the Air Force program manager must make some decisions which have major long-term ramifications, but he may be tempted to capitulate to those ever present short-term pressures such as budget and schedules. It is not until R&M demonstration tests that tangible and immediate problems are apparent--failure to pass the tests. By then, the program has momentum, hardware is being produced in quantity, the contractor is itching for a follow-on procurement, any any delays or significant equipment modifications mean impacts on schedule and budget--the pressure is on for a compromise of R&M requirements. So we can see again, there is need for special incentives and motivation to give R&M the management attention they deserve from the very beginning of the program.

NO EASY ANSWERS

Can the program manager rely on the contractor to meet R&M requirements? Not entirely. The contractor is motivated by profit and survival of the company, and these usually translate into short-term objectives so far as a particular project manager is concerned. Some companies have good R&M engineering staffs, but you will get no more effort than you specify for delivery under the contract, and any design or test alternatives not explicitly stated in the contract can be expected to be selected by the company staff to benefit company interests. The Air Force must look out for its own long-term interests. Contract provisions such as warranties and performance incentives can provide limited insurance that Air Force long-term interests are protected, but as discussed in Chapter 6, these provisions must be supplemented by other R&M engineering tasks, both contractor and Government, tailored to the particular equipment.

Can the program manager rely on the long list of standards, specifications, and manuals in the contract? Again, not entirely. The military standards and specifications for R&M contain numerous alternate procedures and requirements so that they will be adaptable to all kinds of equipment situations. The program manager must provide for, and must strongly support, an R&M engineering advisory team which can intelligently select the critical R&M requirements to put in the contract, and then follow through with surveillance of contractor performance. This team must also help the program manager make program decisions, such as choice of design and test alternatives, which he may not fully understand from a technical standpoint. Standards, specifications, and manuals provide the fabric from which to tailor an R&M program suited to the particular equipment, and this tailoring must be done by a team of specialists motivated to protect the long-term interests of the Air Force.

From all of the above, it is clear that we must have motivated Air Force program managers who perceive the special pitfalls of R&M management and then know how to work around them. Those pitfalls include the American passion for performance which distracts attention, the "ility" image of R&M which implies that the staff will take care of it somehow, the long-term payoff of good R&M which tends to diminish short-term interest, the low-key analytical character of initial R&M work which makes it "dull", and the temptation to grasp for easy answers.

Consequently, R&M require extraordinary management emphasis and the chapters which follow explain what to do to insure that we cash in on the spectacular cost saving benefits of improved R&M.

SYNOPSIS

The shrinking buying power of the Air Force budget demands a variety of management actions to reduce costs.

Improved R&M will enhance the value of the budget by greatly reducing long-term operating and maintenance costs.

Case histories and studies show clearly that the cost of a good R&M program is an excellent long-term investment for the Air Force. The payoff is spectacular.

Operational effectiveness of systems is improved by better R&M performance.

The short-term pressures on a program manager, such as budget and schedule, often conflict with the Air Force's interests in life-cycle savings through good R&M performance.

R&M often suffer from the "ility" or "boiler plate" image. They need center-stage attention from the beginning of the program.

So far, no simple, concise contractual provision has been found to guarantee long-term R&M performance. The program manager needs expert advice to guide the way and monitor the progress.

R&M need extraordinary management motivation at staff levels, as well as at the program office, in order to secure the handsome long-term money-saving benefits which the Air Force must have.

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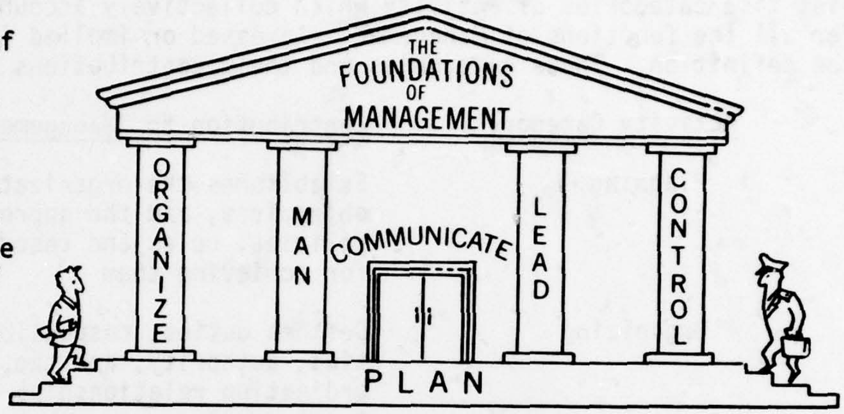
Chapter 3

MANAGEMENT FUNDAMENTALS

INTRODUCTION



This chapter gives a brief explanation of the principles of management, using a traditional approach to the structure of these principles. Whether you manage an Air Force project office, a hardware store or a football team, you will find that all of your management activities can be classified into the categories explained here. If you find that one of the categories is not covered by any of your activities, you may be headed for trouble because a major management function is being overlooked.

Even though essentially all Air Force and industrial managers have some formal education in management, and often considerable experience, a quick read-through of this chapter will be helpful because it explains terminology and concepts we have elected to use throughout this guidebook. Various authors discuss management somewhat differently, but in most cases it is only a relatively minor variation on the theme used here.

Management can be defined as:

> The process of motivating and coordinating an appropriate group of people to perform the actions necessary to achieve a desired set of objectives.

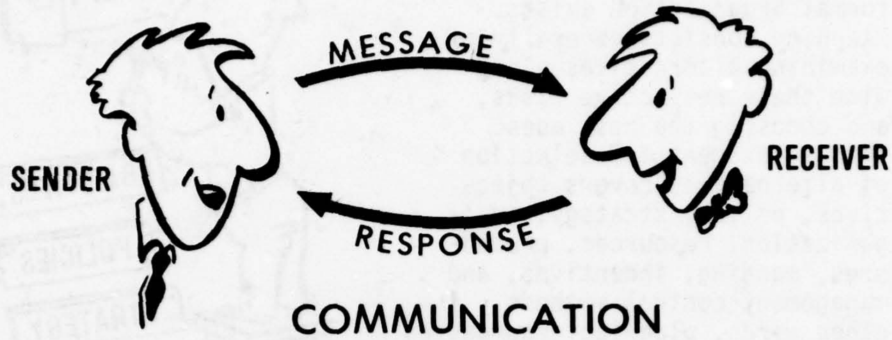
In this definition, the word "coordinating" needs to be given special meaning and emphasis. Coordinate means here that the necessary acts must at least supplement one another (add to), and preferably compliment one another (amplify or multiply each other) so as to yield a synergistic effect. That is, the most productive organization will tend to have many complimentary activities with the remainder supplementary and none counter-productive (subtractive). The organization of people should produce results greater than the sum of the contributions of its individual members.

We can take the above definition of management, and from it list five categories of activity which collectively account for all the functions of management expressed or implied in the definition. These categories and their contributions are:

Activity Category	Contribution to "Management"
Planning	Establishes the organization objectives, and the approach, policies, rules and resources for achieving them
Organizing	Defines duties, responsibilities, authority, and the coordinating relationships between people.
Manning	Secures an appropriate group of people able to perform needed duties
Leading	Instructs, directs, coordinates, and motivates people to perform needed duties to progress towards established objectives using set resources, policies and rules.
Controlling	Measures progress towards objectives and takes corrective action to remove unwanted deviations

You may wonder what happened to "communicating," sometimes listed as a class of management activity by some authors. We consider communicating as fundamental to all human endeavor and obviously must be carried out to execute all of the five management functions above. Of course, communicating is also necessary in engineering, law, medicine, football, and plumbing. In management, communicating becomes most crucial in the "leading" function as explained later, but is an important element of all management activities. There is no doubt that a good manager is also a good communicator who is skilled in employing all the graphic and verbal forms of communications.

It is important for the manager to view communication as a two-way process which includes a message and a response to that message.



Simply sending out a message is no guarantee that communication has occurred. For example, the daily bulletin is not a communication, but just a message. It becomes a communication medium when its originators get some kind of response to its content. When talking on the telephone, you are never sure the other party hears or understands you until you hear an acknowledgement that reflects comprehension of your message. Similarly, an Air Force regulation, specification, or directive is not a communication, but just a message. There is no assurance of communication through these documents, unless response is observed or measured in some way, and then the communication effectiveness might turn out to be very good or very bad. When we send out a management message for the purpose of communication, we should be sure to provide for a measure or observation of its response in some form.

Getting back to terminology, textbooks often list our "manning" function as "staffing," but "staffing" has special meaning in Air Force jargon and therefore is not used here. The texts also commonly use the term "directing" rather than our "leading," but that is mostly a matter of preference. "Leading" is preferred here, because it implies "leadership" and motivation as well as giving directions. The remaining terms used here for the management functions--planning, organizing, and controlling--are widely used.

The five management functions are explained briefly in the following paragraphs, and some comments about program management and systems engineering conclude the chapter.

PLANNING

Planning is done by essentially everyone in an organization, but the process begins at the top. In fact, it will begin before a formal organization exists. Planning consists generally of examining alternatives along with their respective risks, and choosing the best ones. This assessment and selection of alternatives covers objectives, policy, strategy, organization, resources, procedures, manning, incentives, and management control methods. In other words, planning encompasses and is involved in all of the management functions.

The first and most important alternatives to consider in top level plans are the organization objectives. Without these, no one knows where they are headed or what they are supposed to accomplish. The objectives should be clear, concise, specific and expressed in quantifiable or measurable terms, so that subordinates can easily understand them and progress towards them can be measured readily. In addition, the planning premises, assumptions, or ground rules on which the objectives are based should be literally attached to the objectives to aid re-evaluation of the objectives should the premises later change. Finally, the objectives must be prioritized in some way. Priorities serve as a guideline (along with risk assessment) for the allocation of resources, and also guide the preparation of derivative plans by subordinates.

The objectives must be explained and publicized throughout the organization so that derivative planning objectives can be developed by subordinates. (Publicizing plans is an activity under the "leading" category discussed below). Once objectives have been set, everyone should know "what to strive for."

Additional planning is needed to establish the overall strategy, policies, procedures and resources for accomplishing the objectives. That is, "how shall we do it"? Answering this question makes it obvious that planning must consider the other management functions of organizing, manning, leading, and controlling.

Planning actually sets the stage for all of these functions. Planning will yield the overall organization policies, procedures, ground rules and resources for accomplishing those functions in a way which contributes to the objectives, and more detailed derivative plans will be developed down through the organization to carry on the day-to-day management functions.

In general, planning activities can be grouped into two major categories, "strategic plans" and "operating plans." The kinds of questions to ask and typical end results are as follows: (there is not necessarily a one-to-one relationship between questions and results).

Strategic Plans

Questions	Results
What are the assumptions?	Premises
What are the risks?	Objectives
What shall we do?	Priorities
How important is it?	Strategy
How should we approach it?	Policies
What are the ground rules?	Resource needs
What do we need?	Milestones

Operating Plans

Questions	Results
What activities are needed?	Functions
How do we coordinate?	Organization
What are the tasks?	Job statements
Where do we find the people?	Recruiting plan
When does it need to be done?	Schedules
What are the key events?	Procedures
How do we gauge progress?	Control methods
How much money?	Resource allocations
What facilities?	Budgets

Plans will be made by top management in both of the above categories in "top level" detail. These plans will be passed on to the second tier managers to continue planning at the second level of detail. This process will continue all the way to the individual operating level where each person will make his personal plans for getting his work done. In developing derivative plans, two principles should be observed at all subordinate levels:

Contribution to Objectives Principle

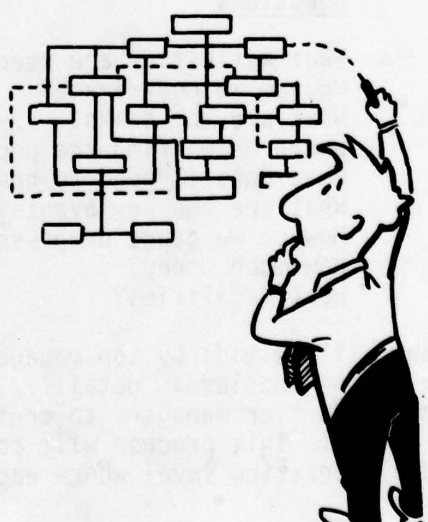
Efficiency of Plans Principle

Contribution to Objectives implies that every plan should provide a positive contribution to or show some positive relationship to organization objectives at the next higher level. Efficiency of Plans implies that implementation of the plans will produce results which contribute to the objectives with a minimum of unnecessary or counterproductive effort. Another way to say it is that the value of the results of the plans should exceed the cost of the effort needed to implement them. Finally, plans need periodic re-evaluation, at least annually, to reaffirm both their contributions and efficiency.

In Air Force planning, many specific policies and techniques are advocated and directed. These include cost effectiveness analysis, life cycle costing, economic analysis, program documentation and review, and numerous others prescribed in the regulations and manuals on program management, systems engineering, test and evaluation, integrated logistics support, and the programming, planning, and budgeting cycle.

ORGANIZING

The management function of organizing has the fundamental purpose of establishing a structure of functional activities and their relationships to serve as a coordinating framework in which to operate. This is accomplished by first listing all of the activities which must be performed in order to accomplish the organization's objectives. Then these activities are grouped according to some predetermined logic. We might, for instance, design the organizational structure by grouping all activities that require similar skills, or we might group them according to the



geographic location where they are performed, or we might use a time base and group activities in their chronological sequence. All of these and many others have been used successfully.

The next major step in organizing is to tie these grouped activities together in a network which clearly delineates their relationships to each other. Inherent in this process is the identification of an individual who represents each grouped activity and who must be delegated sufficient authority to effectively coordinate the activities within his group. Furthermore, there must be hierarchical (up-down) and lateral relationships between groups, and again there must be delegation of authority to individuals who can effectively coordinate the activities between these groups. When these relationships are graphed in the form of horizontal and vertical groups of authority relationships, the result is the conventional organization chart. In addition to the chart, written statements of group functions, and individual jobs, responsibilities, and authority will complete the organization picture. Built into these statements of jobs and functions must be the general procedures for coordinating all the activities within and between groups.

As an example, consider the organization of a typical System Program Office (SPO). The overall objective of the organization is to implement the timely delivery of systems meeting defined operational requirements within the constraints of available resources. In order to achieve the overall objective it is clearly necessary to establish a set of coordinated and specific sub-objectives. These specific sub-objectives are assigned to functional groupings within the hierarchy of the SPO organization. Thus starting with the program definition we typically have functional activity groupings responsible for budgets and schedules, configuration of hardware, engineering, operations and testing, and procurement. Occasionally, some program activities normally included in one or the other of one of these groupings may be singled out and be separately identified. Thus we find some SPOs which include organizational units for systems safety, environmental protection, reliability, maintainability, quality control, etc. The extent to which this is done depends largely on the scope and importance of these particular activities in relation to the objectives of the program.

The program manager has the responsibility to coordinate these grouped activities in such a manner that they support and enhance each other. In other words he facilitates the accomplishment of the SPO's overall objective by generating an organizational climate in which each functional activity accomplishes its assigned tasks. The program manager is assisted in the performance of his logistics duties by the Deputy Program Manager for Logistics (DPML).

In an SPO the R&M manager will typically be located in Engineering. Depending upon the size and scope of the program he may have a large or small staff of R&M engineers assigned to him. In some instances he may be operating as an individual. However, regardless of the size of the R&M function, in his day-to-day activities he will interface with other functions within the SPO. Typically, he either seeks or provides information for prudent decision making. In doing this he communicates freely across the hierarchical structure of the SPO or other staff levels as appropriate. The R&M manager's output is in the form of advice to other SPO engineers and recommendations to the program manager who has ultimate responsibility for the execution of the program.

In summary, when the management function of organizing is complete, the following results will be available:

- Organizational chart
- Activity function statements
- Job descriptions
- Authority delegations
- Coordinating procedures

The next step is to man the organization with appropriate people.

MANNING

Manning or "staffing" as it is more commonly called in the management literature, is the management function of recruiting, selecting, placing, training and appraising qualified people to fulfill the duties which have been defined through the processes of planning and organizing.

The obvious challenge is to pick the right person for the right job. This is not an easy task, and requires recruiters with not only a good understanding of the jobs to be performed, but a keen insight into the human factors associated with those jobs. In fact, it is a good idea to attach to each job description a list of the personality attributes most appropriate for the position. People tend to be loners, social groupers, detail lovers, gregarious talkers, movers, sitters, thinkers, actors, drivers, followers, writers, organizers, leaders, strategists, generalists, specialists, or some complex combination of these traits and many more. The recruiter's job is to sniff out the dominant traits and skills of each person, and to judge whether that person has a good potential for effectively performing the duties of the job.

Once an individual has been hired or assigned to a job, there is a continuing need to train him and develop his abilities to function efficiently. This may include training in technical areas, communications techniques, management skills and interpersonal relations. Appraisal of the individual's job performance can also be considered a development technique.

A periodic function of manning is appraisal of the individual's performance. While most appraisal methods tend to be based on subjective judgments, it is far better to base appraisal on the individual's achievement of quantifiable objectives that he has agreed in advance are reasonable for him to pursue. This method of appraisal serves to keep everyone objectives oriented, and will tend to play down subjective personality judgments hinged on whether or not the person happens to be likeable. The use of an appraisal based on quantifiable objectives also makes discussion of the person's appraisal much more productive, since it is easier to focus on the objectives and how well they were or were not met along with the various reasons why. You might also get some good feedback responses that would be useful for improving the organization structure or procedures. If, on the other hand, you get focused on the individual's personality traits, it is very easy to turn off useful communications or to degenerate the discussion into an emotional exchange that would be counterproductive. Appraisals based on judgment of subjective personality traits also have a strong tendency to get inflated if the subjects of the appraisals have access to them.

While appraisal based on achievement of quantified objectives sounds good, it is easier said than done. Many jobs do not have objectives which are easy to quantify--take a receptionist or recruiter for example.

To summarize, manning consists of:

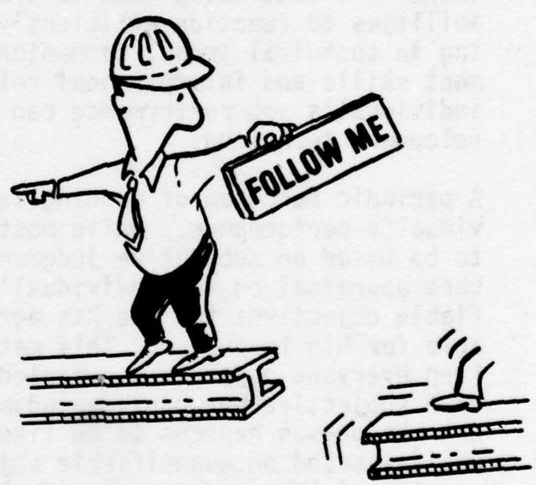
Selecting and placing qualified people to perform the defined jobs

Training and developing their skills

Appraising their performance and making appropriate changes in job assignments, training or development

LEADING

The management function of leading consists of setting the organization activities into motion towards the objectives employing established resources, procedures, policies, organization and schedules, and inspiring enthusiastic participation by subordinates and associates. This is accomplished through the use of orders, directives, instructions, explanations, persuasion, encouragement, motivation, rewards, penalties, and many more. From these it is obvious that the leader must be skilled in using the graphic and verbal forms of communications. He has to be a good coordinator and motivator. He has to work with people and inspire people to work with each other.



A first and fundamental activity for effective leading is to make organizational objectives and priorities very clear to all subordinates. *Everyone should be able to visualize how his duties* contribute to accomplishment of those objectives, and he should be encouraged to suggest changes in his duties if his duties involve some counterproductive actions. He cannot make these suggestions unless the objectives are explicit, tangible things which he can measure or observe. That is why derivative plans must be developed which provide objectives and priorities for all levels to use down through the organization.

A second fundamental activity in leading is to also make very clear, all rules, policies and procedures applicable to the jobs of subordinates, so they will know how to get things done. These policies and procedures result from the planning process, and the task in leading is to explain their use and work out any bugs discovered through their use.

The leader must then initiate action, or set the organization wheels into motion, by issuing instructions in one form or another. It may be at this point that the manager develops his final sets of derivative plans, objectives, schedules, resources, tasks for his subordinate to implement, and includes these in his initiating instructions. These instructions, together with procedures,should insure that activities are coordinated (supplement or compliment one another).

The last and most challenging task of leading is to provide motivation to perform. This is meant to go well beyond the customary rumuneration of most jobs. Motivation involves setting a good example, making work seem enjoyable and satisfying, setting high standards of integrity and performance, praising good work (in private and public), showing how to correct deficiencies (always in private), handling human relations problems with fairness and respect for the dignity of the individual, promoting an atmosphere of open communications in all organization directions, and many more. If all of these leadership actions are handled skillfully, we can succeed even without charisma.

In summary then, leading involves:

Explaining and publicizing objectives

Clarifying policies and procedures

Initiating action with explicit instructions

Promoting coordination of activities

Motivating through a variety of techniques

CONTROLLING

Control requires the measurement of accomplishments, comparing them with preplanned standards, and taking corrective action if deviations are unacceptable. Control procedures should be planned for all organization activities and should be formal for critical activities, but can be informal for lesser activities. The appropriate degree of control depends on the degree to which the activity impacts organization objectives. Control is usually applied to resource expenditures, product quality and quantity, certain services rendered, task accomplishment versus schedules, and compliance with organization procedures.

Controls should focus on a relatively few strategic parameters or indicators of progress towards objectives of the activity, and should avoid unnecessary or redundant measures. Controlling requires gathering data, analyzing and summarizing it, and presenting it in an easy-to-comprehend form. This can be a costly administrative task, and prudence is advisable.

The gathering, analysis and presentation of control data should be planned at an appropriate frequency and on a reasonable scale. For example, if we had a $50,000 monthly budget which is capable of varying by only $10,000 in any month (due to mostly fixed costs), it would be senseless to review expenditures to the nearest dollar on a daily basis. A weekly review, rounded off to the nearest hundred dollars would be more reasonable.

If performance makes unacceptable deviations from the standards, corrective action must be quick enough to do some good, and also should be tailored to reduce the chances of deviations in the future. Obviously, corrective action is implemented by the manager responsible for the activity being controlled.

To minimize the need for corrective action, the organization should plan procedures and policies which motivate people towards organization objectives by creating incentives that appeal to individual human needs and drives. Motivation of the individual to control his own performance toward organization objectives is a far superior approach to external control by superiors. That is because external control can easily lead to a feeling of mutual distrust between superiors and subordinates, resentment, resistance and a tendency to withhold, cover-up or distort information that may put the individual in an unfavorable light. External controls can also be expensive in terms of administrative burden, and can easily degenerate into counterproductive effort if not carefully conceived and prudently applied.

Some examples of procedures or policies which have a self-regulating affect on organized achievement are listed below. (Some of these might be considered motivations under the preceding heading of "leading," but that is unimportant. Their effect is to reduce the need for external control corrections in the organization).

a. Offer monetary incentives for achieving quantity, quality or schedule goals.

b. Appeal to personal pride in workmanship by imprinting the worker's name on the product.

c. Appeal to pride of authorship and the desire for personal fulfillment by asking employees to derive their own objectives and goals from higher level objectives, and later report on their accomplishment of them.

d. Appeal to the desire of the individual to have personal control over his activities, by asking groups to develop their own operating procedures and later report on their effectiveness.

e. Appeal to the spirit of group competition by rewarding groups with the best performance.

f. Appeal to the sense of pride in the organization by setting high standards of performance and making it clear what is expected of its members. However, even with these kinds of incentives for achievement, organization progress towards goals still need to be measured, but the need for corrective actions by management should be significantly reduced and overall organization efficiency increased.

External management control techniques may range from a weekly staff meeting with verbal progress reports, to elaborate data gathering, analysis and charting schemes combined with feedback instructions to the managers of functional groups being controlled.

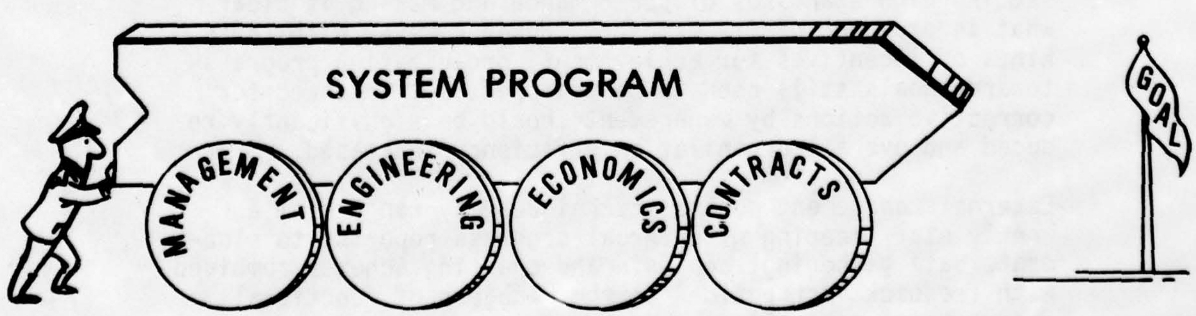
Summarizing, management control requires:

- Selection of activity performance parameters worthy of tracking
- Setting standards of performance
- Choosing appropriate scale and frequency of observations
- Comparing performance with standards
- Taking timely action to correct deviations and to reduce chances of repetition
- Search for self-controlling procedures founded on individual incentives and motivations

<u>PROGRAM MANAGEMENT</u>

In Air Force terminology, program management refers to the management processes involved in developing, testing and producing new military systems. The Program Manager is given broad responsibilities for producing a good system and is delegated substantial authority to make the decisions needed to fulfill those responsibilities. The objective is to "decentralize" *program management* as far as it is prudent to do so, and focus the responsibility and day-to-day decision making in the program office.

The Department of Defense (DoD) and Air Force policies governing the Program Manager's role are explained in DoD Directive 5000.1 which is an attachment to Air Force Regulation 800-2, Program Management. The regulation outlines the major management responsibilities of the Program Manager, with emphasis on general planning and reporting requirements, and his decision-making authority. Anyone involved with a system acquisition program must be thoroughly familiar with AFR 800-2.



THE DOMAIN OF PROGRAM MANAGEMENT

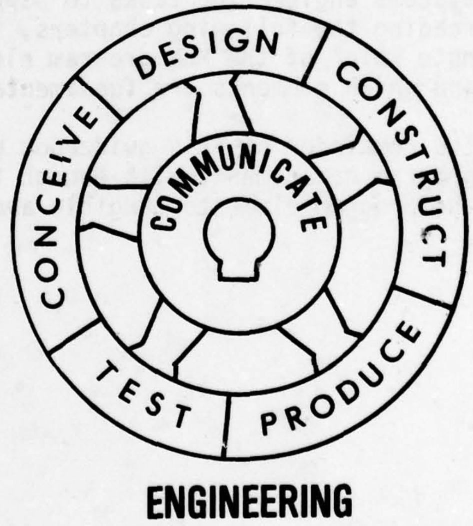
R&M MANAGEMENT

The R&M manager's job is not a simple one since most of the people he must influence do not work for him. He must motivate many people in other elements of the organization. Therefore, while he is first of all a manager, he needs to have some knowledge of the various professional specialties involved in the program. These include systems and equipment engineering, contract law and regulations, configuration control, economic decision making, and perhaps others like aeromedicine or psychology. The R&M manager has a formidable task of leading the R&M program along a hazardous path of pitfalls scattered throughout the development cycle. He must be a manager skilled in applying the management principles described in this chapter.

One purpose of this Reliability and Maintainability Management Guide is to clarify the technical and management pitfalls in R&M, and to show how to formulate a successful R&M program based on sound engineering and management principles.

SYSTEMS ENGINEERING

The term "engineering" usually means the application of traditional technical and scientific skills (mathematics, physics, chemistry, etc.) to conceive, design, construct, test and produce new things. "Management," on the other hand, is the application of human behavior principles and insights (psychology, philosophy, physiology, etc.) to plan, organize, man, lead, and control any human endeavor. Clearly, management is involved in the orderly activities of any group, but engineering is not. Whether we talk about engineering, management, or some other disciplines, communication is always the hub of organized activity.



"Systems engineering," as the term is used in the Air Force, is a more general term that encompasses both engineering and management aspects. It means that the military system must be conceived, designed, constructed, tested, and produced, taking into account the performance and economic trade-offs involved across all functional and support elements of the system and over the entire life span of its use. That is, systems engineering is expected to yield the most cost effective system considering operational performance, producibility, and supportability. To achieve this goal, various management planning, organizing, leading, and controlling policies and procedures are prescribed. Air Force Regulation 800-3, Engineering for Defense Systems, explains what those policies and general procedures are. The Program Manager is responsible for seeing that systems engineering is employed in his program.

This introduces us to the elements of reliability and maintainability (R&M) programs explained in the next two chapters, since these R&M programs are part of the systems engineering process.

As the reader will notice, R&M programs consist of a mix of engineering and management elements which mesh with other systems engineering tasks to support R&M objectives. (When reading the following chapters, it might be instructive to note which of the R&M program elements are basically managerial and which elements are fundamentally technical or engineering).

The remainder of this guidebook gets into the specifics of R&M program management, with enough technical description to make the program elements tangible and meaningful.

Chapter 4

ELEMENTS OF A RELIABILITY PROGRAM

INTRODUCTION

To successfully reach its goal, a reliability program requires coordinated performance of a series of tasks by managers and technical specialists. This series begins with the first conceptual studies of the new system, continues through production, and ends only when the system is phased out of use. The procuring agency (AFSC), the manufacturer (contractor), the user (operational command), and his support agency (AFLC), all have responsibilities in this chain of events.

The staff R&M manager needs a detailed understanding of the reliability engineering and management tasks, including who does them and when they must be done. He must understand the technical terminology of reliability engineering and how to specify reliability performance, and he must know the engineering data required to track a contractor's R&M program. He should understand the relative importance of the various activities and the possible consequences of skipping or curtailing them. He should recognize major options with corresponding costs and risks. He should know where to get additional technical people for advice. This short chapter is written to fulfill those needs.

STANDARD RELIABILITY PROGRAM ELEMENTS

MIL-STD-785

Reliability Program

for

Systems and Equipment

Development and Production

The chart which follows lists the elements of a hardware reliability program and shows the importance of each element during the life cycle phases of development. This list generally follows the outline of MIL-STD-785, but with some changes to aid continuity of the discussion. MIL-STD-785 is the basic standard for planning reliability programs for DoD development and production contracts and gives guidelines for preparing a reliability program plan. However, the application of MIL-STD-785 provisions is subject to the discretion of the procuring authority. To intelligently exercise this discretion, the procuring authority needs expert advice from someone with R&M

RELIABILITY PROGRAM ELEMENTS

Element	Life Cycle Phase				
	Conceptual	Validation	Full Scale Development	Production	Deployment
Requirements Definition	xxxxxxxxxxxx	xxxxxAAAAAAA	A.......		
Reliability Model	xxxxxxx	xxxxxxxxxxxx	xxxxx.......		
Reliability Prediction	xxxxxxx	xxxxxxxxxxxx	xxxxx.......		
Reliability Apportionment	ooooooo	oooooooooooo	ooooo		
Failure Modes Analysis	ooooooo	oooooooooooo	xxxxx.......		
Design for Reliability	ooooooo	xxxxxxxxxxxx	xxxxxxxxxxxx	....	
Parts Selection	ooooooo	xxxxxxxxxxxx	AAAAAA.......	....	
Design Review	ooooooo	xxxxxxxxxxxx	xxxxxx......		
Design Specifications	xxxxxxxxxx	xxxxxxxxxxxx	xxx.........		
Acceptance Specifications	xxxxx	xxxxxxxAAAAA	A.........		
Reliability Evaluation Tests	-----	xxxxxxxxxxxx	xxxxxx		
Failure Analysis	-----	xxxxxxxxxxxx	xxxxxxxxxxxx	oooooooooooo	oooooooooooo
Data System	-----	xxxxxxxxxxxx	xxxxxxxxxxxx	oooooooooooo	oooooooooooo
Quality Control		oooooooooooo	xxxxxxxxxxxx	xxxxxxxxxxxx	oooooooooooo
Environmental Tests		xxxxx	........AAAA	AA.........	
Reliability Acceptance Tests		xx	..........AAA	Aoooooooooo	

First contract

—KEY—

------------ooooooooooooooxxxxxxxxxxxxxxAAAAAAAAAAAAA...............

Desirable activity (for highest success probability)

Necessary activity (errors seldom disastrous)

Very important activity (errors often disastrous)

Critical activity (errors usually disastrous)

Low key activity (to update previous results) engineering and management experience. The procuring authority is usually advised by the project manager and sometimes is the project manager. However, the project manager is rarely an R&M engineer and therefore he also needs the advice of R&M specialists. The explanations which follow should aid communication between manager and advisor, and help the R&M advisor provide the correct advice to the project manager.

First, a definition of reliability may be helpful. Reliability is a performance attribute of an item and defines its ability to properly function under specified conditions for a certain period of time or a certain number of operating cycles. Reliability can be quantified as a probability. For example, we could say that the probability is .90 that a Model-A machine gun will fire successfully for 60 seconds in rainfall rate of one inch per hour. Reliability can also be quantified as a Mean-Time-Between-Failure (MTBF). That is, Model-A machine guns have an MTBF of 570 seconds firing over 60 second intervals in a rainfall rate of one inch per hour. These probability and MTBF numbers are mathematically related to one another and are called "reliability figures of merit," or simply "reliability figures" to be more brief. Definitions of these and other R&M terms can be found in MIL-STD-721, Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety. The mathematical relationships can be found in R&M engineering books.

Before explaining the separate reliability program elements listed on the chart, some general comments about the chart would be helpful.

The relative importance rating of the elements represents the subjective judgment of the authors based on years of experience, and is meant to apply to the "average" development program. The chart is designed to give the R&M manager an overview or feeling for the average situation. Every development program is different and the reliability program to go with it must be tailored to specific needs. This tailoring must be done by reliability specialists working for the Air Force program manager.

Only the first conceptual study contract milestone is shown. Work shown to the left is Air Force homework leading to the first statement of work. These conceptual studies and subsequent contractual work will lead to more and more specific design and acceptance specifications until the production contract is solicited. Several contracts may be used between the conceptual phase and the production phase, with initiation occurring at the beginning of each phase following go-ahead decisions from Air Force and Department of Defense management. On some programs many of the conceptual and validation phase tasks are accomplished by Government planning organizations or by the program office. This does not affect the relative importance of the tasks or the necessity for having them accomplished at the proper time. Therefore, the R&M manager must review all the required tasks, and for those which are not to be accomplished contractually insure appropriate Government organizations have been designated to accomplish them.

DEFINITION OF REALISTIC REQUIREMENTS

The first and most important task in a reliability program is selection or definition of realistic requirements. This is a procuring activity task. While execution of this task requires the knowledge of reliability engineers it is closely tied to the managerial function of planning. The basis for the selected requirements should be questioned by managers and planners at all organization levels, and that includes the user, supporter and contractor, as well as AFSC. These requirements are the objective of the reliability program, and hardly anything is more wasteful or disrupting than to strive for the wrong objectives. Managerial scrutiny of the requirements should begin early in the conceptual phase and continue through validation and into full scale development. As the chart shows, the final setting of realistic requirements is critical at the beginning of full scale development.

The word "realistic" needs emphasis. Whether a complex or simple system, the realism of the reliability requirement will determine much of the long-term success of the R&M program. Too high a reliability figure can lead to excessive costs in attempting to achieve it, program disruptions when it becomes evident that the figure cannot be met, litigation based on claims of impossibility, fouled plans for logistic support, and finally, possible compromise to an unnecessarily low reliability figure because of schedule and cost pressures late in the program. On the other hand, too low a requirement at the beginning usually results in insufficient R&M program emphasis with the specified requirement being easily met, and loss of an opportunity to get higher reliability and lower support costs.

The procuring activity must define the requirement with inputs from the using command and AFLC, since the final requirement must be operationally adequate and logistically supportable. (See AFR 66-14, and AFSC Supplement 1, Equipment Maintenance

Policies, Objectives, and Responsibilities, and AFR 80-5). A tradeoff analysis should be performed using systems cost effectiveness analysis and life cycle cost techniques, since reliability is a system performance parameter which strongly affects system effectiveness and life cycle cost. In these analyses, reliability should be varied over a reasonable range of values to establish the sensitivity of system effectiveness and life cycle cost to the reliability parameter. These sensitivity curves should then be used, along with the projections of reliability engineers, to select reliability requirements which strike a reasonable balance between operational and logistic needs, and the available technology to fulfill those needs.

The reliability which can be reasonably achieved for a particular type equipment using available technology must be estimated by reliability specialists. These specialists have a variety of ways to come up with reasonable estimates, and all are based on the use of historical data in one way or another. The most direct approach is to survey the reliability achieved by similar types of equipment in field use, examine the caliber of each reliability program used during development of those equipments, make adjustments for technology progress since those equipments were developed, adjust for complexity differences between the old equipments and the new, and finally adjust for differences in reliability program emphasis planned for the new equipment. This is not an easy task since it depends on finding good historical records. Furthermore, it is important that the proper comparisons be made. A historical MTBF using field data is a different measure than a MIL-STD-781 specified MTBF. Methods of estimation with a more analytical flavor are based on expected numbers of part types in the new equipment, the parts quality levels which should be available, the equipment configuration anticipated, the environment in which it will be used, and mathematical computations which take these parameters into account. Remember that even in those systems touted as breakthroughs, state-of-the-art, or "all new and different" in concept, the really new things are only a small part of the total and the rest of it is conventional hardware.

In addition, the Reliability manager must recognize the difference between Reliability terms used in reporting within the Air Force and terms used in the contract. These terms may differ, but the contractual terms must be translatable into the reporting terms. AFR 80-5 provides the standard reliability terms for reporting. AFSC Supplement 1 to AFR 80-5 (Nov 1978 draft in coordination as this is written, presumably in effect as you read it), also provides guidance for converting AFLC data (from the AFLC DO-56 Product Performance System) to standard reporting terms by proper sorting of how malfunction codes and action taken codes. With this guidance the AFSC program manager can obtain from AFLC data formatted to minimize definitional differences.

Summarizing the above, reliability requirements are developed from systems effectiveness and life cycle cost studies, coupled with projections on what is reasonable to achieve using known technology. To determine realistic requirements, the assistance of experienced reliability specialists is necessary. While not a trivial problem, methods and data exist to solve it. The procuring activity is responsible for this task, but the desires of the user and support agency must be considered. Significance of this task ranges from very important to critical depending upon development phase.

DEVELOPMENT OF A RELIABILITY MODEL

A reliability model is a mathematical equation which defines the relationship between the failure rate of an assembly (equipment, or system) and the failure rates of all the parts which make up the assembly. Each part, in turn, has a reliability model which relates its failure rate to part quality, operating stress or derating level, and the physical environment in which the part is to function.

The reliability model of the assembly is derived by reliability engineers from functional diagrams, circuit diagrams, or detail design drawings of the assembly. The result is a flow diagram which depicts the series or parallel interdependencies between all the parts. This diagram is then expressed as a mathematical equation which becomes the reliability model.

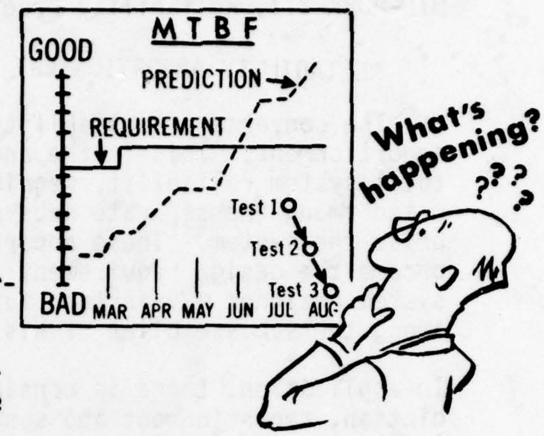
Failure models for the separate parts are developed through analysis of laboratory test and field data, and detailed studies of the physical mechanisms which give rise to part failure. This is a very complex business done only by Government and commercial laboratories that have specialized equipment and people. The models are compiled in MIL-HDBK-217, Reliability Prediction of Electronic Equipment.

The resulting reliability model of an assembly, equipment or system is the analytical basis for making reliability predictions. While this model may be rather crude during the conceptual phase, it will be expanded and refined as more system details are evolved in validation and full scale development. The model must be good, otherwise the very important reliability predictions to be tracked later by management will be misleading.

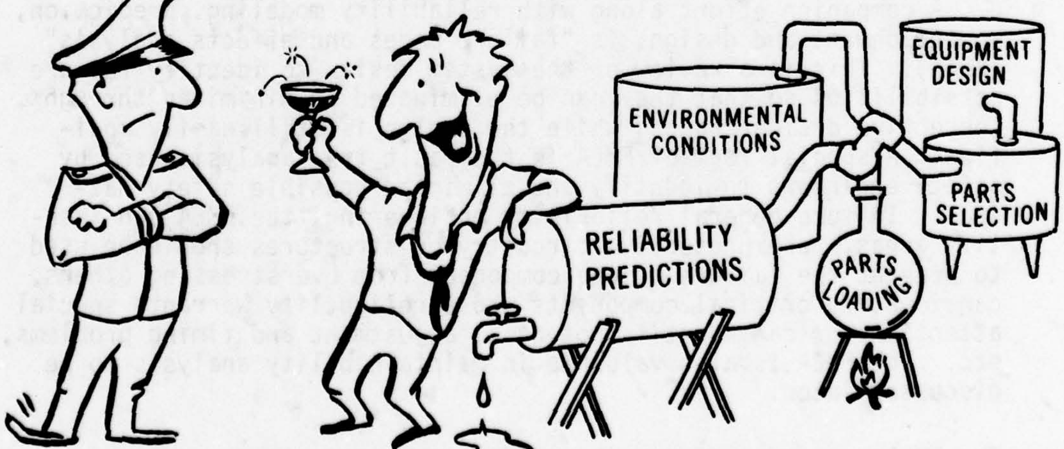
The project manager should be certain that the agency (usually the equipment contractor) who develops this model does it correctly. This model development should be reviewed in detail for the project manager by technical R&M specialists who are independent of the contractor.

RELIABILITY PREDICTIONS

The reliability of an assembly, equipment or system is predicated by inserting into its reliability model the failure rates of the separate parts. These part failure rates are obtained from the parts reliability models by considering the quality class of each part, its proposed operating stress level (or derating) and the physical environment in which it will operate.



During the conceptual phase, predictions will be less accurate, because of incomplete system and parts data obtained from estimates or design specifications. As equipment design progresses during validation and full scale development, predictions will improve and become the quantitative backbone of the reliability program. These predictions should be compared with reliability requirements and test results throughout the development phases by both engineers and managers. This will serve to illuminate reliability program progress and problem areas, and support the need for any engineering changes. It will show a pictorial, historical record of progress that will be a focal point of discussions during design and program reviews.



"It's tasty, cheap and really saves on doctor bills."

For engineering details on systems reliability modeling and prediction techniques, and specific models for predicting failure rates of electronic and mechanical parts, consult MIL-HDBK-217, Reliability Prediction of Electronic Equipment.

RELIABILITY APPORTIONMENT

The converse of reliability prediction is reliability apportionment. This is the analytical process by which the total system reliability requirement is apportioned or allocated among the separate subsystems or equipments which comprise the system. These apportioned reliability figures then become the design requirement for each subsystem. The subsystem designer may in turn further apportion his requirement among the subassemblies of his subsystem.

In application, there is considerable interplay between prediction, apportionment and system design. First, the apportionment helps to establish a system and subsystem design approach which should meet the system reliability requirement. As detail design progresses and parts are selected, predictions are performed to see if the selected design can actually meet requirements. If not, the design may be adjusted or the apportionment redone to set more realistic subsystem goals.

Initial apportionment is performed by the group responsible for system integration (usually a contractor) so that vendors or equipment designers can be given design requirements. Occasionally, when the Air Force is purchasing individual equipments for "in-house" integration, the apportionment will be an Air Force responsibility.

FAILURE MODES AND EFFECTS ANALYSIS

A companion effort along with reliability modeling, prediction, apportionment and design, is "failure modes and effects analysis" (FMEA). This is a review of the system design to identify failure possibilities so that they can be eliminated or minimized through corrective design changes while the design is still easily modified. A special form of FMEA is the fault tree analysis used by safety engineers to identify and eliminate possible safety hazards. In more general reliability engineering, the FMEA can identify areas where protective circuitry or structures should be used to prevent the failure of one component from overstressing others, can identify critical components whose reliability warrants special attention, or can identify potential adjustment and timing problems, etc. The FMEA is also valuable in maintainability analysis to be discussed later.

The FMEA must be performed by someone who is familiar with and able to influence detail design. Hence, it is usually the responsibility of the equipment designer. The extent of the

FMEA can range from a simple examination of the system or equipment functional diagram, to a detailed analysis of the design drawings and schematics considering the failure rate of each part and its likely mode of failure.

Therefore, the time and cost required for a FMEA depend on its emphasis, which in turn depends on the complexity and purpose of the system. In most cases, a rather detailed FMEA is warranted, even though it is much more expensive than the reliability modeling and prediction activity. It is a good investment since corrective actions resulting from the FMEA can be easily implemented before design is frozen. The same changes resulting from later hardware tests will be much more expensive to implement.

DESIGN FOR RELIABILITY

Design for reliability is an omnibus title, carrying a myriad of individual elements related by the common fact that they all must be considered by the designer of the system, equipment or assembly to assure its reliability. The following list includes typical considerations to illustrate the point. A more complete checklist for a given item depends on whether it incorporates electronics, mechanics, structures, hydraulics, pneumatics or some other technology.

- Simplicity of design
- Producibility of design
- Use of Government and industry standard design and layout practices
- Use of redundant or fail-safe designs (use FMEA)
- Provisions for optional modes of operation
- Use of preferred or proven parts and materials
- Selection of appropriate load or derating factors for parts and materials
- Controllability of parts and materials quality
- Future availability of good replacement parts and materials
- Consideration of aging or fatigue effects
- Consideration of human factors on reliability in manufacture, operation or maintenance
- Prediction and control of physical environment

including temperature, moisture, vibration, shock, dust, chemicals, radiation, ambient pressure, and electrical interference

The producer of the hardware is responsible for formulating and carrying out this activity. The Air Force, however, is responsible for selecting a competent producer and insuring that the contract motivates the producer to perform these design tasks to the best of his ability. The reliability program elements to follow include these motivations.

Aside from such overhead costs as reliability training programs and preparation of reliability design manuals and checklists, it does not cost much more to design an item for reliability than to design it without consideration of reliability. Whatever the small increased cost may be, it is well worth the investment at the design stage. Fixing defective systems at the testing stage is far more costly.

PARTS SELECTION

Parts selection is a critical reliability engineering element. There is no question that parts quality is a costly item, and for this reason, contractors are tempted to compromise parts quality. Yet wisdom says, "You cannot make a silk purse out of a sow's ear." With rare exceptions, you cannot make a satisfactory Air Force system from commercial grade parts. If the Air Force system is something like Minuteman or a manned space system, even high quality military grade parts may be inadequate. For example, the Minuteman program established specially controlled parts manufacturing lines for its own use. A great deal of effort has been expended to produce high quality parts for Air Force use.

While standard military quality specifications provide assurance that parts can withstand the environmental extremes of Air Force use, these specifications alone do not assure low failure rates, and so further controls have been created. For example, in the field of electronics, the most successful have been Established Reliability (ER) specifications. These specifications require tests which verify specified failure rates. Applied to passive electronic components, they have been in effect for several years. Indeed, it is now possible to buy resistors and capacitors to ER specifications as cheaply as to standard military quality specifications.

For semiconductor electronic devices, "TX" (testing-extra) and "TXV" (testing-extra-visual) specifications are preferred in Air Force systems. These require, in addition to standard military quality tests, the performance of a burn-in (operation at full ratings for a period of time, usually 168 hours) to cause parts with latent defects to fail. Those parts are thus excluded from the batch. "TXV" specifications require a visual inspection of the part before the lid is hermetically sealed on, in addition to the burn-in.

Microcircuits purchased under MIL-M-38510, Microcircuits General Specification, are required to be tested to a defined quality level using test methods of MIL-STD-883, Test Methods and Procedures for Microelectronics. Class S represents the highest level for use in critical systems. Class B represents Air Force preferred quality for normal usage, and Class C a relatively low quality for those rare cases when reliability is not a great concern, such as an extremely simple item in a non-critical application. However, even Class C parts have failure rates several times better than commercial products (see MIL-HDBK-217).

Selection of parts is therefore an extremely important matter, and in full scale development is critical. During the validation phase, the use of high grade parts is not always essential, if provision is made for their use in later stages. Lower grade parts may often be used in validation units not scheduled for reliability testing, but their form-fit-function must be the same as the higher grade parts to be used later in the full scale development and production units, permitting direct substitution without design changes. However, the selection of parts to meet the reliability requirements must begin in the first equipments built. Preparation of preferred parts lists can be fruitful even in the conceptual phase where at least part policies must be established.

Only microcircuits listed in MIL-STD-1562 and procured in accordance with MIL-M-38510 are standard for new design. When nonstandard microcircuit devices are approved for use, the general requirements of MIL-M-38510 apply. Nonstandard devices must be screened and qualified in accordance with the requirements of MIL-STD-883. Only JANTX semiconductor devices selected from MIL-STD-701 are standard. When a JANTX device is not listed, the selection of nonstandard devices must conform to the following order of precedence: (a) a JAN device listed in MIL-STD-701, (b) a JAN device covered by MIL-S-19500 but not listed in MIL-STD-701, and (c) a commercial device. As a minimum, a TX burn-in should be required for all nonstandard devices.

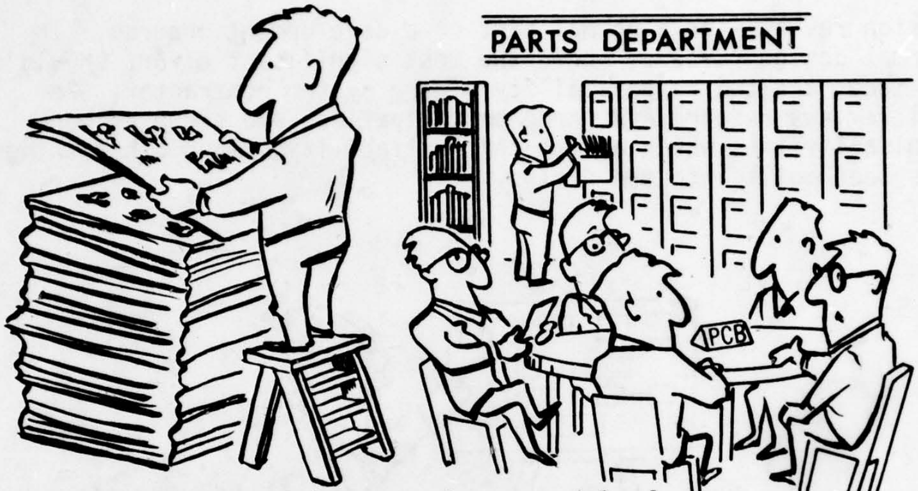
Review of parts lists is not only necessary to assure the use of preferred quality levels, but also to assure that currently preferred versions are used and that future availability and cost are considered. Also, nonstandard parts are often necessary and the review procedure must make sure that adequate qualification and reliability screening tests are applied to those parts.

Parts selection and control are so important that review board procedures are used to help assure the Air Force that the job is done with its long-term interests protected. These interests include not only reliability, but also maintainability, logistics supportability, commonality, availability, and cost of parts. All have direct impact on system life cycle costs. MIL-STD-965 Parts Control Program, defines criteria and guidelines for setting up parts control procedures in a contract. The procedure selected is at the discretion of the procuring activity. Basically, two types of control programs are outlined. One is for large system procurement employing a prime system integration contractor, and requires the use of a Parts Control Board (PCB). This is procedure II of MIL-STD-965. Procedure I, a less formal setup is generally used for small equipment development programs. Both procedures require procuring agency approval of parts selected for use in the hardware.

The Chairman for the PCB is usually the prime contractor. However, someone else may be designated as Chairman of the PAG by the procuring activity. While the procuring activity always has the right to disapprove PCB actions, the PCB normally makes the part selection decisions. This organizational arrangement requires Air Force management emphasis and participation, since board chairmanship is often in the hands of a contractor whose long-term interests and motivation may not correspond with that of the Air Force. Short-term goals are often an overriding concern for the contractor.

To aid the procuring activity in parts approval decisions, the Military Parts Control Advisory Group (MPCAG) may be employed. This is a Department of Defense organization which provides advice to the military departments on the selection of parts in assigned commonality classes. Primary contact points are the Defense Electronics Supply Center, Dayton Ohio, for electrical and electronic parts, and the Defense Industrial Supply Center, Philadelphia PA for mechanical parts. Support for semiconductors, printed circuit boards and circuit board connectors is also available from the Rome Air Development Center, Griffiss AFB, NY.

In summary, parts selection and control are extremely important development program activities which can cause significant development costs. Furthermore, they can be a significant administrative burden to the Air Force Project Office and to support Government laboratories and supply centers. Because of the sheer volume of parts decisions in large programs, and the time and cost pressures involved, it is tempting for parts control activities to cut corners, simplify the procedures, or drift towards a rubber-stamp type operation. These tendencies must be resisted by the Air Force project manager, and the Air Force staff people should carefully question the adequacy of support. The impact on life cycle cost, system effectiveness, and logistic supportability is great. The cost of a good parts program can be considerable but the costs of later failures, re-design, and retesting can make it inexpensive by comparison.



Parts selection and control are critical and a significant administrative burden.

DESIGN REVIEW (MIL-STD-1521)

The design review has both management and engineering aspects. To the manager, it is a controlling activity. To the engineer, it is a technical critique of the work accomplished. Therefore, the design review is an activity where management and engineering are closely coupled. It is a powerful management tool for the Air Force program manager, and he must assume a personal role in its conduct.

During the design review, all reliability efforts leading to design decisions are formally reviewed. This includes requirements, modeling, predictions, apportionment, failure modes and effects analysis, parts selection, and overall design for reliability. Because of the volume of these tasks, the review is, of course, done at a summary level of detail. In an efficiently run program, a series of informal detail design reviews will be conducted between designer and supporting engineers within the contractor's facility. In addition, the contractor should seek consultation with Air Force specialists to iron out any questions in advance. Then the formal design review should run smoothly and be a summary of key decisions for the Air Force, along with supporting rationale.

Another comment should be made. In an effectively managed program, the designer will consider reliability engineers and other supporting agencies as partners in meeting program goals, rather than as critics to be placated. This attitude is fostered only when management treats reliability as an essential design parameter, rather than a necessary evil which interferes with the designer's flexibility.

Design reviews are a normal part of a development program. Informal design reviews, where the most significant effort should be made, are the responsibility of the system contractor. Formal reviews require Air Force participation, and serve as control activities which assure that reliability, among other things, has been built into the design.

Design review is a very important critique and control activity.

DEVELOPMENT SPECIFICATIONS

The Government's ultimate control over the hardware producer is through contractual specifications. These specifications are incorporated into the statement of work which becomes part of the contract. The statement of work not only includes overall equipment or system performance requirements, but also specific design restrictions necessary for military systems. These restrictions generally support the goals of standardization, logistic supportability, reliability, maintainability, safety, configuration control and so on. In total, they may be costly restrictions during development, but money-saving over the long run.

Selection of appropriate specifications is initially an Air Force task under the direction of the project manager. These specifications go into the first contract of the conceptual phase. As the program proceeds, more detailed specifications will evolve from contractor design effort and these will be inserted into later contracts, but only after careful review by the project manager's engineering staff. The development of specifications is a continuing task for both the Air Force and the contractor until a production contract is solicited.

The preparation of specifications by a contractor is expensive. Therefore, the Air Force should take advantage of any suitable standard military component specifications which exist. For example, military specifications now exist for over 500 standard microcircuit devices under MIL-M-38510, Microcircuit General Specification, and new ones are being added continuously. It would be irresponsible for the project manager to allow a contractor to repeat any of this work which has already been carefully done by Government laboratories. Furthermore, these Government specifications insure uniform and predictable quality, standardization, and lower life cycle costs. They also save development dollars which can be better spent on unique system design tasks which the Government laboratories are not able to handle.

Many system design requirements and considerations which affect reliability are contained in the standard references (boiler plate) found in almost every contract. For example, MIL-E-5400, General Specification for Airborne Equipment, is included in almost every avionic system specification. MIL-E-5400, in turn, references MIL-STD-454, General Requirements for Airborne Equipment, which in turn references preferred parts specifications and other design requirements necessary for production of reliable electronic equipment. This "boiler plate" represents years of experience and is a practical response to the familiar quotation, "They who do not learn from the past are condemned to repeat it". Repetition of past mistakes, such as the use of dissimilar metals causing galvanic corrosion, is encountered in the best of efforts. Yet contractors should not be discouraged from challenging boiler plate requirements that they consider unrealistic. Such challenges should be given a complete technical evaluation by the program manager and his technical experts.

The boiler plate alone, however, is not enough. First of all, quantitative reliability requirements tailored to your program must be clearly defined in the development specification. This is never in the boiler plate. Furthermore, reliability can be defined in various ways (i.e. operational reliability, serial reliability, etc.) and it must be clearly stated what definition applies to the quantitative requirements. Standard terminology for Air Force reporting of reliability is contained in AFR 80-5, but these definitions are not necessarily levied on the contractor. The contractor requirements must be translatable into standard terminology for Air Force use, and must be clearly understood by the contractor and the procuring activity. Any special requirements, such as the use of higher grade parts than normal, special screening techniques, equipment burn-in, reliability evaluation tests, etc. must be specified. The desired elements of the reliability program must also be defined. This includes such items as predictions to be made and the methods to be used, failure modes and effects analysis, design reviews, data submittals, data reporting systems, component failure analysis, etc. Reliability standards such as MIL-STD-785, Reliability Program for System and Equipment Development and Production must be referenced in whole or in part since the degree of application must be tailored to the procurement by the procuring activity. The use of MIL-HDBK-217, Reliability Prediction of Electronic Equipment should be specified, with deviations subject to the approval of the procuring activity. Reliability acceptance testing is also a critical specification requirement. Specific test plans and environments must be selected from MIL-STD-781, Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution. Another example is MIL-STD-965 which defines the procedures for parts control and standardization. A final example is the temptation to use plastic encapsulated semiconductor devices and micro-circuits which are not included in any standard part specification. However, they might be accepted as nonstandard parts through a Parts Control Board decision. Because of the historically poor reliability of these devices, it is common practice to include in the development specification a specific prohibition of their use.

Thus a great deal of attention to reliability inputs for the development specification is necessary, and the Air Force program manager must rely on his reliability specialists. Because of differences between programs, and continuous changes in engineering technology and reliability methods, every procurement will require a unique set of reliability requirements.

At the system level, the evolution of the development specification starts in the conceptual phase and continues through validation into full scale development. The specification used in full scale development must be complete and unambiguous.

Acceptance Specifications

A critical aspect of the procurement documentation is the system or equipment acceptance specification. Acceptance criteria, are, of course, delineated in the same procurement documents as the design criteria, but are backed up by another set of military standards. MIL-STD-781, Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution, provides a variety of reliability demonstration plans and test levels. The plans define statistical criteria, and the test levels define the severity of environmental conditions. The procurement documentation must state which test plan and test level will be used for reliability quantification and, if appropriate, which test plan and level will be used for production verification. The number of samples used must be defined. In addition, the measurements to be taken during the test and the rules for considering a failure as relevant or non-relevant must be stated. A relevant failure counts against the equipment being developed while a non-relevant failure does not. Therefore, a non-relevant failure must be very carefully defined, since this is a shelter area where the contractor may seek refuge if the acceptance tests yield many failures. A non-relevant failure is generally one which is no fault of the equipment being developed, such as a failure in the monitoring test equipment, or a failure due to equipment misuse. Also, and extremely important, the test environment must be defined.

Reliability Evaluation Tests and Reliability Growth

A special reliability test, and a most often neglected tool, is the reliability evaluation test. This is a test without acceptance criteria, performed by the contractor to obtain information on reliability deficiencies of the hardware.

When equipment is first fabricated, it ideally should meet its reliability requirements. In practice this seldom occurs, especially in complex non-digital systems. Design defects, workmanship problems, and parts defects all detract from the inherent reliability potential of the hardware. These deficiencies must be identified, their causes determined, and corrective action taken before the hardware can demonstrate its potential reliability. The "fly before you buy" concept was designed to provide the opportunity for identification and correction of hardware deficiencies, and hence reliability growth should be an essential feature of the system validation phase. A military handbook on reliability growth is in preparation and scheduled for publication in the near future.

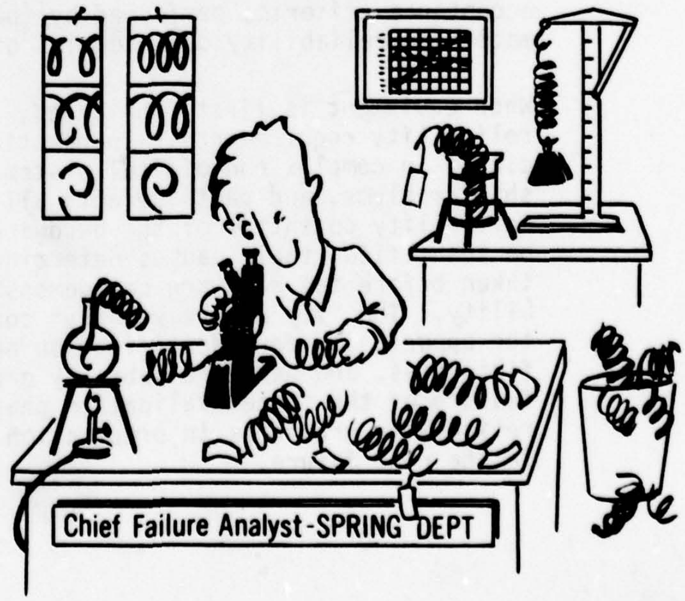
During the conceptual phase, it is desirable to conduct reliability evaluation tests on critical components being considered for use in validation models of the equipment or system.

The magnitude of the reliability evaluation and improvement effort can be quite large. One major electronic system development contractor has issued a reliability planning and management guide for its people which claims that the first model of a large electro-mechanical system will initially demonstrate only one-tenth of its inherent reliability. Furthermore, the guide says that about 100 times the predicted MTBF of test experience is needed to find and eliminate the reliability deficiencies. It also says that the problems found are about equally divided between parts, workmanship, and design deficiencies. While the exact growth time may be questioned, and such efforts as parts screening can eliminate many problems before fabrication, it is certain that any contractor must plan for a reliability growth effort. The contractor's Reliability Program Plan must acknowledge the need for reliability tests, failure reporting, failure analysis, and corrective action. Cost and schedule impacts can be reduced by utilizing other scheduled tests to provide reliability information. Any operational test of the system can be used to obtain reliability information. If sufficient testing is planned for other purposes, it is even possible to eliminate special reliability evaluation tests entirely. Of course, provision for reliability reporting, failure analysis, and corrective action must be included in the test planning in any case.

The cost of reliability evaluation testing can be very significant, depending upon the nature of the equipment and the contractor's approach to the problem. The effort is very important during validation and full scale development and cannot be deleted.

FAILURE ANALYSIS

Failure analysis is performed by the hardware manufacturer. It consists of statistical analysis of failures to determine their relative importance and their history of improvement as problems are eliminated. It also consists of engineering analysis to determine the cause and cure of each failure. The latter includes the "autopsy" of failed parts to establish



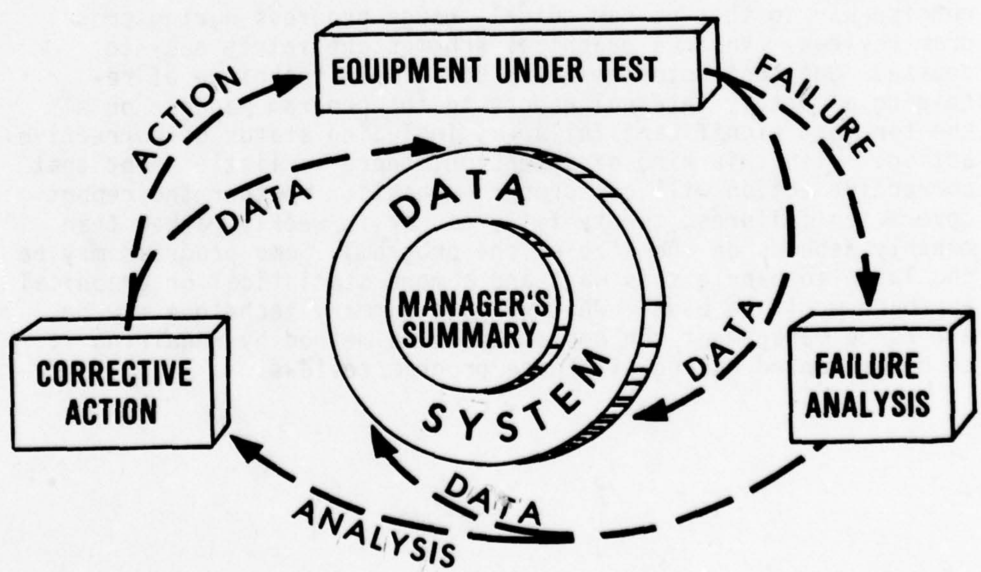
the physical or chemical cause of the failure. Such autopsies require specialized equipment such as X-ray machines, electron microscopes, metallographs, hermeticity test equipment, and so on. While some system contractors maintain quite sophisticated failure analysis laboratories, others depend on outside laboratories or part vendors for failure analysis. The part vendor is often an unsatisfactory source of failure analysis information, and usually an alternative is preferable.

Failure analysis is useful throughout a program, but the bulk of the activity should take place during validation and initial full scale development when most reliability growth should occur. In the conceptual phase, failure analysis is desirable for critical components being considered for use in validation phase equipment. In production and deployment, failure analysis will be used to correct deficiencies which jeopardize the achieved reliability.

The cost of this effort is difficult to predict since it depends upon the number and types of failures encountered. Nevertheless, it must be estimated by reliability specialists and included in planning.

DATA SYSTEM (AFSCP/AFLCP 400-11)

Reliability growth requires a data system to assure the reporting of failures and implementation of corrective action. The data system not only documents failures, but also records the results of failure analysis discussed above, and the result of corrective action taken. It is the documentary communication system upon which the testing-analysis-fixing cycle depends. It also gives both the contractor and Air Force project managers performance indicators which allow them to measure progress.



The data system must meet two basic requirements:

* It must record data on failures, analyses and corrections
* It must be compatible with standard Air Force data systems

In the conceptual, validation, full scale development and production phases, the data system will be internal to the contractors, with Air Force visibility and control through reporting of summary data. In the deployment phase, the Air Force Maintenance Data Collection System (AFR 66-14, AFM 66-1) will be used. AFM 66-1 data provides the input to the DO-56 Product Performance System. Therefore, it is important that the contractor's data system be compatible with the AFM 66-1 system, so that valid comparisons can be made between reliability data collected during development and production, and reliability data collected during operational use.

For development, test and evaluation programs conducted in-house by AFSC organizations, the AFSC Systems Effectiveness Data System (SEDS) is being promoted by AFSC, and is sometimes required (see AFSC Supplement 1 to AFR 80-5). AFSC also requires that SEDS be used by contractors if they do not already have an adequate data system. The SEDS data system is designed for use with the CDC 6500/6600 computers and is fully implemented at Air Force Flight Test Center, Edwards Air Force Base, California.

In large development programs, data systems can produce data quantities which are overwhelming to the project manager. He must therefore be sure that summary data is compiled in some concise way so that he can quickly gauge progress during program reviews. Various graphical schemes are fairly easy to devise. One contractor employed the simple technique of requiring a monthly internal report to the program manager on the ten most significant failures, including status of corrective action. With this kind of attention, there is little doubt that corrective action will get proper emphasis. Whether the report covers ten failures, twenty failures, or is weekly rather than monthly depends on the size of the program. Some programs may be too large to handle this way, and a more statistical or graphical approach would be best. Whatever the summary technique may be, Air Force management can employ the same method by requiring it to be presented during Air Force program reviews.

QUALITY CONTROL

Without an effective quality control program, most of the other reliability efforts would be wasted. For instance, equipment expertly designed for high reliability, including the specification of the best parts and materials, will fail reliability tests if the equipment is manufactured with shoddy workmanship and incoming parts and materials are not inspected to make sure they meet specifications.

Reliability defects or problems can be generally classified into one of the following four categories:

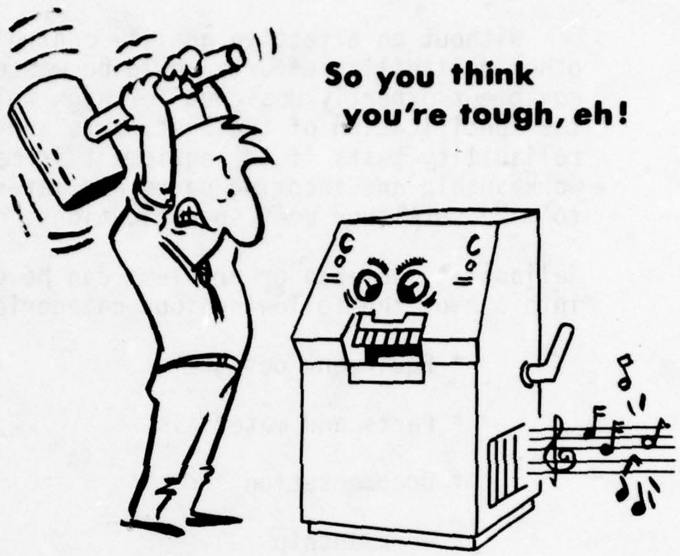
* Equipment design
* Parts and materials
* Documentation
* Workmanship

The reliability program elements discussed thus far have emphasized the first three categories. The quality control program covers all four categories with emphasis on the fourth, workmanship. In the context of quality control, workmanship includes a wide variety of actions by people, all reflecting how well the standards of quality are actually carried out. These actions include manufacturing operations, purchasing practices, testing procedures, handling, storage, delivery, and installation. The quality control program must insure that workmanship does not detract from the inherent reliability engineered into an equipment or system.

Essentially all contracts for equipments or systems in validation, full scale development or production will require the use of MIL-Q-9858, Quality Program Requirements. This specification requires the contractor to have a quality program based on standards, records, and corrective action. The exact program is up to the contractor, but it must meet certain minimum requirements and must be completely visible to Air Force quality control people. The quality control program must also extend to subcontractors and vendors.

In the deployment phase, a quality control program is also necessary to insure that maintenance procedures, replacement parts and equipment modifications do not detract from the inherent quality of the operational equipment.

ENVIRONMENTAL TESTS



Before system or equipment reliability acceptance tests begin, components, subassemblies, and equipments must go through environmental qualification tests. These include such tests as shock, vibration, acceleration, temperature, humidity, sand, dust, salt spray, nuclear radiation, electromagnetic interference, and so on. Acceptance specifications must include the most severe field environments expected. These relatively short duration tests will bring out failure mechanisms which may never show up in the long-term reliability acceptance tests, even though the latter may include vibration and temperature cycling. Therefore, these environmental tests are an essential and sometimes costly part of the overall reliability program.

The importance of thorough environmental tests is illustrated in the results of a 1971 study by Air Force Flight Dynamics Laboratory which found that 52% of the failures in the operational equipments studied were environmentally induced, reflecting the inadequacy of environmental testing during development and production. The study also showed an almost one-to-one correspondence between waiver of environmental requirements or tests and subsequent severe environmental problems in the field.

Individual environmental tests are relatively short in duration, but a series of different tests and retests is time and equipment consuming. Therefore, they are expensive and a common source of program program delays. The delays are usually due to poor planning (not leaving a reasonable time for failure analysis, design correction and retest) or inadequate design or quality control leading to excessive failures.

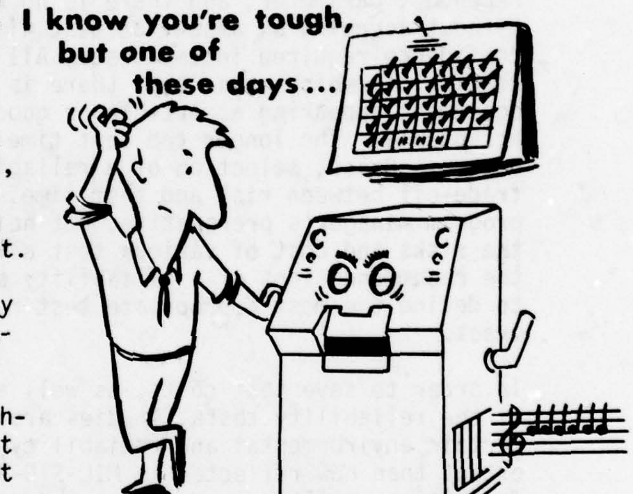
Regardless of time or cost, environmental testing is an essential part of any reliability program and not a safe place to look for "money-saving" shortcuts. The life cycle cost penalty can dwarf any development cost savings.

Towards the end of the validation phase, environmental tests are very important, but not critical. Failures in this phase need analysis along with definition of corrective action, but implementation and retest are not always necessary. It depends upon the seriousness of the problem.

Environmental tests are rated critical towards the end of full scale development. This is when the equipment design should display full acceptability for production. Environmental tests must be completed prior to the beginning of production. During production, limited environmental tests are needed at least periodically to insure that production quality remains satisfactory and that production fabrication methods have not degraded the capability of the equipment.

RELIABILITY ACCEPTANCE TESTS

Reliability acceptance tests are designed to estimate the MTBF of the equipment. They may include certain temperature cycling and vibration routines. A variety of standard test procedures can be selected from MIL-STD-781, Reliability Tests: Exponential Distribution, depending upon the use of the equipment.



A clearly defined and closely monitored reliability acceptance test is a critical program element at the end of full scale development. Without it, the contractor is not likely to be motivated to put needed effort into other reliability program elements described above, except possibly for the environmental tests. Effort may be diverted by the contractor to those tasks which lead to the timely delivery of other data and hardware called out by the contract. The reliability acceptance test provides data to demonstrate delivery of specified reliability to the Air Force as called out in the acceptance specifications. Without this data, the Air Force will be simply banking on faith and hope. A decision to go into production cannot be made prior to successful completion of this test. A reliability acceptance test will not guarantee the achievement of specified reliability, but the lack of an acceptance test will almost certainly guarantee that adequate reliability will not be achieved.

These tests are rated very important at the end of validation, simply because they are needed to evaluate the effectiveness of all the other reliability program efforts during the validation phase. They are critical at the end of full scale development, because a production decision is due at that time. They need to be repeated at the beginning of production, and again at intervals during production, to insure that production methods have not degraded the inherent reliability designed into the equipment.

Reliability acceptance tests can be quite costly. Most of the cost is due to the time required. Reliability is a time-dependent parameter, and there is no way to verify reliability without accruing an amount of test time commensurate with the confidence required in the test. All reliability tests are statistical which means that there is always some risk of poor equipment appearing acceptable or good equipment appearing unacceptable. The longer the test time the lower these risks become. Hence, selection of a reliability test is always a trade-off between risk and test time. This trade-off is the program manager's prerogative, but he must fully understand the risks and cost of various test alternatives. Here again the recommendations of a reliability specialist are needed to define the most appropriate test routine to put in the contract.

In order to save test costs, as well as to enhance the validity of the reliability tests, studies are underway to integrate certain environmental and reliability test routines to a broader extent than now reflected in MIL-STD-781. If these studies yield definitive results, improved procedures will be incorporated into the testing standards.

SCHEDULING RELIABILITY TESTS

Reliability testing takes time and it is obvious that enough time must be provided in the schedule to run the tests. Scheduling the reliability acceptance test is the greatest problem. This test must be scheduled for late in full scale development because if it were done earlier changes in configuration would make it invalid.

On the other hand, it cannot be scheduled too late for two reasons. First, it is not uncommon for equipment to fail the test. Therefore, time must be allowed for modification of the equipment and retest prior to the end of the contract. Second, enough reliability testing must be completed to make a production decision which usually occurs before the end of full scale development. Most contracts require successful completion of both environmental and reliability tests prior to the equipment being considered qualified.

RESOURCE REQUIREMENTS

Now that the scope, content, and purpose of an average reliability program are understood, the manager needs to know something about the engineering resources available to get such a program properly accomplished. We have emphasized several times that the program has many options and must be tailored to the specific equipment or system being developed. This tailoring is beyond the capability of most program managers and they need professional help to get the job done right. Of course, 95% of the technical work will be performed by the equipment contractor, but the other 5% which is performed by the Air Force (requirements, specifications, reviews, test monitoring, etc.) is crucial to success. The brief observations and suggestions below focus on this crucial 5%.

TECHNICAL MANPOWER

The Air Force program manager needs the services of a reliability engineer. Large program offices such as the F-15 will usually have trained specialists assigned full time to the program. Other activities will depend on outside help. This outside help can come from several sources. For example, each of the AFSC product divisions has a reliability staff office which can provide part time or temporary assistance to specific programs in the division. The Reliability Branch at the Rome Air Development Center is a focal point of reliability know-how in the electronics field, and is frequently asked to provide reliability engineering support to the AFSC product divisions and laboratories. Finally, contractual support is available. Space and Missile Systems Organization employs large numbers of contractor personnel supplied by TRW and Aerospace Corporation for reliability support, and the Electronic Systems Division obtains some reliability support from MITRE Corporation. Private engineering organizations not engaged in hardware production can be hired also. For example, ARINC Research Corporation, Battelle Laboratories, and the Illinois Institute of Technology Research Institute have supported Air Force programs. Finally, in some situations, hardware manufacturers can be employed. Such situations might include reliability improvement programs for equipments in the Air Force operational inventory. Of course, hardware manufacturers should not monitor the reliability efforts of competitors. Hence, though it may sometimes require a service contract, there are many avenues open to the manager who needs reliability engineering support.

When time permits, the program manager can also provide his personnel with reliability training through courses at the Air Force Institute of Technology and several other educations programs listed in Appendix A.

REFERENCE PUBLICATIONS

Commercial books on reliability engineering are plentiful. Commercial books on reliability program management are far fewer and concentrate on the manufacturer's in-house situation. The Air Force R&M manager, or the contractor R&M manager working on Air Force programs, should have a library which contains the following documents (in addition to this management guide):

* AFR 80-5, Air Force Reliability and Maintainability Program, and AFSC Supplement 1.

These documents provide the manager with the Air Force policy on reliability requirements necessary for various types of contracts. Incidentally, a programmed guide to the policy of AFR 80-5 is contained in the Proceedings of the 1972 Annual Reliability and Maintainability Symposium published by the Institute of Electrical and Electronics Engineers (IEEE). This guide utilizes logical flow diagrams to simplify the selection of R&M requirements appropriate for a particular kind of development program. It should be noted that, while these documents provide such guidance as whether or not a reliability test is required for a particular program, they do not provide guidance in determining such technical details as test length, test conditions, etc. Such details, as well as the quantitative design requirements, the specific reliability tasks to be performed, and the data items to be delivered, must be determined by the program manager together with his supporting reliability specialist.

* MIL-STD-785, Reliability Program for Systems and Equipment Development and Production. This document describes the various tasks making up a reliability program. For many systems in full-scale development, it may be applied in total as a requirement for the contractor. However, the document will not provide quantitative requirements or cite a specific demonstration plan. It must be reviewed to determine the extent to which the tasks are applicable to your program. In many programs, only certain tasks should be used, and your statement of work must specify which ones.

* MIL-STD-781, Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution. This document describes the various test plans and environmental test levels that may be used for reliability demonstration. From these plans, the R&M manager must select the best for his program, and specify it in the statement of work. The selection must be a satisfactory trade-off between the risks involved, the test time, and the number of test samples which can be purchased. These test plans are based on an exponential distribution of failures, which means that the failure rate of the system is essentially constant. This is a valid assumption for electronic systems. However, items such as engines which exhibit a predominantly time dependent failure rate due to wear-out effects, cannot validly employ test plans from MIL-STD-781. For such items, a reliability test based on a defined minimum life must be designed. This is a fairly simple job for any competent statistician.

* MIL-HDBK-217, Reliability Prediction of Electronic Equipment. This document provides failure rates for electronic and some electromechanical parts as a function of the stress applied to them. It also contains instructional information on reliability prediction for assemblies of parts. In addition, the RADC Nonelectronic Reliability Notebook, RADC-TR-75-22 ((A005657), has failure rates for various nonelectronic components such as pumps, valves, tanks, instruments, etc., found in large electromechanical systems. Nonelectronic part failure data is also published in NRPD-1 "Nonelectronic Parts Reliability Data, 1978" published by the Reliability Analysis Center, a DOD Information Analysis Center located at RADC.

*AFSCP/AFLCP 400-11, Reliability and Maintainability Data Sources. This pamphlet contains descriptions of some twenty sources of reliability and maintainability data. The sources cover a broad range of parts, equipments and systems including electronics, propulsion, missiles, auxiliary power units, aircraft structures, and so on. It is especially useful for the Air Force and contractor reliability engineer who is searching for failure rate data upon which to base realistic reliability requirements or reliability predictions.

The various reliability textbooks, and the proceedings of the Annual Reliability and Maintainability Symposium, can also be consulted for educational purposes or in search of solutions to particular problems.

In preparation of this writing are two other documents of interest to the Air Force Reliability Manager. The first is "Reliability Growth Management", a proposed military handbook in preparation by a Tri-Service Committee and scheduled for publication about July 1979. Schedules for the same time is a RADC Exhibit on Reliability Testing Using Prior Data. This will provide test plans which incorporate existing information (the "prior"). The advantages of testing using a prior are a more meaningful definition of test risks and the potential for reduced test time, at no loss of confidence, if the prior is favorable.

COMPUTERIZED PREDICTION

The Rome Air Development Center offers to Air Force managers a computer program for performing reliability predictions. The program is resident in the RADC computer and may be assessed through the ARPA Computer Network or by direct lines to RADC. On arrangement with RADC, the use of the program may be offered to contractors as government furnished property to be used in meeting contractual reliability prediction requirements. Using the service provides a low cost means for performing reliability predictions and permits automated reiterations for revision and trade-off analyses. It should reduce the costs of predictions significantly. Starting October 1979, RADC will charge program offices with computer use fees. It is expected, however, that the costs to the program office will still be less than either manually performed predictions or contractor procured programs.

FACILITIES

Facilities for reliability engineering include reliability test chambers, failure analysis facilities and parts screening apparatus. Access to a computer, while not really essential, is a great aid in analytical studies such as the prediction and statistical analysis of failure trends.

Test chambers have been in use for a long time, and it is a rare equipment contractor who does not have a reliability test chamber.

In contrast, failure analysis and parts screening facilities are not widely available. A basic failure analysis capability is not expensive, yet is not available in every manufacturer's plant. More sophisticated facilities, utilizing expensive equipment such as scanning electron microscopes, are found only in the larger industrial plants. Lacking failure analysis facilities, the contractor is dependent on outside laboratory support or analysis by the part vendor. Parts screening facilities are necessary only when the contractor cannot obtain the desired screening from his part vendors, or finds it more economical to do his own.

Air Force facilities for reliability engineering in the program office need include only office space, an appropriate reference library, and possibly access to a computer. On a broader level, the electronic failure analysis and reliability research and development laboratories at Rome Air Development Center provide an Air Force in-house facility from which the program manager can seek technical support. Availability, of course, depends upon workload and your program priority.

SYNOPSIS

Hardware reliability engineering is a thoroughly developed discipline, especially in the electronics area, with the standard reliability program elements described in MIL-STD-785. The execution of these elements, however, must be tailored to the objectives and needs of the particular equipment being developed, and are subject to execution with varying degrees of emphasis and skill by contractor personnel. Therefore, the program manager needs expert advice to prepare statements of work and to monitor the contractor's efforts.

The program elements which stand out as particularly critical are the identification of realistic requirements, selection of quality parts and materials, thorough environmental and reliability evaluation tests, and carefully planned and executed reliability acceptance tests.

Chapter 5

ELEMENTS OF A MAINTAINABILITY PROGRAM

INTRODUCTION

A maintainability assurance program involves coordinated performance of a series of tasks beginning with the conceptual phase and continuing through full scale development. Maintainability is largely determined by the overall configuration of the system or equipment and is pretty much fixed by the end of full scale development. The job had better be done right by that time, because retrofit changes to enhance maintainability during production and deployment are extremely expensive and disruptive.

Maintainability is an attribute directly linked to the manual skills of people, and therefore is directly related to human engineering and human factors in design. Maintainability is also directly linked to logistics planning for maintenance and support, and continuous coordination with AFLC throughout the development program cannot be overemphasized.

As one might suspect, maintainability and maintenance have not been developed into a deterministic engineering discipline to the extent that reliability has. There is more of a subjective flavor, because of the human factors involved. Nevertheless, maintainability engineering is organized into an orderly sequence of steps which can lead to reasonably predictable and measurable results. This chapter explains the engineering and management elements which will yield those results.

STANDARD MAINTAINABILITY PROGRAM ELEMENTS

> MIL-STD-470
> Maintainability
> Program Requirements
> (For Systems and Equipments)

A hardware maintainability program has many similarities with a hardware reliability program, as the following chart shows. The list of maintainability tasks is based on MIL-STD-470, with some editorial changes. Again, the ratings of relative importance of the tasks are subjective judgments from experience and apply to an "average" maintainability program. As with the reliability program, the emphasis on separate tasks must be tailored to the specific equipment being developed

MAINTAINABILITY PROGRAM ELEMENTS

Element	Life Cycle Phase: Conceptual / Validation / Full Scale Development / Production / Deployment
Requirements Definition	xxxxxxxxxxxxxxxxxxxxxxxAAAAAA..........
Maintenance Concept	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx.......
Maintainability Analysis	xxxxxxxxxxxxxxxxxxxxxxxxxx.......
Design for Maintainability	ooooooxxxxxxxxxxxxxxxxxxxxxxxxx............
Maintainability Prediction	ooooooxxxxxxxxxxxxxxxxxx.......
Design Review	oooooooxxxxxxxxxxxxxxx.......
Design Specifications	xxxxxxxxxxxxxxxxxxxxxxxxxx........
Acceptance Specifications	xxxxxxxxxxxxxxAAAAAA.........
Detailed Maintenance Plan	---ooooooooooooooooooooxxxxxxxxAAAA....................
Data System	xxxxxxxxxxxxxxxxxxxxxxxxoooooooooooooooooooooo
Technical Manuals	ooooooooooooxxxxxxxxAAA....................
Maintainability Acceptance Test	xx..........AAA............

First contract

KEY

------------oooooooooooooxxxxxxxxxxxxxxAAAAAAAAAAAA.............

- Desirable activity (for highest success probability)
- Necessary activity (errors seldom disastrous)
- Very important activity (errors often disastrous)
- Critical activity (errors usually disastrous)
- Low key activity (to update previous results)

and this tailoring must be done by a maintainability engineer motivated to protect the Air Force's long term interests.

Maintainability is simply a measure of the speed with which something can be fixed or checked over. More formally, it is defined as a characteristic of design and installation expressed as the probability that an item will be restored to (or retained in) a specified condition within a given period of time using certain procedures and tools. The "retained in" case usually refers to preventive maintenance. A typical maintainability specification might say, for example, that 90% of all failures must be repaired in less than 15 minutes using certain test equipment, tools, spare parts and personnel, and also that the mean-corrective-maintenance-time or mean-time-to-repair (MTTR) will be five minutes. With these two parameters, a corresponding maintainability demonstration test can then be selected to determine whether the equipment meets those requirements.

The median time to affect a repair (a time which will be bettered by 50% of all repairs and exceeded by the other 50%) may also be used as a figure of merit. For preventive maintenace, the frequency (e.g., the mean time between scheduled maintenance actions) is usually specified as well as the duration. (Note: The mean time between unscheduled maintenance is equivalent to the mean time between failures which is a reliability parameter rather than a maintainability figure of merit).

An important measure of maintainability which is usually invoked for avionic equipment is maintenance man-hours per flying hour. While obviosuly related to the time to effect a repair, it also includes consideration of the number of personnel required which directly affects the support requirements. It is possible to specify maintenance man-hours per operating hour, which would cover ground equipment, though this has seldom been done.

Finally, the skill levels of the maintenance personnel are an important consideration and maintainability requirements must include the skill levels involved (e.g., the equipment shall possess a mean time to repair of 30 minutes when maintained by personnel of skill level 3, as defined in AFR 35-1).

TESTABILITY

A recent development in maintainability engineering is the concept of testability. This refers to the design of cost effective fault detection and isolation (FD/I) capabilities within a system. Obviously, FD/I parameters impact maintainability. One cannot predict or demonstrate maintainability without considering the FD/I methods used. Yet, FD/I design has been a neglected discipline. The specification of FD/I parameters is not standardized, and a recent study found 35 different figures of merit used in various Air Force procurements. Until recently, there has been no method for demonstrating or evaluating FD/I capability. As a result, the FD/I capabilities of Air Force systems have been virtually uncontrolled, and indication of poor FD/I performance has aroused high level Air Force concern.

In answer to the need for a standardized testability discipline, RADC initiated a broad study program in FY-78. The results will be available in FY-79 and will ultimately be incorporated into the existing maintainability standards.

In the following discussion of maintainability program elements, testability considerations will be described and such guidance as now exists provided.

DEFINITION OF REALISTIC REQUIREMENTS

Like the reliability program, the identification of realistic requirements is critical. Initial requirements should be sought from the operational command, since they are best able to visualize the dynamics of field use. However, these initial requirements may be stringent, and should be considered negotiable by everyone concerned in the early phases of development. Too stringent a requirement (repair time too short) will require sophisticated fault location methods with attendant cost, weight and perhaps reliability problems, and may unnecessarily complicate design of the package for quick tear-down and assembly. It can also lead to approaches which merely transfer the repair problem to a remote facility with a possible increase in total repair time and other support costs through transportation and repair of large modules. On the other hand, too loose a requirement will increase equipment downtime, which will then reduce operational readiness which in turn increases force size requirements at great expense. Therefore, the user, supporter and developer must conduct an iterative examination of the MTTR requirements before they are made firm.

These trade-off studies should employ systems effectiveness analysis and life cycle costing techniques, where maintainability can be parametrically varied over a reasonable range to determine how it affects system effectiveness and life cost. Of course, maintainability requirements must be developed in harmony with reliability requirements since they both affect cost and effectiveness in an interdependent way. That is, very high reliability eases the maintenance problems since the item need not be fixed very often. Low reliability, on the other hand, will call for a rapid fix capability to maintain the same item effectiveness.

Considering testability, a stringent MTTR requirement may dictate the use of an extensive built-in-test system with attendent weight and cost penalties. These must also be weighed against the need for rapid repair. FD/I parameters (percent of faults to be detected by FD/I, allowable false alarm rates, ambiguity of fault location, etc.) must also be specified and must be realistically achievable and demonstrable. Guidance will be available from an RADC study, "BIT/External Tester Figures of Merit and Demonstration Techniques", scheduled for completion June 1979, though the final report will probably not be published until September 1979.

There are many trade-offs involved in the selection of maintainability requirements, and these must be made during the conceptual and validation phases so that firm requirements are available for full-scale development. The requirements must be ultimately set by the program manager, but the supporting analytical studies must be made by his staff and the contractor, with major inputs from the operational command and Air Force Logistics Command (AFLC).

MAINTENANCE CONCEPT

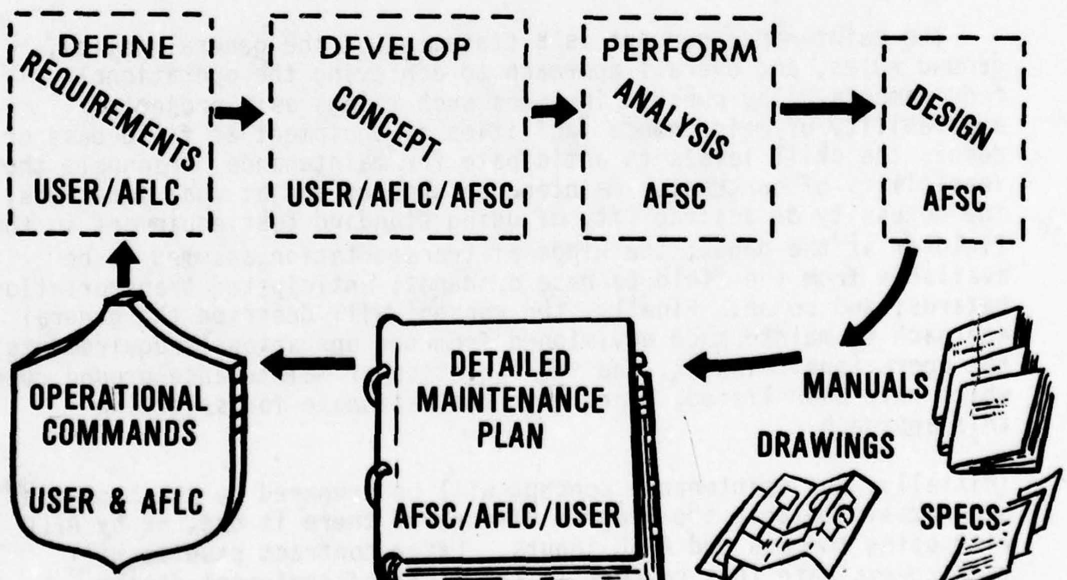
The maintenance concept is a statement of the general policy, ground rules, and overall approach to achieving the operational requirements. The concept includes such things as: projected availability of maintenance facilities or equipment at field base or depot; the skill levels to anticipate for maintenance personnel, the feasibility of contractor maintenance support and at what locations; the necessity or desirability of using standard test equipment in the field or at the depot; the kinds of transportation assumed to be available from the field to base or depot; anticipated transportation hazards; and so on. Finally, the concept will describe the general approach to maintenance envisioned from the operational requirements, the operational mission, and the logistics or maintenance ground rules which have been listed, along with the rationale for selecting this approach.

Initially, the maintenance concept will be prepared by the Logistics organization within the Program Office, if there is one, or by AFLC with using command and AFSC inputs. Later contract studies will then re-evaluate this concept in the light of equipment design studies, maintainability analyses, and systems effectiveness analyses. By the middle of full scale development, the concept should settle down to a stable statement of groundrules on which to base detailed equipment design and maintenance plans.

The R&M program manager should note that there is no standard data item in the DoD Index of Data Items (Acquisition Management Systems and Data Requirements Control List) which would be suitable for delivery of a maintenance concept under contract. While the first version would be written by the program office staff, a practical approach to getting subsequent iterations through contract effort is to combine the Maintenance Requirements and the Maintenance Concept into an introductory section of the Detailed Maintenance Plan discussed below. This keeps all relevant information together in a single document making it easier for everyone to review. A suitable alternative would be to define two unique data items, one for the concept and one for the Detailed Maintenance Plan.

The concept must, of course, consider testability in that trade-offs between built-in-test and external test and between automatic and manual systems must be reflected in the maintenance concept.

Before continuing with our discussion of the other maintainability program elements, let's take a quick look at the overall maintainability program cycle depicted below. Very simply, the requirements come from the user, the initial concept comes from the user and AFLC, the analysis, design, and test results come from the AFSC development contractor, and the Detailed Maintenance Plan evolves through successive iterations of all five tasks. The AFSC program manager is responsible for the plan and employs contractors to complete its



THE DETAILED MAINTENANCE PLAN EVOLVES THROUGH ITERATION.

development. The Plan is ultimately used by AFLC to prepare an Integrated Logistics Support Plan for use during production and deployment. A cooperative team effort between user, supporter, and developer is essential throughout this cycle. While this development cycle is an iterative process, the requirements and concept should be firm at the beginning of full scale development and all elements must be solidified towards the end of full scale development.

MAINTAINABILITY ANALYSIS

Maintainability analysis includes several kinds of analytical efforts performed by the development contractor, all for the purpose of deriving the best approaches to detailed equipment design and maintenance procedures. These analyses strive to find the design configuration and maintenance procedures which will satisfy operational requirements within the ground rules of the general maintenance concept documented earlier. These recommendations should then be negotiated with the using and supporting commands.

A revision of the requirements and overall concept would then be incorporated into a revision of the Detailed Maintenance Plan prepared by the development contractor.

Maintenance and maintainability analyses consider the tasks which must be done to restore an assumed equipment configuration to operation following a failure, and also the tasks involved in preventive maintenance and replacement of consumables. The analyses should provide the preferred modular configuration or packaging plan; identify special test equipment needs; assist in locating test points and built-in fault location aids; define the maintenance actions best performed in the field, at intermediate locations, or at a depot; provide guidelines for discard-at-failure or repair decisions; provide maintainability parameters which permit the computation of maintainability predictions; and finally, guide the preparation of technical manuals for system maintenance. Thus, some form of maintenance or maintainability analysis is done at all levels of the system and in all phases of the program through full scale development. Maintenance and maintainability analyses are reflected in the system and equipment design, the support equipment recommendations, the technical manuals, and the Detailed Maintenance Plan.

Maintenance and maintainability analyses are accomplished by applying subjective judgements based on practical experience, and also various analytical procedures. Three specific analytical procedures included in these analyses are the following:

OPTIMUM REPAIR LEVEL ANALYSIS

Optimum Repair Level Analysis (ORLA), also known as Level of Repair Analysis (LORA) is an analytical procedure for establishing the least cost feasible repair or discard decision for maintenance actions at each maintenance level and is intended to influence the equipment design in that direction. It considers such factors as the cost of repairing a failure at the operational site versus the depot, the cost of discarding a failed module versus repair, and so on. Inputs needed are reliability prediction, equipment design options and equipment cost estimates. Its function is to convert the maintenance concept to the maintenance plan in an iterative process as increasingly refined and stable data become available. In the Air Force, the standard reference for ORLA procedures is AFLCM/AFSCM 800-4, "Optimum Repair Level Analysis". The Navy uses MIL-STD-1390, "Level of Repair" which will ultimately become a tri-service document, replacing AFLCM/AFSCM 800-4 for Air Force use.

MAINTAINABILITY APPORTIONMENT

Maintainability apportionment or allocation is analogous to reliability apportionment and is the analytical method by which a system maintainability requirement is distributed or allocated to subassemblies, subsystems and components. It requires inputs from a reliability prediction, and is performed by the system contractor to establish numerical maintainability requirements for his suppliers or subsystem designers.

FAILURE MODES ANALYSIS

Failure modes, effects and criticality analysis (FMECA) determines the affects of a failure on a system or equipment, including chain reaction failures. Its use in reliability engineering was discussed earlier. In maintainability engineering, it helps establish failure detection logic, test points, and test procedures, which in turn affect equipment design, test equipment requirements, maintenance procedures and technical manuals.

Methodology is described in proposed MIL-STD-1629, "Procedures for Performing a Failure Mode, Effects and Criticality Analysis," which is in the coordination cycle as this is written.

All of these analysis tasks are relatively inexpensive insurance against the discovery of disruptive maintenance problems during system tests. Later in development, major design changes are expensive and upsetting to the program, and management is tempted with undesirable design compromises. Lack of good analysis can lead to a patchwork approach to final system design. Good analysis is both an Air Force requirement and a prudent investment of development money.

It should also be noted that the results of the preceding analyses are required inputs to Logistics Support Analysis, such as described in MIL-STD-1388, and to Life Cycle Cost Analyses. (Note: Paragraph 5.3 and subparagraphs of MIL-STD-1388 provide a detailed listing of items that should be addressed by maintainability analyses).

DESIGN FOR MAINTAINABILITY

The task of designing for maintainability consists of defining specific hardware layout and packaging configuration which will implement the design guidelines derived through maintainability analyses. This task gets into the details of hardware design such as module configuration and arrangement, choice of built-in failure indicators, electric cable layout, connector selection, fastener selection and placement, tubing layout, circuit board layout, access panel placement, test point selection and access (MIL-STD-415), grease fitting placement, materials selection for easy maintenance, design for safety and other human factors, and many more.

Of course, the design must comply with standard military design specifications called out in the contract. Many provisions in these standard design specifications have been inspired by the need for maintainable systems and equipments. In general, the designer should follow good engineering design practices for easy and economical maintenance. Guidelines to good design practice can be found in a very general outline form in MIL-STD-470. More specific guidelines for electronic equipment design can be found in the AFSC Design Handbooks DH 1-8, Microelectronics and DH 1-9, Maintainability, available through the Aeronautical Systems Division of AFSC and RADC-TR-74-308, "Maintainability Engineering Design Notebook, Rev II and Cost of Maintainability" (in 3 volumes). Also specific maintainability design criteria are contained in MIL-STD-1472, "Human Engineering Design Criteria for Military Systems Equipment and Facilities". Design guidelines and requirements for all classes of equipment can be found in the standard military design specification for those specific classes. Of interest to testability is RADC-TR-78-224, "A Design Guide for Built-in-Test."

As mentioned before, the results of this detailed design work may lead to a re-evaluation of the maintainability requirements, the maintenance concept, and the maintainability analyses. Design is part of the maintainability iteration cycle and must settle down to a fixed configuration by the end of full scale development.

The results of design will be documented in the contractor prepared design specification and drawings, and the technical manuals mentioned below.

As with the design for reliability, it should not cost much more to design a highly maintainable system than a poorly maintainable system (though the mechanization could indeed be more costly). The

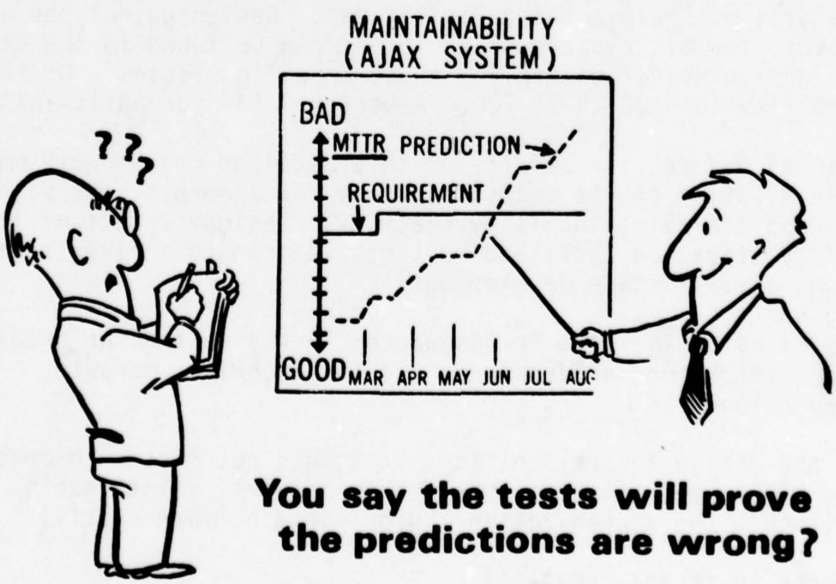
Note: RADC-TR-78-224 (A069384)
RADC-TR-74-308, Vols I - III (A009043)(A009044)(A009045)

early and proper attention to these details will result in an overall savings in development costs by eliminating disruptive redesign work which would otherwise be necessary when maintainability problems are discovered during system tests.

MAINTAINABILITY PREDICTION

Maintainability prediction is an analytical effort performed by the system designer. These predictions estimate the MTTR of the system or equipment and show the potential of a certain design for meeting maintainability requirements. Initially, these predictions will be based on rough estimates from contractor experience with certain equipment layouts, but as design progresses the predictions will get more reliable as specific maintenance details evolve.

Maintainability predictions will be presented in the reliability and maintainability allocations, assessments and analysis report (Standard Data Item DI-R-3535 in the DoD Acquisition Management Systems and Data Requirements List). When periodic R&M control status reports are required the current maintainability prediction should be included for trend visibility. Prediction methods are presented in MIL-HDBK-472, "Maintainability Prediction." MIL-HDBK-472, though still the DoD standard, was published in 1966, and there is some concern that the methods are not completely appropriate to modern technology. A recently developed maintainability prediction method is presented in RADC-TR-78-169 (A059753), "Maintainability Prediction and Analysis Study." This will ultimately be incorporated into MIL-HDBK-472. It should also be noted that MIL-HDBK-472 presents four methods for maintainability prediction and the particular method desired must be specified.



DESIGN REVIEW

The formal Air Force design review will cover all the elements of the maintainability development cycle (requirements, concept, analyses, design, tests) at a summary level of detail. As in the case of reliability, this is the best opportunity for an overall engineering critique and management appraisal of the program progress. The Air Force program manager, his deputy for logistics, and his technical advisors must personally participate in this review. Representatives from the using and supporting commands should also participate in this review.

As in the case of reliability engineering, informal reviews should be arranged between the contractor and Air Force engineers in advance of the formal review. This will help insure efficient conduct of the formal review.

DESIGN SPECIFICATIONS

Design specifications tell the designer what ground rules or criteria he must follow in coming up with a specific hardware design to meet performance requirements. Initially, the design specifications will be rather general Air Force prepared specifications, and will reflect only the overall concept envisioned together with the relevant military equipment design standards. As the contractor's maintainability analysis and design work progresses, he will develop more detailed Part II product specifications which reflect the results of those studies. These specifications are not a separate maintainability program data item delivered under the contract. Instead, maintainability design parameters are incorporated into the design specification for each hardware element along with design parameters inspired by other engineering considerations. Of course, maintainability design parameters must also be included in specifications supplied to subcontractors and vendors. Testability considerations, such as built-in-test requirements must also be included in the product specifications.

ACCEPTANCE SPECIFICATIONS

Acceptance specifications prepared for use at the end of validation and full-scale development, must include maintainability demonstration tests to verify achievement of the specified requirements. We should note that maintainability requirements can be specified in various ways such as: the mean-time-to-perform corrective maintenance; the maximum time in which a specified percentage of all failures must be repaired; the median time for all repair activities; the percentage of repairs which can be performed in a specified time; average system downtime including corrective and preventive maintenance in a specified period of time or as a percentage of total operating time; maintenance man-hours per flight hour; and any combination of the above. The exact measures are not critical if they are understood and satisfactory to the Air Force procuring, using, and support agencies and adequately defined in the specification. They must also be translatable to the standard maintainability reporting terms required by AFR 80-5.

The acceptance test, however, must correspond to the form of the requirement. MIL-STD-471, "Maintainability/Verification/Demonstration/Evaluation", provides a variety of test plans to measure different maintainability parameters. Other tests not in MIL-STD-471, such as tests on the effectiveness of built-in test equipment or support equipment, must be formulated and incorporated into the acceptance specification. The next revision of MIL-STD-471 will contain methods for evaluating fault detection and isolation capabilities. This should be available late in 1979.

DETAILED MAINTENANCE PLAN

The Detailed Maintenance Plan is the principal long range maintenance planning document which contains the most up-to-date conclusions derived in part from all steps in the maintainability development cycle. That is, it includes requirements, general support concept, modular configuration of the system or equipment, maintenance approach, support equipment, facility and personnel needs, and many other maintenance considerations which have been developed from the design requirements. This plan will be incorporated into the Integrated Logistics Support (ILS) Plan developed by AFLC for the entire system.

Since this maintenance plan is of prime interest to AFLC, the Deputy Program Manager for Logistics (DPML) in the Program Office should directly participate in defining this data item. As contract work progresses from phase to phase, this document will grow in detail and credibility, and finally be integrated into the total ILS Plan. If the total ILS Plan is a contract data item at the beginning of the program, this integration could, of course, be done then.

AFR 800-8, "Integrated Logistics Support Program for Systems and Equipment", explains policies and responsibilities for ILS. AFR 66-14, "Equipment Maintenance Polices, Objectives and Responsibilites", and AFSC Supplement 1, address the more specific maintenance policies and responsibilities which form a part of ILS. These documents should be consulted before development of the Detailed Maintenance Plan. An extensive description of the complete range of ILS activities is found in AFP 800-7, "Integrated Logistic Support Implementation Guide for DoD Systems and Equipments". It is an all service document, and is available from the U. S. Government Printing Office.

DATA SYSTEM

A data system is as important to maintainability engineering as it is to reliability engineering. The general data system requirements discussed for reliability also apply here. That is, the system needs to be closed loop (test results recorded, problems analyzed, and actions implemented), and should be compatible with the AFM 66-1 maintenance data system so that development program data can be compared later with operational field data. In fact, the data requirements for both reliability and maintainability should be integrated into a single data system for efficiency.

Analysis of maintainability data during development is more difficult than analysis of reliability data, since results are so strongly dependent upon support equipment and personnel. During the validation phase, the field test equipment, technical manuals, and technicians may not be available and maintenance results could be far better or far worse than in deployment. Hence, a true picture of maintainability progress is trickier to obtain than a measure of achieved reliability. On the other hand, maintenance problems during validation and full scale development provide valuable data for improving test equipment and technical manuals, as well as the basic hardware. Therefore, the data system is essential even though maintainability estimates derived from its data may be rough.

TECHNICAL MANUALS

A major product of the maintainability program is data for preparation of technical manuals. These manuals will be used by operational support people for system maintenance including calibration, repair, and preventive maintenance. They must be written to match the expected skill levels of personnel in the field, intermediate, or depot organizations. These manuals will be affected by every part of the maintainability program.

MAINTAINABILITY ACCEPTANCE TESTS

I have just simulated a typical failure out in the field. Your job is to........

Maintainability demonstration or acceptance tests are very important at the end of the validation phase and are critical at the end of full scale development. They provide the incentive for a contractor to pursue an effective maintainability program, and also provide the last chance for the Air Force to uncover and correct any deficiencies before the system reaches the field. Test procedures are found in MIL-STD-471, Maintainability Verification/Demonstration/Evaluation.

Unlike reliability demonstration, maintainability demonstration does not require long time periods. Failures are simulated by introducing faults into the system, and the times needed to restore the system are recorded. Hence, even for a complex system, a maintainability demonstration can be run in a few weeks rather than several months often required for reliability verification. While we have time economy, there is always the troublesome question of whether faults induced truly represent those which will be encountered in the field. These faults or failure modes are selected for simulation using reliability predictions to identify the most likely cases. Even assuming this is a good selection, there are limitations to the simulation process. Intermittent failures, for example, cannot be easily simulated and these are extremely troublesome to repair. Hence, the recording of maintenance times for actual failures encountered in other system tests is a good procedure, and may be used to supplement these maintainability test results. If a lengthy and controlled system test is planned for some other purpose in the program, it may be possible to utilize that test to verify the achievement of the maintainability requirements at the same time.

The capability of the fault detection and isolation (FD/I) features may also be determined from data generated during maintainability and other system tests. Methodology will be available in the next revision of MIL-STD-471, expected in late 1979. Until this is available, each program office must create its own procedure for determining FD/I capability and incorporate it into its test plans.

RESOURCE REQUIREMENTS

As we have seen above, the general drift of the maintainability program is like the reliability program, except that human factors play a much bigger role (procedures, hardware layout, skill levels, technical manuals, equipment handling, etc.)

As in the reliability case, the maintainability program must be tailored to the specific hardware development program by experienced maintainability experts. The program manager should not attempt to simply reference MIL-STD-470 in the Statement of Work, since many options are open and the Air Force needs to lay out the ground rules from the start. He will need expert help for preparing requirements, selecting military specifications and tests, reviewing progress, monitoring tests, etc.)

TECHNICAL MANPOWER

The previous discussion on reliability technical manpower also applies here simply by replacing the word reliability used there with maintainability. Briefly, the program manager should have his own in-house maintainability manager, but that person in turn needs help, especially on large programs or to fill gaps in experience. Help can be obtained from Air Force laboratories, non-profit engineering support contractors, or other contractors with no competitive interests in the hardware to be developed. The use of experienced maintenance personnel from AFLC and the using command as technical advisors should not be overlooked.

REFERENCE PUBLICATIONS

There are some good commercial reference books on maintainability engineering, but the R&M manager's library should include at least the following Government publications which have been referenced in the preceding discussions (in addition to AFR 80-5):

*AFR 66-14, "Equipment Maintenance Policies, Objectives and Responsibilities," and AFSC Supplement 1. This delineates Air Force maintenance program policies and responsibilities, and outlines specific considerations to be included in developing maintenance concepts and plans.

*AFR 800-8, "Integrated Logistics Support (ILS) Program for Systems and Equipments." This gives policy and responsibilities for ILS throughout the life cycle of systems and equipments.

*MIL-STD-470, "Maintainability Program Requirements (for Systems and Equipments)." It describes and discusses the maintainability program elements corresponding essentially to our outline above.

*MIL-HDBK-472, "Maintainability Prediction." It gives maintainability prediction methods.

*RADC-TR-78-169, "Maintainability Prediction and Analysis Study." It provides a new prediction method not yet incorporated into MIL-HDBK-472. (A059753)

*MIL-STD-471, "Maintainability Verification/Demonstration/Evaluation." It defines the various demonstration test plans.

*AFSC DH 1-9, "Maintainability Design Handbook." This is one of a series of AFSC design handbooks developed under the supervision of Aeronautical Systems Division. It discusses maintainability factors, design considerations and demonstration tests.

*AFLCM/AFSCM 800-4, "Optimum Repair Level Analysis (ORLA)." This describes ORLA; shows the methodology and gives examples.

*AFP 800-7, "Integrated Logistic Support Implementation Guide for DoD Systems and Equipments." This describes the evolution of an ILS program, what it is, its relationship to other program elements, and the program manager's responsibilities. This is an all service document available from the U.S. Government Printing Office.

*MIL-STD-1338, "Logistics Support Analysis." This standard establishes the requirements for Logistics Support Analysis applicable to both the Government and contractors.

*AFSCP 800-21, "A Guide for Program Managers: Implementing Integrated Logistics Support." The title is self-explanatory.

*RADC-TR-78-224, "A Design Guide for Built-in-Test." The title is self-explanatory. (Available in NTIS).

In addition to the above list of publications, various textbooks on maintainability are available, and technical papers on particular aspects are contained in the proceedings of the Annual Reliability and Maintainability Symposium.

COMPUTER PROGRAMS

While many computer programs have surely been written by contractors to carry out routine maintainability computations, there are no standard routines in wide use.

FACILITIES

Facilities required for maintainability engineering are not extensive. Access to a computer is helpful in performing some of the analytical studies, but other than this, no special facilities are required. Maintainability testing may sometimes require a mock-up of the aircraft or missile in which a subsystem is installed, or test equipment which simulates other systems that interface with the subsystem on test. Otherwise, no special facility is required. Maintenance tools and test equipment proposed for use with the system in the field, spare parts, and technical manuals will, of course, be required.

SYNOPSIS

Hardware maintainability engineering consists of an orderly sequence of steps strongly influenced by human engineering and logistic support considerations. The elements of a standard program are outlined in MIL-STD-470, but are subject to interpretation, and might be executed with various levels of skill and thoroughness by contractor personnel. Therefore, the Air Force program manager should have expert advice to prepare statements of work and to monitor execution of the tasks. All elements of the program must be fully coordinated with both the using and support commands who will be doing the maintenance.

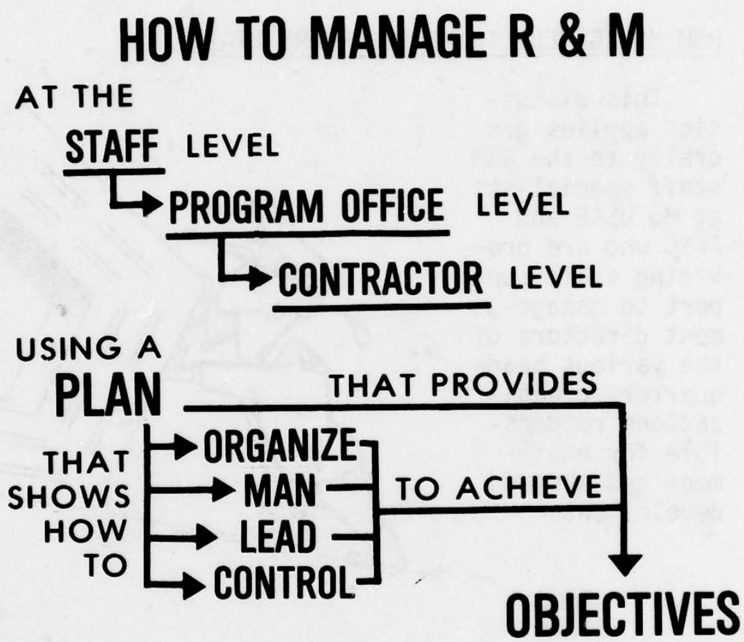
The most critical elements are identification of realistic requirements, thorough analysis and design, evolution of a good maintenance plan, and demonstration of achieved results through realistic acceptance tests.

Chapter 6

RELIABILITY AND MAINTAINABILITY

MANAGEMENT BY ORGANIZATION LEVELS

INTRODUCTION



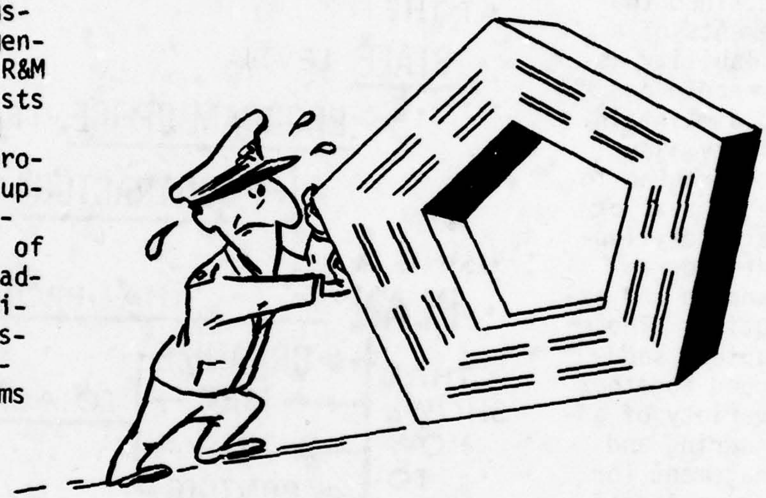
The two preceding chapters explained the elements of a reliability assurance program and a maintainability assurance program in the context of system development program planning and execution. Those chapters sandwiched together a variety of engineering and management (or combination) tasks in a logical sequence as they might appear in a system or equipment program plan, and cut across many organization levels.

In the present chapter, the viewpoint is different. Here, the overall Air Force program for R&M assurance in system or equipment development is viewed at separate organization levels and focuses on the management and contractual highlights at those levels. While managers must understand the logic of the R&M program structures explained before, the present chapter homes-in on the principal management guidelines at a given organization level which will help insure success. Whether you work in headquarters staff, the program office or in the contractor's plant, there will be something here which helps achieve Air Force R&M goals through your organization. The guidelines will not be subtle or revolutionary, but basic necessities which are, nevertheless, easily overlooked or underplayed.

The management discussions treat reliability and maintainability collectively, with some exceptions, and the discussions are organized according to the traditional management functions of planning, organizing, manning, leading and controlling as explained in Chapter 3. At the end, the subjects of warranties and other contract incentives are briefly discussed separately.

R&M MANAGEMENT IN HEADQUARTERS STAFF

This discussion applies generally to the R&M staff specialists at Hq USAF and AFSC who are providing staff support to management directors of the various headquarters organizations responsible for equipment and systems development.



PLANNING FOR R&M

Planning consists of defining objectives and then developing policy, strategy, organization, procedures, etc. for achieving them.

Objectives, policy, organization and procedures for implementation of the R&M program are well documented and explained in the following publications:

* AFR 800-2 and AFSC Supplement 1, Acquisition Program Management

* AFR 800-3, Engineering for Defense Systems

* AFR 80-5 and AFSC Supplement 1, Air Force Reliability and Maintainability Program

* MIL-STD-785, Reliability Program for Systems and Equipment Development and Production

* MIL-STD-470, Maintainability Program Requirements (For Systems and Equipments)

Those publications in turn reference many other relevant documents dealing with Integrated Logistics Support (ILS), development testing, maintenance, human engineering, and so on; however, the above five are the basic set for R&M and systems program management in general. In the area of general program review and control, the following regulations are relevant, but of course apply to any functional category of program activity:

* AFSCR 800-1, Command Review of Systems Acquisition Programs

* AFSCR 800-18, Joint Operational and Technical Review (JOTR)

The staff challenge here is to keep all of these documents current, compatible, and readable, with hopefully no conflicts between them. This is especially challenging in the area of maintenance, logistics, and maintainability where there is such a large collection of Air Force and tri-service documents in being.

ORGANIZING FOR R&M

The R&M staff responsibility at Hq USAF for policy is in the Deputy Chief of Staff, Logistics and Engineering, Directorate of Maintenance and Supply, Engineering and Support Division (LEYE). The Hq USAF, Deputy Chief of Staff, Resource Development and Acquisition, Directorate of Development and Programming, Deputy Directorate for Program Integration, Management Policy Division (RDPXM) is required to establish an R&M focal point for the application of R&M in individual programs. At Hq Air Force Systems Command, the staff R&M focal point is the Deputy Chief of Staff, Systems, Directorate of Acquisition and Engineering Policy, Engineering Management Division (SDDE).

MANNING FOR R&M

In manning, the staff assures that training programs provide the qualified people needed. "Qualified" means not only educated, but experienced. Both AFIT and civilian institutions are utilized to build up this career area.

LEADING FOR R&M

This is where the staff level people are extremely effective. The staff motivates and directs the program managers to give R&M the support that is essential. This direction is most effectively given through the Program Management Directive (PMD). That directive explicitly states the scope of the R&M program expected and its priority relative to other program objectives. It also explains that R&M will be a subject of detailed review at the various program review milestones, and that technical specialists will be on hand to review these efforts at Headquarters. It is in this document that the stage for the R&M program is set.

CONTROLLING FOR R&M

Here is the second area where the staff level people are extremely effective. Control is exercised through the review and approval processes, that is, review and approval of documents and briefings. For example, the Program Management Plan (PMP) which responds to the PMD must incorporate R&M program plans which will be effective, even if the entire PMP is not to be approved at Headquarters (only done on a few major programs).

AFR 80-5 details R&M program activities to be performed and requires review of Hq USAF/LE of all waivers to this policy. The regulation also requires Hq USAF/LE approval for contract schedules calling for full scale production before notification R&M testing and analysis is completed.

The various program reviews required by AFSCR 800-1 and 800-18 provide another opportunity to control and motivate R&M achievements. AFR 80-5 provides standardized R&M terminology for reporting R&M. Not only is R&M a review agenda item, but R&M specialists assist the Commanders in assessing the quality and thoroughness of the reported R&M programs.

SUMMARY

The most vital and powerful forces which the staff exerts on R&M achievement is through leadership and control. This leadership and control are the compass and rudder of the R&M program. The prime focus of this direction and control effort is on the System Program Manager. His personal attitude towards R&M will have a first order impact on the shape of the entire R&M program, and profoundly affect the life cycle cost of the system.

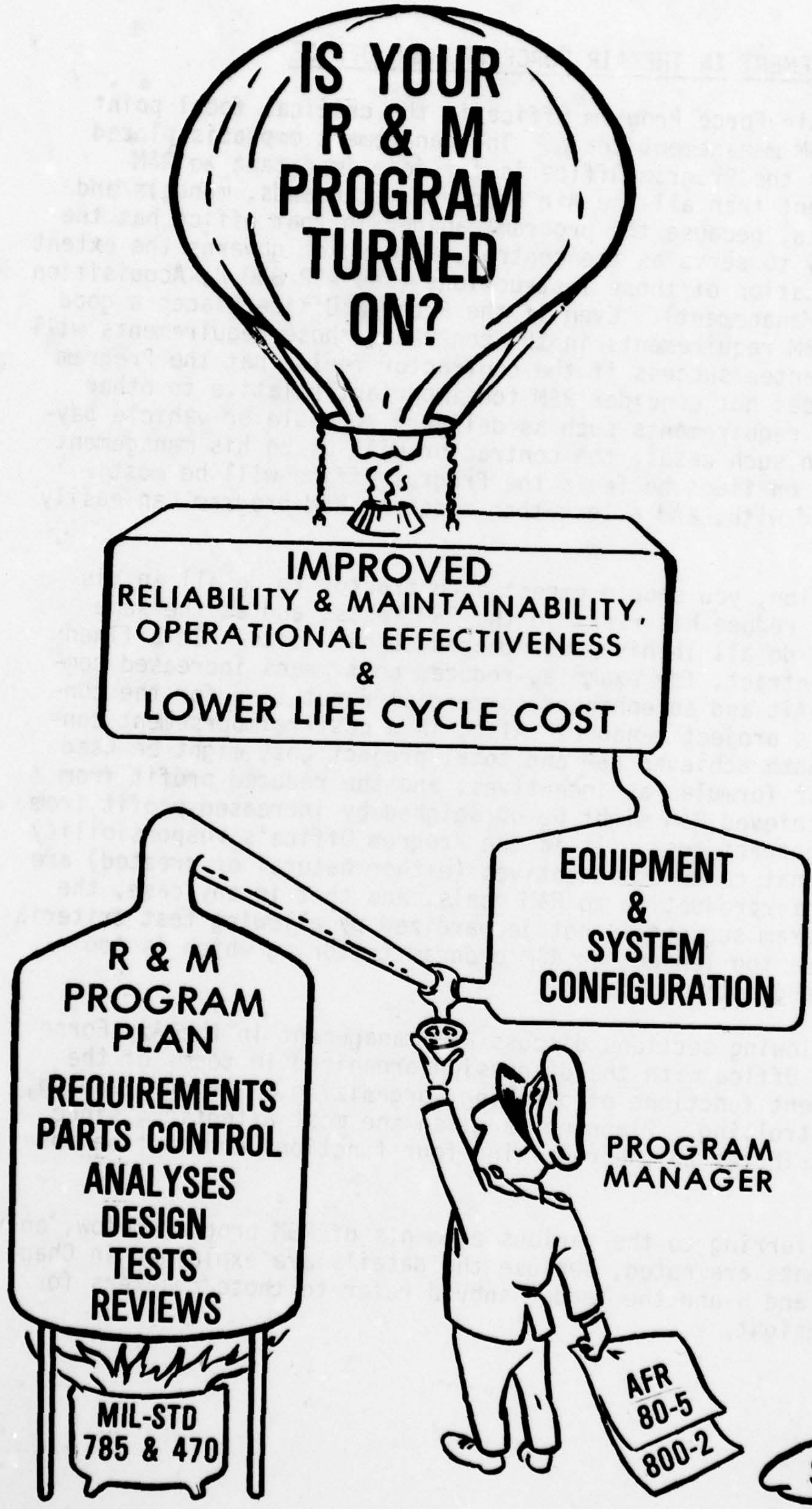
R&M MANAGEMENT IN THE AIR FORCE PROGRAM OFFICE

The Air Force Program Office is the critical focal point in the R&M management chain. The management emphasis placed on R&M by the Program Office is far more important to R&M achievement than all the Air Force R&M standards, manuals and guidebooks, because the program manager in that office has the authority to serve as the control valve which governs the extent of application of those instructions (see AFR 800-2, Acquisition Program Management). Even if the Program Office places a good set of R&M requirements in the contract, those requirements will not guarantee success if the contractor feels that the Program Office does not consider R&M too important relative to other contract requirements such as delivery schedule or vehicle payload. In such cases, the contractor will place his management emphasis on items he feels the Program Office will be most concerned with, and a less than adequate R&M program can easily result.

In addition, you should expect a contractor to do all in his power to reduce his risks in the R&M tests, and at the same time, to do all in his power to reduce his costs. In a fixed price contract, for example, reduced cost means increased company profit and an enhanced commercial reputation for the contractor's project manager. Also, in a cost-reimbursement contract, both achieved R&M and total project cost might be used in profit formulas as incentives, and the reduced profit from lower achieved R&M might be outweighed by increased profit from lower contract cost. It is the Program Office's responsibility to see that contract incentives (either natural or created) are not counterproductive to R&M goals, and that in any case, the R&M program success is not jeopardized by allowing test criteria which are too lenient or R&M program tailoring which is too skimpy and optimistic.

The following sections discuss R&M management in the Air Force Program Office with the discussion organized in terms of the management functions of planning, organizing, manning, leading, and controlling. Planning is given the most attention, since it contributes to the remaining four functions and must be done first.

When referring to the various elements of R&M program below, only highlights are noted, because the details are explained in Chapters 4 and 5 and the reader should refer to those chapters for more insight.


IS YOUR R & M PROGRAM TURNED ON?
IMPROVED RELIABILITY & MAINTAINABILITY, OPERATIONAL EFFECTIVENESS & LOWER LIFE CYCLE COST
EQUIPMENT & SYSTEM CONFIGURATION
R & M PROGRAM PLAN
REQUIREMENTS
PARTS CONTROL
ANALYSES
DESIGN
TESTS
REVIEWS
MIL-STD 785 & 470
PROGRAM MANAGER
AFR 80-5
800-2
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PLANNING FOR R&M

Planning consists of identifying desired goals and then delineating the best course of action to achieve those goals. R&M planning is not really a separate activity, but is an effort which must be sandwiched into overall planning for the system. In the conceptual phase, for example, the choice of system design alternatives must include their potential reliability and maintainability and attendant support costs in order to select the most cost-effective system alternative. In later development stages, R&M estimates are needed as inputs for system support planning for spare parts, depot facilities, training, etc. Hence, R&M is a key element in overall program planning, and from this planning should emerge a set of realistic R&M objectives.

The next phase of planning is to construct an R&M program which will assure that those R&M objectives are actually achieved. The preceding discussions in Chapters 4 and 5 have explained the structure of such a program. Specific R&M planning tasks at the Program Office level within the framework of that structure are explained in the following paragraphs in roughly chronological order.

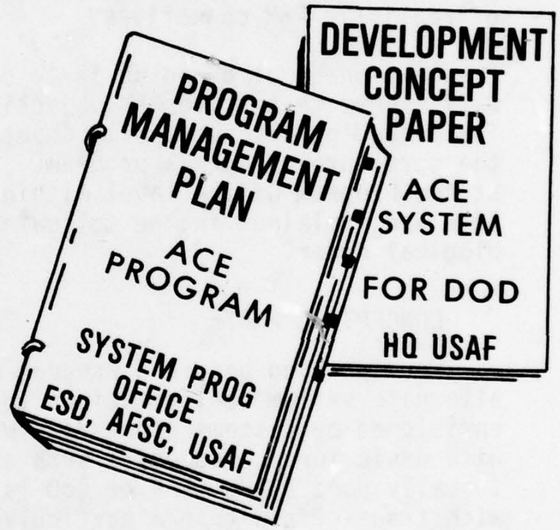
CONCEPTUAL PHASE

Perhaps even before a Program Office is formally established, alternate system configurations to meet an operational need are envisioned by systems planners. While AFSC may not be concerned with basic force trade-offs such as airplanes versus missiles, (usually done at Hq USAF or DoD levels), AFSC will be concerned with trade-offs within a particular vehicle or system configuration category. Such trade-offs will include the cost and effectiveness impact of performance parameters like altitude, speed, and range, and the design of subsystems such as armament, electronic countermeasures and fire control. In these studies, the potential reliability and maintainability of the total system must be considered.

Reliability impacts directly on probability of mission success, and indirectly on such items as the weight of the system if, for example, redundancy is required to overcome a poor reliability potential. Maintainability will also affect training requirements and support costs for personnel and spares. Both reliability and maintainability will impact life cycle costs. In general, system R&M estimates are necessary to identify the best possible system alternative, and to provide a valid picture of the cost-effectiveness of the proposed system for comparison with other system alternatives. Of course, both the system using command and AFLC must be asked to provide their minimum acceptable requirements.

R&M estimates in the conceptual stage must necessarily be based on historical data. Here, AFLC records in the product divisions, records of individual Program Offices, and if applicable, the reliability prediction formulas discussed in Chapter 4 are all helpful. Also helpful is an experienced R&M engineer who can interpret the different ways R&M are measured. These first estimates will begin the R&M planning activity, but must be repeatedly modified and refined as more data becomes available in later phases.

After preliminary system trade-offs are made and preliminary R&M objectives are set, the next activities of the Program Office are preparation of the Air Force Program Management Plan, and preparation of inputs to AFSC and Hq USAF for a Development Concept Paper assuming one is required.



The Program Management Plan (PMP) is the master plan for achievement of the program objectives and is prepared by the Program Office in response to a Program Management Directive from Hq USAF and a corresponding Program Direction (AFSC Form 56) from Hq AFSC. R&M planning in the PMP document must provide for:

a. Definition and refinement of realistic quantitative R&M requirements, to be finally demonstrated in the full-scale development tests.

b. Parts selection using military standard parts to the maximum extent possible. Should the particular program require extraordinary parts quality levels like in Minuteman, the program must provide for procurement of these special parts.

c. Tracking R&M progress throughout the program to provide a continual measure of achieved versus required R&M.

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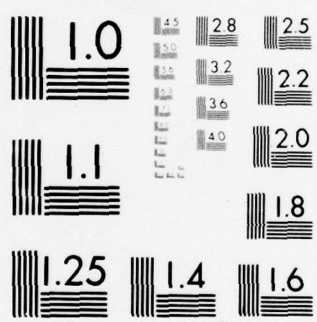
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d. A planned period of R&M growth during validation and full-scale development, using all available failure and maintenance data for R&M problem analysis and correction during this period.

e. Program review milestones for assessment of R&M progress (these may, of course, be merged with other review milestones as appropriate).

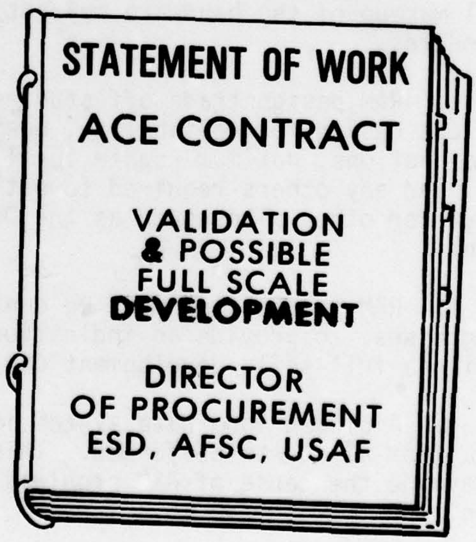
f. Adequate manning to insure competent R&M planning and surveillance of the contractor's efforts, and the possible need to use outside agencies for R&M support.

g. Interface with the eventual using and support commands on R&M requirements and plans.

The Development Concept Paper (DCP) represents in effect a contract with the Secretary of Defense for conduct of a major program. R&M performance "thresholds" may be required in the DCP. These are the minimum performance limits and a DoD program review will be triggered if R&M performance sinks below them. Hence, it is obviously important that realism prevail in planning these thresholds, and in planning a program capable of meeting them. It is also very important that the R&M term presented in AFR 80-5 be used. These are designed to prevent confusion between various R&M figures of merit (e.g., measures of operational reliability versus measures of logistics demand) which can cause even successful R&M achievements to appear dubious.

VALIDATION PHASE

The Secretary of Defense approval of the DCP marks the transition to the validation phase for major weapon systems. For lesser systems and equipments, approval will be at a lower level as specified in the Program Management Directive. Hardware will be developed and tested by competing contractors in the validation phase, and R&M planning will focus on the contractual requirements. The statement of work prepared by the Program Office will be written using



AFR 80-5 and AFSC Supplement 1, Reliability and Maintainability Programs for Systems, Subsystems, Equipment and Munitions, as the basic guidance documents. The following items are critical inclusions in the statement of work:

a. Quantitative R&M requirements must be specified and defined. It is recognized that these requirements might not have to be achieved by the prototype hardware developed and tested in the validation phase. However, the hardware must be designed to be inherently capable of achieving the required R&M, and R&M predictions should substantiate this.

b. R&M testing is a must. This may be evaluation testing or demonstration testing or both, but the extent of the R&M test program, its intent and, if applicable, the acceptance criteria must be clearly established.

c. Parts selection must be controlled. However, because of difficulties in obtaining preferred quality parts in small quantities, it may not be practical to fully employ them in validation hardware. Any substitute parts must be identical in form, fit and function to the preferred parts, to preclude difficulty with including preferred parts in the later systems.

d. Fundamental design features which will affect maintainability must be evaluated. For example, built-in test provisions must be included in the validation phase equipment in order to evaluate its functional effectiveness, even though the exact physical makeup of the hardware may not correspond to operational standards.

e. R&M design trade-off studies need to be performed. These include design for reliability, design for maintainability, redundancy options, optimum repair level analysis, failure modes analysis, and any others required to optimize the design or to provide input for other plans such as the Detailed Maintenance Plan or ILS Plan.

f. R&M predictions must be continually refined as the design progresses, to provide an indication of potential R&M for use in making a full-scale development decision.

g. A closed loop data system is required for obtaining R&M data from all tests performed. This data will then be used to determine the cause of R&M problems and formulate corrective action.

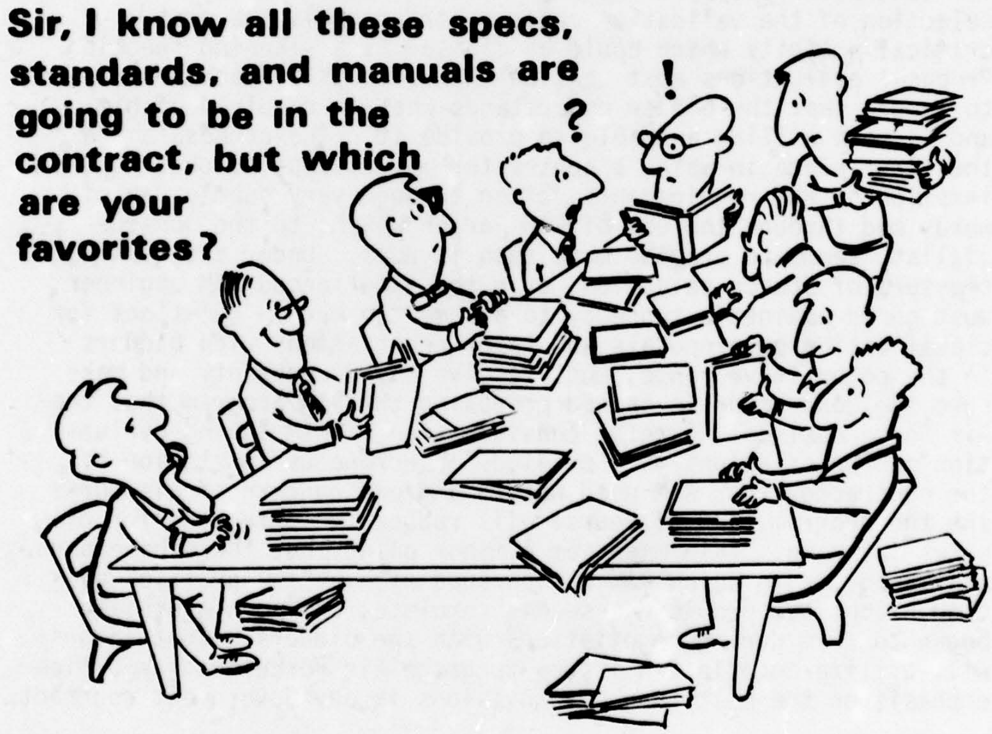
h. Program and design reviews are essential for control and motivation of the entire R&M program, and to insure that detailed R&M design effort is progressing in a professional way.

i. Appropriate deliverable data items must be selected to give the Air Force Program Office needed visibility into the above activities and document results.

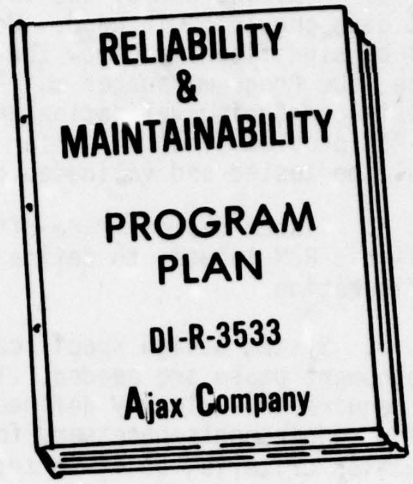
The above list of validation phase statement of work provisions represent planning highlights never to be overlooked. More details and explanations have been covered in Chapters 4 and 5 and in AFR 80-5 and MIL-STDs 785 and 470.

Once the statement of work has been prepared and the request for contractor proposal has been issued in industry, source selection of the validation phase contractors is the next critical activity which could be classed as a planning function. Proposal evaluations must consider R&M aspects of each proposal to insure that the bidder understands what is required of him, and is both willing and able to provide it. The proposals are the first place in which a contractor may attempt to obtain relaxation of R&M requirements, often through very subtle use of words and through the use of R&M jargon which, to the non-specialist, seems to promise more than it does. Under the working pressure of source selection, even the experienced R&M engineer must guard against a tendency to assume too much. Questions for clarification or proposals and later negotiations with bidders in the competitive range, must resolve any uncertainty and make sure the contractor is indeed proposing the R&M program that the Air Force desires. Careful consideration of R&M during evaluation and negotiations will preclude an erroneous conclusion by the contractor that R&M need not be a great concern of his during the program, and of course will reduce the potential for disputes later on. This may seem a minor point, but there have been many programs in which R&M was pursued with a "low profile" even though contract provisions seemed complete, and such a profile began to form during negotiations with the bidders. Contractors will utilize negotiation issues to gauge Air Force Program Office emphasis on the multitude of provisions in any Government contract.

One good way to put early emphasis on R&M is to require bidders to submit a Preliminary R&M Program Plan with the proposals for evaluation by the source evaluation team. (This practice is called out in MIL-STD-470 and 785, but its applicability to a particular contract solicitation in the validation phase is subject to the judgment of the Program Manager). Deficiencies in the preliminary R&M Program Plan will then be the subject of precontract negotiations, and these deficiencies must be ironed out before any contract is signed. If properly written, the negotiated R&M Program Plan can then be incorporated into the contract and become the basis for contractual compliance. This precontractual approach to the R&M Program Plan will insure that the R&M program gets off to a good start, with the Government and the contractor having a mutual understanding of the R&M program elements and the ground rules for their execution.



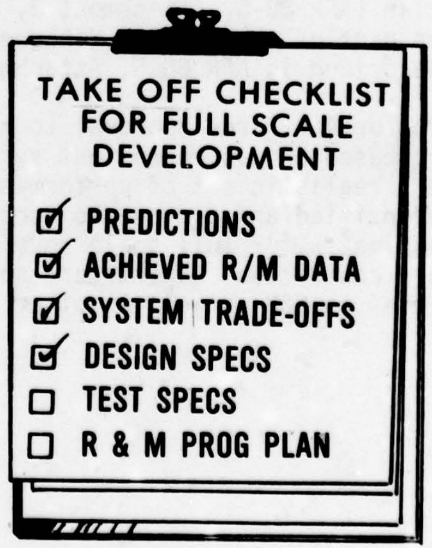
In the R&M Program Plan, the contractor defines his approach to achieving R&M requirements, his milestones, and his organization. This plan is very important since it establishes the understanding between the contractor and the Air Force on the R&M effort expected and provides a reference for review and control. Hence, this document must reflect the Statement of Work requirements and completely describe an adequate program to pursue them. The approved R&M Program Plan (preferably negotiated before contract signing) should leave no doubts about what will be accomplished. The program elements to be included in a standard R&M program were described in Chapters 4 and 5. Guidance for the contractor in writing this plan is given in the Data Item Description DIR-R-3533, Reliability/Maintainability Program Plan, listed in the DoD Acquisition Management Systems and Data Requirements Control List.



Another plan to be prepared during the validation phase is the Preliminary Integrated Logistics Support (ILS) Plan. Air Force Pamphlet 800-7, Integrated Logistics Support Implementation Guide, discusses the ILS procedure in great detail and should be consulted for further information.

By the end of the validation phase, the Program Office must have the following R&M products in hand in order to make decisions and plans for the next development phase:

a. Predictions of the potential R&M of the system must be up-to-date. These must be realistically derived and commensurate with the expected operational environment and the selected parts quality. An historical record of these predictions should have been continuously updated through the validation phase.



b. Achieved R&M of the validation hardware based on actual test data should be in hand. Most of the time, the achieved R&M will be significantly below the predicted and required values. Hence, the Program Manager must have a track record of R&M growth experienced during validation and sound engineering solutions to all R&M problems found. As far as possible, these solutions should be tested and validated during the validation phase.

c. System design trade-off studies should be complete using realistic R&M inputs, to define the most cost-effective system configuration.

d. System design specifications intended for the full-scale development phase are needed. These must incorporate quantitative R&M requirements clearly defined, and all the corresponding R&M design requirements necessary for their achievement, that is, parts selection criteria, built-in test features, modular configuration, environmental criteria, etc.

e. System acceptance specifications are needed which define R&M demonstration tests to be performed in the full-scale development and production phases, including the test plans and test levels, system burn-in requirements, ground rules for test measurements, ground rules for classification of failures, and so on. Environmental qualification tests must also be defined.

f. The R&M program plan for full-scale development and production must be completed by the contractor (or competing contractors) by the end of validation. This plan will then be used for negotiating a follow-on full-scale development contract.

g. The Program Manager must write an Air Force R&M Management Plan (AFR 80-5, Attachment 3, Paragraph 4e). This will be submitted as part of the Program Management Plan (PMP). Its contents are described in AFR 80-5, Attachment 4.

DoD or Air Force approval to proceed to full-scale development will be based on assurance that system trade-offs have produced a balanced and realistic set of performance parameters, risk areas have been identified and reduced to acceptable levels, cost and schedule estimates for full-scale development are reasonable and acceptable, and contractual aspects are sound (AFSCP 800-3). These factors refer to R&M as well as other performance parameters.

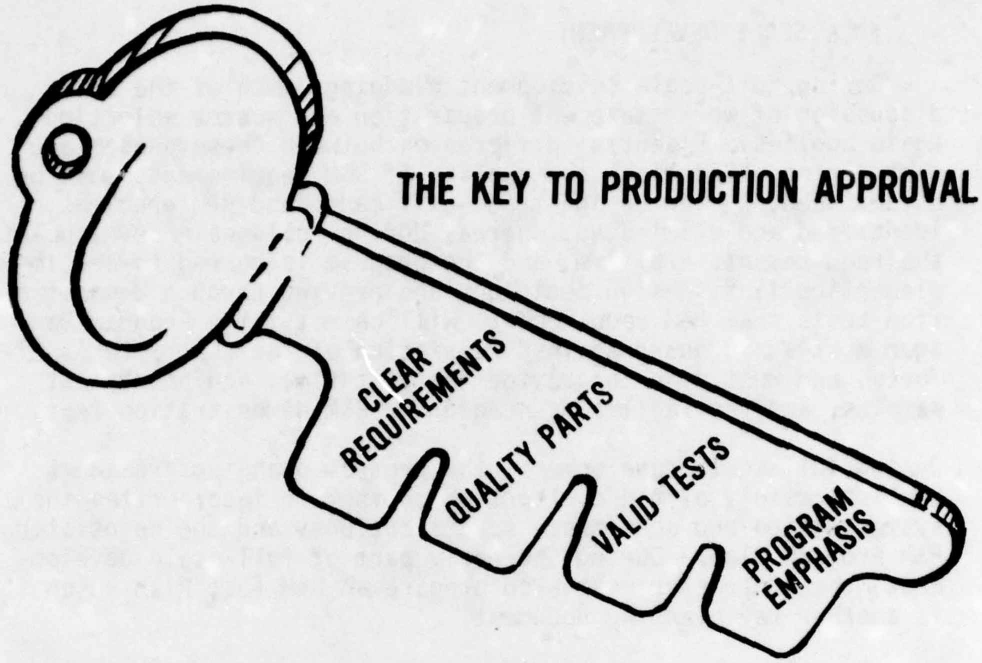
FULL SCALE DEVELOPMENT

During full-scale development planning, much of the above discussion of work statement preparation and source selection again applies. Essential differences between these phases are that during validation, the realism of R&M requirements must be established, system design trade-offs made, and R&M problems identified and eliminated, whereas during full-scale development, the requirements are firm, and the program is geared toward implementing final design decisions and proving through demonstration tests that R&M requirements will be met. The Program Manager must again guard against relaxation of the contractor's efforts, and must plan to provide the test time, equipment test samples, and the facilities needed for R&M demonstration tests.

During full-scale development, the program planning framework consists mainly of the contract which in turn incorporates the system design and acceptance specifications, and the negotiated R&M Program Plan. During the early part of full-scale development, the contractor must also prepare an R&M Test Plan which is another key planning document.

The R&M Test Plan provides the execution details of the R&M demonstration tests. While general ground rules are covered by the contractual documents, the plan covers the multitude of particulars which must be defined before the tests are run. It is a potential source of compromise to the intent of the test requirements and careful review is essential. Data Item Description DI-R-3538, Reliability/Maintainability Demonstration Plan gives particulars for writing this plan.

Next to unambiguous requirements and the selection of quality parts, the R&M tests are the most essential element in the R&M program during the full-scale development phase. Without clear requirements, no program can have a reasonable chance of success. Without quality parts, you're doomed. Without a good test, there is no way of knowing what has been accomplished and it is almost certain that the program will be emasculated. With clear R&M requirements, quality parts, valid tests, and strong emphasis by the Program Office, a reasonable and competent contractor is not likely to neglect the other program elements and the R&M program will almost surely be a success.



Finally during full-scale development, a final Integrated Logistics Support Plan will be prepared utilizing R&M inputs from the Detailed Maintenance Plan (see Chapter 5).

PRODUCTION

In production, R&M activity will be concerned mainly with finding and fixing problems arising during production. These will be primarily workmanship and parts defects, since most design problems should have been rectified by this time. Periodic production reliability verification must be performed to identify and correct reliability degradation during the production run. Engineering change proposals (ECPs) must be evaluated for their effects on R&M. Quality control plays its most important role during this phase.

DEPLOYMENT

Finally, in deployment, field data must be used to track field R&M, identify problems and determine fruitful areas for R&M improvements. The AFLC Improved Reliability of Operational Systems (IROS) Program will indicate which particular system components are the most costly to support. This data may provide the opportunity to design system modifications which will reduce support costs. By comparing the costs of the improvements with the field costs and potential savings, AFLC and AFSC can determine the economic attractiveness of proposed system changes.

ORGANIZING FOR R&M

Inputs to the R&M Manager's activities are required, not only from AFSC R&M engineering specialists, but also from the using and supporting commands. Both the using and support commands are a source of R&M requirements and experience data. Representatives of these commands will also review R&M progress and gather planning information. The realism of R&M objectives, at least in early program stages, will be based significantly on AFLC field data banks. The Program Office must therefore establish good working relationships with these agencies.

The R&M Manager will also require the services of various specialists. One of the most important is the parts specialist. Even in the best of programs it is probable there will be requests for the use of parts not on Air Force preferred parts lists. Sometimes a new type of part is required, some parts seem to resist standardization, and often a contractor may not be aware of a preferred part that will meet his needs. Difficulties in obtaining preferred parts and the obsolescence of parts on the preferred listing add to the problem. It is the role of the parts specialists to review parts lists, and especially requests for nonstandard parts, to accomplish the following:

a. Determine if a preferred part may be used in place of a proposed part.

b. Recommend quality assurance procedures for nonstandard parts.

c. Identify acceptable replacements for standard parts which are obsolete.

d. Assist in locating sources for preferred parts.

The assistance of parts specialists is available from the Defense Electronics Supply Center, Dayton, Ohio, for all types of electrical and electronic parts, and from Rome Air Development Center, Griffiss AFB NY, for microcircuits, semiconductors, printed circuit boards and their associated connectors. Assistance on selection of mechanical parts, including nuts and bolts is available from the Defense Industrial Supply Center, Philadelphia PA. The R&M manager of a program involving electronics must arrange for an interface with those organizations.

The R&M manager will also require the use of environmental specialists to assure proposed environmental tests are commensurate with the mission requirements. The support of specification writers is also needed to see that all referenced standards are up-to-date and that the standard "boiler plate" is intact. Quality control specialists will be needed to evaluate and negotiate proposed quality programs. Of course, an R&M engineering specialist will be needed to keep the requirements unambiguous, evaluate contractor's inputs, and translate the technical jargon into terms meaningful to the Program Manager. This specialist will also provide information to aid in test planning, such as the time required for reliability tests for various sample sizes and confidence levels.

When the Program Manager does not have available to him a full time R&M specialist, his organization should include provision for part time or temporary support from other Air Force offices. These can include the reliability staff in his own division or center, the services of R&M engineers from other Program Offices, or the use of specialists from other agencies, such as the Reliability Branch of the Rome Air Development Center.

Industrial support may also be a part of the Program Manager's R&M organization. Reliability specialists from industry have been hired as a source of manpower for such activities as providing full time test monitors for lengthy reliability tests. They have also been used as program monitors and proposal evaluators, though these jobs must be left to Air Force personnel whenever possible. In using industrial sources, hardware manufacturers should generally be avoided with preference for research firms not concerned with manufacturing. Otherwise conflicts of interests and friction are likely between the system contractor and the monitoring contractor.

MANNING FOR R&M

AFSC 2895 is the Air Force Specialty Code for a reliability engineer. An officer with this AFSC and a Master's degree in reliability from the Air Force Institute of Technology (AFIT) would be a valuable asset on the Program Manager's staff. Equally valuable would be a military or civilian Air Force member with an engineering, physics or mathematical degree and several years' experience in R&M support. While the supply of such personnel is increasing, it still falls short of demand. Hence, a particular Program Manager may be forced to create his own R&M specialist or rely on outside agency support as discussed above. However, AFR 80-5 stipulates that AFSC will provide an R&M support specialist for each system program or project.

There are many sources of R&M education. Starting September 1979, AFIT will offer a program leading to a Master's degree in Reliability Engineering. AFIT also conducts short courses in R&M Engineering, one of two weeks duration and a more detailed course of ten weeks. Many civilian universities also conduct short courses in R&M Engineering and the University of Arizona has a degree program in Reliability Engineering. Courses can be located from university circulars and from listings in the Newsletter of the Institute of Electrical and Electronic Engineers (IEEE) Reliability Group. The IEEE Reliability Group also publishes quarterly transactions of technical papers on reliability, and with the American Society for Quality Control and several other professional societies related to product assurance, sponsors a yearly symposium of reliability and maintainability, held each January. The proceedings of the symposium provide good educational material for the aspiring R&M engineer, and are available through most Air Force technical libraries. (See Appendix A of this guidebook for a list of schools and symposia which provide R&M educational opportunities).

In starting a program, it is advisable for the Program Manager to seek experienced help, even on a temporary basis, if he does not yet have an R&M specialist on his staff. Available short courses and selected literature reviews could then be used to bring a designated, but inexperienced, R&M engineer up to a reasonable competence fairly rapidly. On a long program, the use of regular university courses or degree programs might be a good investment, if there is some reasonable assurance the individual will be retained.

For period of high activity above the capability of a normally adequate R&M staff, such as concurrent reliability tests at competing contractors, contractual support should be considered.

The use of other Government agencies such as in-plant AFPRO or DCASO representatives located at contractors' plants may also be a useable source of supplemental manning, providing the in-plant representatives are able to devote the necessary time and have the know-how.

Finally, it must be recognized that the presence of a trained R&M engineer in the office does not relieve the equipment or subsystem engineer of his responsibility for the R&M of his assigned hardware. It is the task of the R&M engineer to manage the R&M program and provide specialized support to the equipment engineers. The equipment engineers are responsible for seeing the R&M aspects are accorded appropriate consideration in the design of their equipment by the contractors. Should the equipment engineer dismiss R&M as outside his responsibility, likely results are the overloading of the R&M engineer as he tries to independently impact all the various equipment procurements, a degradation of the contractor's R&M program since he is more likely to be concerned with pleasing the equipment engineer than the R&M engineer, and possibly a conflict of direction to the contractor from the equipment engineer and the R&M engineer. While the special skills of the R&M engineer are needed to maintain an effective R&M program, the equipment engineer has responsibility for total equipment performance including R&M.

LEADING FOR R&M

The Program Manager must obviously lead the R&M effort. Working agreements must be arranged with the other Air Force offices involved. This will include arrangements for the use of specialists within the Program Manager's division staff, the establishment of liaison with using and support commands, and formal working agreements with the Air Force laboratories, Defense Electronics Supply Center, and sources of field data as appropriate. The Air Force team should be in working shape, with responsibilities clearly understood, well in advance of the first Source Selection Board meeting.

The statement of work and contractual documentation are an essential, but not sufficient element in directing the contractor. Air Force direction is also supplied in official responses to key contractor prepared data items such as his proposal, R&M Program Plan, prediction and test plans, as well as by Air Force responses to design and program reviews.

Motivation of both Program Office personnel and the contractor for R&M progress will be directly proportional to the concern evidenced by the R&M manager. Because the effects of R&M program deficiencies do not become obvious until the equipment is in test, there is a tendency by both Air Force and contractor management to focus their attention on more immediate and obvious problems. However, when R&M problems do appear in tests, it will be expensive and it might be impractical to correct them. Hence, the astute Program Manager will maintain an R&M emphasis throughout the program to preclude unpleasant surprises in its late stages.

CONTROLLING FOR R&M

The Air Force approval of contractor data items constitutes an important control over the contractor R&M program. When correction of data deficiencies and the program activities they represent is a prerequisite for data approval, the contractor must take some action. However, the Program Manager and his R&M advisors must be keenly aware from the very beginning of the program, that the Air Force's claim of data deficiencies must be based on explicit contractual standards of acceptable data submission. The contract must be explicit as possible in defining the scope, procedures, and data sources, for studies, analyses, and plans. Especially in fixed price contracts, or in cost reimbursement contracts incorporating a large target price profit incentive, the contractor is strongly motivated to save money. (In a fixed price contract, every dollar saved is a dollar earned). Therefore, the contractor is motivated to provide analyses and reports with only the minimum degree of completeness which he thinks the Program Office will accept. Without tangible standards of data completeness in the contract, the Air Force R&M manager's task is frustrated in the early analytical phases of the R&M program.

Periodic design reviews provide another monitoring device for checking the progress on the R&M program. Periodic reviews of both the contractor's and the Air Force programs and comparison to previously established R&M milestones will also help keep the R&M program under control. During the validation phase, frequent review of achieved R&M, and status of corrective actions for known problems, will be the key items for R&M control.

The most significant R&M control over the contractor will be the R&M demonstrations. As previously mentioned, the loss of this control is usually fatal to an R&M program. Further, any compromises in R&M demonstrations should be considered only with a clear understanding and the most critical examination of the risks involved.

Other important control devices over the contractor's R&M efforts are the parts selection criteria, parts quality assurance (screening) procedures, and system quality control requirements.

Once the equipment is in the field, R&M visibility is provided by the Air Force maintenance data systems. While visibility alone does not constitute control, programs like IROS use this data to focus management attention on the items with the highest support costs, and thereby provide the manager with the information he needs to direct his R&M improvement program.

Finally, all the standard management control techniques such as PERT, PERT-COST, milestone charts, etc., should be applied to R&M as well as other program elements. R&M engineering is not a separate program running concurrently with system development, but it is an integrated part of the overall program.

SUMMARY

The hallmarks of a well-managed R&M program at the Air Force Program Office can be listed as follows:

1. R&M requirements are realistic, and if necessary, are updated to stay realistic until the final system requirements are fixed for full-scale development.

2. The Program Office has arranged for the support of technical specialists, (R&M, specifications, parts control, environmental testing).

3. Liaison arrangements have been made with the using and support commands.

4. Appropriate R&M program elements are explicitly defined in contractual documents, and compliance is enforced.

5. Air Force R&M specialists review submitted R&M data items and provide timely feedback to the contractor.

6. Design reviews, contractor program reviews, and internal Program Office reviews include R&M program status, the status of R&M data items, and correction of their deficiencies.

7. Reliability growth during the validation phase is planned and monitored by the program manager.

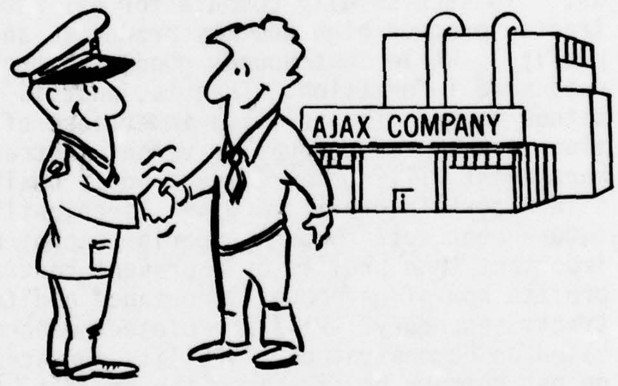
8. R&M demonstration tests are well defined and professionally monitored by Air Force R&M specialists.

9. Air Force preferred parts are used to the maximum extent possible.

10. R&M are considered essential system parameters which must be built into the design, along with other performance parameters.

R&M MANAGEMENT IN THE CONTRACTOR'S ORGANIZATION

This discussion is directed toward the system or equipment project manager in the contractor's organization who is the counterpart of the Air Force System or Equipment Program Office Manager. The project manager is our focal point, because he is the person who makes the project management decisions which ultimately reflect the contractor's success in achieving R&M objectives. We will make some management suggestions which should assist the project manager and his company achieve the reliability and maintainability objectives which will hopefully benefit both the company and the Air Force. We will do this in the frame work of the five management functions explained in Chapter 3; planning, organizing, manning, leading, and controlling. The discussion is not specialized to any particular technology field such as electronics or engines, but should be applicable anywhere.



PLANNING FOR R&M

Planning must be started before any other activity in a project can be initiated, since planning impacts all the other management functions. In general, planning consists of identifying desired goals and then delineating the best course of action to achieve those goals. We will separate planning at the contractor's facility into two major categories: those plans which are independent of any particular contract, and those which are made for the purpose of executing a specific contract. The first category will cover plans which should be made to insure that the company will be in a good competitive position with respect to R&M when a particular contract bid opportunity comes along. The second category of plans will be dictated, for the most part, by R&M requirements in the contract which has been won.

PLANNING INDEPENDENT OF A PARTICULAR CONTRACT

First of all, the project manager must be sure he understands overall company goals. Perhaps the goal may be stated as: "To successfully compete for Air Force development contracts, produce high quality products, and make a reasonable profit." While that sounds good, the project manager will need more information. That is, what is top management's attitude towards the relative importance of successful competition versus product quality versus contract profits? Is top management willing to reduce product quality in order to maintain a certain profit margin? Is competitive position for future contracts through superior technical capability more important than profits on a present contract? Are reasonable profits now of paramount importance and future Air Force contracts secondary? Will the project manager receive a bonus based on demonstrated reliability in acceptance tests or based on net company profits from the project? In other words, the project manager needs to know company goals and their priorities so that he can plan his work accordingly. He needs to have a feeling for the management trade-offs his superiors will view with favor.

From the Air Force's view of this example, hopefully high quality products come first, capability for successful competition comes second, and profits come third. We can argue that this order of precedence is also best for the long range interests of the company, because quality will lead to successful competition which in turn will lead to profits. However, priorities often get changed or are disregarded when the company gets into competitive bidding for Air Force contracts. The basic reason for this is that the Air Force is required to award contracts to the lowest qualified bidders. It is clear that a contractor can make his lowest bid if he proposes to do that which is the minimum acceptable. Since it is almost always more costly to build higher quality products, the successful bidder usually is the one who offers the lowest quality that can just barely be considered acceptable. Thus, building high quality products does not necessarily lead to successful competition.

Whatever those company goals may be that impact R&M plans, they should be written as concise statements which will fit on a single page or briefing chart, and should include some way of expressing the relative importance of each goal. They should be framed and hung in the project manager's office, and he should present these company goals at the beginning of each summary briefing to his superiors to make sure they have not changed their minds. The goals should also be frequently exposed to subordinates and associates as a reminder.

More detailed objectives for the company R&M program should then be fashioned so as to support those company goals, and the project manager should be able to explain whey they do support them.

Assuming now that the R&M objectives of the company have been identified and prioritized, we will turn to some of the things which must be done to delineate the best course of action or strategy to achieve those objectives. To develop that a strategy, the following questions need to be considered and answered. In doing so, company policies must be considered at the same time.

* Company Reference Library

What are the best R&M engineering and management books to have on hand? What military standards and manuals? What symposia proceedings and technical journals? Any standard computer programs desirable? Any R&M data service subscriptions needed? What about parts selection references?

* Survey of Potential Contract Requirements

What R&M requirements should be anticipated for the company's product lines? What is past history? What changes to anticipate for future? How should company respond to warranty or incentive provisions?

* Facility Needs

What kinds of environmental and reliability test facilities should the company own? What R&M service subcontractors are available? What are data processing needs? What about failure analysis facilities?

* Organization Alternatives

What is the best way to organize so that R&M engineering has the necessary influence in product design, fabrication, and testing? How will the company organization relate to the Air Force R&M organization?

* Manpower Alternatives

How many R&M engineers, technicians, and administrators are necessary? What experience and education is necessary? What are the educational opportunities? What is the available service subcontractor support?

* Data and Communication Systems

What are the requirements for collection, analysis, and distribution of data within the company? What will be the Air Force contractual requirements? What summary data does management need to control the R&M program? Does the company need an R&M policy and procedure guidebook for managers and engineers?

Answers to the above questions should result in the selection of the best alternatives to an overall R&M policy, organization and program for the company independent of any particular Air Force contract. More detailed "derivative plans" will then be developed from those basic ground rules.

PLANNING GOVERNED BY A PARTICULAR CONTRACT

If the overall company R&M policies, facilities and organization are in operation, "derivative plans" for a particular contract get down to planning contract execution details within the framework of the company R&M structure. Both MIL-STD-785 for reliability and MIL-STD-470 for maintainability specify the preparation of program plans. These plans generally describe how the company plans to accomplish the contract tasks and deliver contract products. The plan will show the tasks to be accomplished, their time-phasing, milestones and review times, the company R&M organization and its relationship to functional divisions of the company (engineering, manufacturing, etc.) the facilities and subcontracts to be employed for engineering, failure analysis and testing, the relationship of R&M tasks to related contract efforts such as safety, value engineering, and logistics studies, etc., the data and communications systems to be employed, among other things. For more specifics, the contract program plan task would have to be consulted. A standard Data Item Description, DI-R-3533, from the DoD Acquisition Management Systems and Data Requirements Control List, also lists the specific contents required in a Reliability/Maintainability Program Plan. In addition, many management factors pertinent to planning an R&M program have been discussed in Chapters 4 and 5.

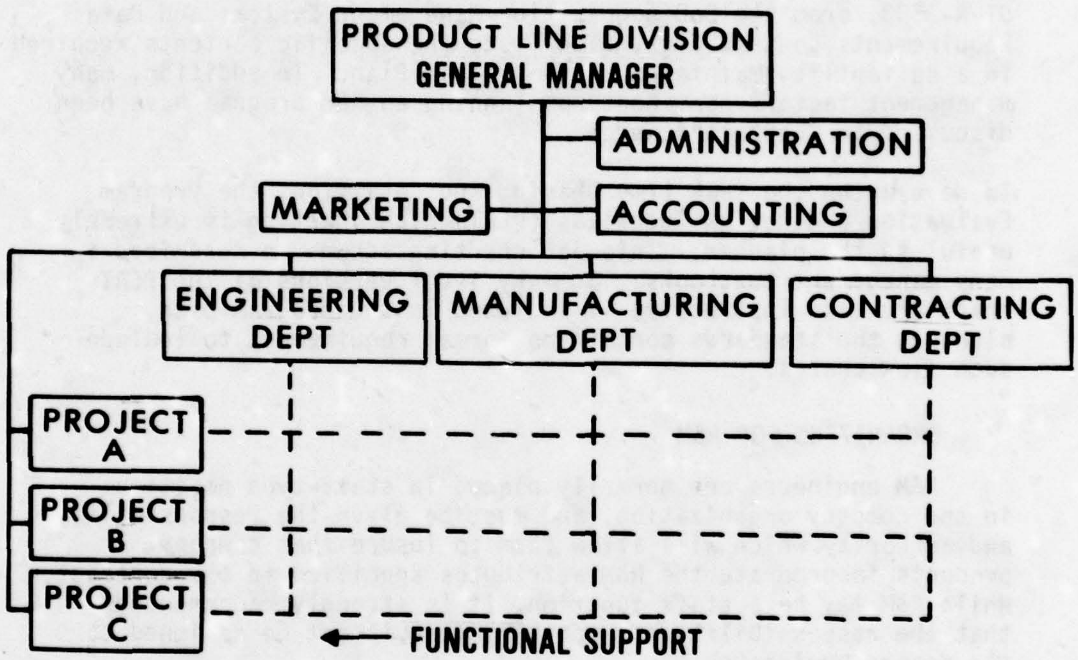
In developing the task time phasing and data flow, the Program Evaluation and Review Technique (PERT) type charting is extremely useful to the planner. This job charting scheme is described in many management textbooks. Summary level versions of the PERT chart are also instructive if included in the program plan, although the standards contain no formal requirement to include such flow charts.

ORGANIZING FOR R&M

R&M engineers are normally placed in staff-type positions in the company organization, and must be given the responsibility and authority which will allow them to insure that company products incorporate the R&M attributes specified in the contract. While R&M may be a staff function, it is strongly recommended that the responsibility for the R&M of equipment be assigned to the design engineers.

The staff R&M engineers must operate and conduct themselves in such a way that they will be regarded as helpful assistants in accomplishing detailed design and analysis tasks, rather than critical overlords to be passified. Consequently, the R&M staff engineer is often challenged by the human relations element in his job. He has to be helpful and persuasive, but firm and resolved when critical R&M issues are at stake. He must not only have detailed design review responsibility, but must also have authority to sidetrack designs which threaten R&M achievement so the project manager or chief engineer can resolve the matter. It is best, of course, for the R&M staff engineer to work out design issues at the design engineer's level without escalating the problem.

In large military product companies, organization arrangements similar to those following are quite common.



In the Product Line Division, R&M engineers are normally located at staff level in each project office as well as in the Engineering Department. A quality control (QC) group will be at staff level in the Manufacturing Department. Company policies and procedures must explain the responsibility, authority and working relationships between all these R&M and QC people at staff and subordinate levels.

There are many variations on this theme, but if R&M support within the project office and division is much less visible than explained and depicted here, company achievement of Air Force standard R&M requirements may be in jeopardy.

MANNING FOR R&M

The task of manning includes both the staffing of an organization and its training. We shall assume here that the Project Manager knows how to man his project office with people trained in the basic principles of R&M engineering that he needs, along with the necessary levels of experience. These R&M engineers might be hired "off the street" or might be assigned to the Project Office from the Engineering Department. They also might be outside consultants, at least in part.

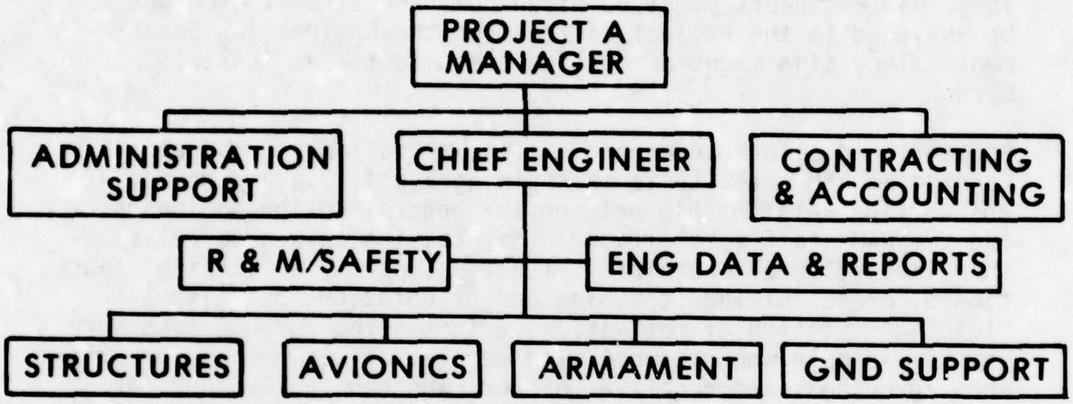
As mentioned before under organizing, a challenging aspect of manning an R&M activity is maintaining a positive and harmonious working relationship between the general design engineers and the R&M staff specialists. (Maintaining this good relationship is partly an "organizing" function, partly a "manning" function of proper hiring, training and orientation, but also a "leading" function of motivation). In manning for R&M make sure you hire people who can work with people. It is no job for grinches, grouches, and negative thinkers who habitually look for what is wrong and find it painful to praise what is right. It also helps to plan a thorough orientation and training program for new people, not only to explain procedural and organization matters, but also to explain the special human relations challenges of the job. That is, how to win cooperation and be helpful, positive, timely, and persuasive in achieving a good engineering response to R&M tasks.

Informal contact between R&M specialists and design engineers should be frequent. A formal design review, for example, should represent the results of a series of earlier informal design discussions between the designer and the R&M people, thus representing their best joint efforts rather than a "trial balloon" created by the designers to be criticized by the R&M people. The latter course is a time-wasting, friction-creating, and usually an ineffectual procedure.

Finally, the R&M specialists should be prepared to personally handle the special statistical tasks such as R&M prediction and test analysis. They should not badger the other engineers to perform analyses which the R&M specialists are supposed to be expert at doing themselves.

In some companies, a "Product Assurance" group is included in the General Manager's staff, and that group's function is to oversee and control the operations of R&M, quality control, safety, value engineering, etc., throughout all departments and projects. This is considered a very good idea.

The company project office might typically be organized as follows:

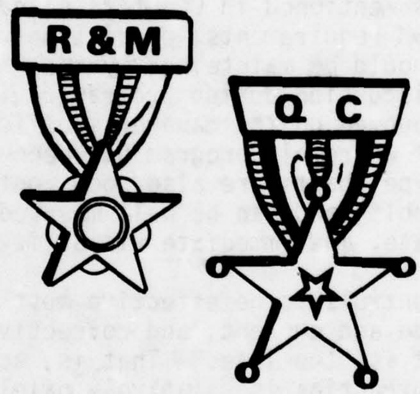


The project manager is the company counterpart of the Program Manager in the Air Force System Program Office. Within the project office, the R&M staff group will have engineers who are specialists in avionics, structures, engines, armament, etc. These specialists will guide and often execute the detailed R&M tasks needed in those areas. The project R&M group leader must work in harmony with other R&M and QC engineers working at staff levels in Engineering and Manufacturing, and he must also communicate on a technical level with the R&M staff engineer in the Air Force System Program Office. The Engineering Data and Reports Group is responsible for the R&M data system described in Chapters 4 and 5, and the final composition of all technical reports and specifications. Of course, they will need inputs from the engineers in the various specialty groups. Support for failure analysis and environmental test work will usually come from the Engineering Department as needed, or possibly from subcontractors administered by the Engineering Department.

LEADING FOR R&M

Leading consists of making objectives clear, giving timely directions for achieving the objectives, (showing the way), and motivating people so that they will want to achieve them.

In this function, the R&M staff supervisor and the project manager must be persuasive communicators. They need to stress the importance of R&M in achieving company goals and in achieving the specific objectives of the contract at hand. They need to make all procedural matters as clear and unambiguous as possible. They need to listen for complaints or evidence of friction between designers and R&M specialists and need to resolve those situations quickly. They should sponsor working group sessions between designers and R&M specialists where the R&M people present helpful hints on how to get R&M needs folded into the design before the design work gets too far along. They should also explain the military R&M standards and manuals, (sometimes a herculean task), and the implications of contractual requirements.



Finally, supervisors should try to come up with some motivational incentives or awards that will encourage support and cooperation with the R&M program. This is especially important in the quality control area in the Manufacturing Department when tedious, repetitive tasks can lead to boredom and apathy.

CONTROLLING FOR R&M

Controlling in management is the process of periodic measurement of performance relative to established goals, determining deviations, and redirecting efforts back towards the desired goals. The goals must be visible, the performance must be measurable and the redirection must be timely. Various progress charting schemes, and design or program reviews are typical control methods.

In the R&M program, R&M requirements provide the goals, and R&M predictions and measurements provide the observations of progress. In the quality control area, the percentage of defective parts found on incoming inspection serves to gauge acceptable parts quality from suppliers. Checkout failure rates in production line testing also serve as measures of quality control and reliability progress. The R&M data system described in Chapters 4 and 5 serves as the data gathering tool, and the manager's summary of that data is his measure of progress relative to the goals he has defined at the beginning.

As mentioned in Chapters 4 and 5, graphical presentations of R&M requirements, predictions, and measurements versus time should be maintained by the R&M staff office for display and discussion during program reviews. These charts should be mounted on the manager's office wall as a continuing reminder of where his program has been and where it hopes to go. PERT-type charts are also good control tools as well as planning tools, and can be wall mounted for quick reference, easy update, and immediate visibility.

Controls to be effective must be timely. Data must be accurate and current, and corrective actions has to be taken before it is "too late." That is, action should be taken when the correction is relatively painless (in terms of pride and dollars), otherwise the controlling action can degenerate to a demotivating, discouraging action which people will try to avoid through holding back information. An example is Failure Modes and Effects Analysis (FMEA). This is a valuable design guidance tool if begun on time, but can also become merely a burdensome activity if the useful information comes too late to affect design and test procedures.

After design is complete, a very effective control method to insure that poor workmanship, parts deficiencies, and design defects get the attention they should, is to focus management attention on the "top ten" R&M problems of the month. These "standout" deficiencies can be identified through statistical analysis of failures recorded in the data system. Monthly management review of these R&M "standouts" and their proposed solutions (determined by failure analysis, and appropriate action by redesign, vendor control, quality control, etc.) will insure a vigorous program for correction of R&M deficiencies.

WARRANTIES

While warranties have been used relatively little in Air Force development contracting, they are receiving increased attention at Air Force staff levels as one possible approach to achieving enhanced reliability of operational equipments. The airline industry has used equipment warranties for many years as an incentive for suppliers to provide reliable equipment and to give the airlines a more firm basis for planning operating budgets, support facilities, and manpower. Airline equipment warranties have been widely used for equipments and subsystems such as avionics, engines, tires, batteries, etc., and generally apply for the expected useful life of the equipment--perhaps for as long as ten years. The airlines have found warranties to be cost effective contractual instruments.

TYPES OF WARRANTIES

The World Airline Suppliers' Guide, published by the Air Transport Association of America, describes four basic types of warranties used within the industry.

STANDARD OR FAILURE FREE WARRANTY

This type of warranty (which has been termed a "Reliability Improvement Warranty" by DoD) applies to avionics as well as a range of other items. The warranty extends for a specified number of operating hours or calendar time or a combination of both. The vendor normally assumes responsibility for labor and material costs necessary to correct any failures occurring during the warranty period.

ULTIMATE LIFE WARRANTY

This type of warranty applies to major structural elements, such as wings, fuselage, and landing gear. The agreement warrants that such components will be free from defects for a stated number of flying hours.

RELIABILITY GUARANTEE

The vendor is required to have his product achieve a stated mean time between failure (MTBF). Such agreements generally recognize that the initial deployment will experience infant mortality and thus require that the MTBF be demonstrated after some initial period of operational use. The warranty typically runs until the warranted MTBF has been demonstrated for a stated number of consecutive months. If at any time the vendor's product fails to meet the specified MTBF, the vendor is required to (a) supply additional spare units to support the airline's operations until the required MTBF is achieved, and (b) provide technical assistance and/or modification kits and labor to achieve the warranted MTBF.

MAXIMUM PARTS COST GUARANTEE

Agreements are established with the airline on a maximum materials cost per flying hour (or other measure of usage) for maintaining, modifying, repairing, and overhauling selected items. Typical applications include aircraft tires and brakes.

Other types of warranties, such as maintainability guarantees and mean time to repair guarantees, have been used on occasion. The types of greatest interest in Air Force contracting are the Failure Free Warranty and the Reliability Guarantee, or a combination of both. The reason for this is that the greatest amount of support costs are associated with the kinds of equipment which are suitable for these types of warranties; (avionics and ground electronics). Warranties of these types are normally for a period of three to five years.

USE OF WARRANTIES

Warranties have been used successfully by the Air Force on such things as tires, brakes, and hydraulic components, as well as on electronic and electromechanical equipment. Criteria which define the conditions under which a warranty would be an appropriate contractual instrument are listed in Interim Guidelines Reliability Improvement Warranty (RIW) published in July 1974 by the Directorate of Procurement Policy (AF/LGP). Warranties are not generally used when an Air Force support capability already exists or the equipment can be readily repaired by the average Air Force technician in the field. The type of equipment that is most suitable for a warranty is new and complicated equipment which might initially have relatively low reliability and would require a major effort to establish an Air Force support capability.

The main value of a warranty is that it extends the contractor's responsibility for his equipment for a long period of time beyond delivery. As explained in an earlier chapter, a contractor is not normally motivated to build any more than the minimum acceptable reliability into his equipment since to do so would cost him more and reduce his profit. The situation is changed considerably when a RIW is included in the contract. Now he must not only consider production costs but also support costs for a long period of time (3 to 5 years). He is strongly motivated to build more reliability into his equipment so as to reduce his support costs and make the sum of his production and support costs a minimum, and thus his profit a maximum. For example, assume the contractor can make a reliability improvement which would cost him $150,000 to incorporate and save him $50,000 per year in repair costs. If the warranty period were longer than three years he would obviously consider the change. Thus the use of an RIW may increase reliability and reduce the life cycle cost for the Air Force, if the warranty period is long enough to permit the contractor time to recoup any expenses he may incur in improving his product. Of course, this conclusion assumes that the contractor remains in a sound financial condition over the period of the warranty and is able to fulfill its provisions.

A comprehensive study of the use of warranties for defense avionic procurement has been made ("Use of Warranties for Defense Avionic Procurement," ARINC Research Corporation, RADC-TR-73-249 dated Jun 73 (769399). This study recommended the expanded use of failure free warranties since they are most easily administered and are most compatible with existing supply and maintenance administration systems.

It is always best for the Government to state its intention of incorporating warranty provisions in a later production contract before the equipment has been designed in a validation phase contract. This will allow the designer to make reliability and support cost trade-offs which he might not otherwise consider. It is possible, however, to incorporate an RIW in the production contract without the intention being previously stated, although the effectiveness in this case would be less.

WARRANTY COSTS

Airline experience with warranties indicates that the cost of a warranty ranges from 4 per cent to 10 per cent of the acquisition cost per year of coverage. The smaller figure is for uncomplicated, inherently reliable equipment. These numbers are presently merely as an indication of the general cost of a warranty. Each case must be judged separately.

SUMMARY

Warranties are widely and successfully used by airlines, but have been used comparatively little by the Air Force. The Air Force is studying wider use of warranties. Criteria for application of warranties are given in Interim Guidelines Reliability Improvement Warranty (RIW) published in July 1974 by the Directorate of Procurement Policy (AF/LGP). If the equipment being developed combines several of the attributes listed there, the program manager should surely ask his R&M staff specialist to examine the use of warranty provisions in the production contract. (However, such a decision should be made before the statement of work for the validation phase is prepared if possible, so that potential contractors will be aware of the long-term nature of the program).

Even if a warranty is judged a good bet for the equipment procurement, all the R&M program elements described in Chapters 4 and 5 cannot be abandoned. For example, if the equipment is to be eventually supported by Air Force logistics, standard military quality parts must be used as far as possible. Also, the Air Force would not want to be forced into buying all kinds of unique test equipment that a contractor might employ to support warranty repairs, if standard military test equipment could have been readily accommodated in the initial equipment design.

The combined warranty provisions and R&M program elements need to be tailored to the specific circumstances and objectives of the equipment being developed.

OTHER CONTRACT INCENTIVES

A reliability incentive can be incorporated into the provisions of a contract which rewards the contractor with an added fee for exceeding a specific reliability and penalizes him for falling short. The amount of the reward and the penalty need not be the same, in fact some schemes have rewards or penalties only. A warranty is also a form of reliability incentive, since the contractor's profit or loss at the end of the warranty period will depend largely on the reliability attained by his product.

Here are some examples of contractual reliability incentives which have been used: One manufacturer who was designing electronic equipment was rewarded for reducing the number of parts in the equipment. The idea here was that fewer parts in the equipment would make it more reliable. A satellite producer was rewarded for satellite lifetime. The longer the satellite remained operational in orbit, the greater his reward. A space launch vehicle manufacturer was incentivized on launch success. He received a reward each time there was a successful launch and was penalized for each failure. An electronic equipment manufacturer was given a reward or penalty based on the number of failures that occurred during the reliability demonstration test. Other such schemes have also been used.

Reliability incentives have not been very widely used, although Air Force policy encourages the use of incentives in general. Perhaps the reason is that it is difficult to structure an incentive around objective R&M performance criteria, free from things beyond the contractor's control, so that financial settlements can be readily agreed upon after hardware delivery. Another reason may be that there are many people who are not personally convinced that incentives have the positive value often touted. They believe that the contractor is already well paid under the contract to produce equipment with the required performance, that this is the basic incentive, and to pay an added incentive is a waste of money.

Another incentive for a contractor to build reliable equipment is the company reputation. A company desires a good reputation for several reasons, not the least of which is its effect on subsequent business and profits. In fact, a company's very survival may depend on the quality of its products. The value of a good reputation is, of course, not measurable and its importance to different companies varies. It should be noted that reputation is less important to a company in its military business than in its commercial business, because of the strict rules that military source selection proceedings must follow.

The program or project manager should ask his staff R&M engineer and contract people to consider the use of special contract incentives to enhance the chances of reaching R&M objectives. The DoD/NASA Incentive Contracting Guide, AFP 70-1-5, gives guidelines for developing incentive provisions.

As with warranties, all the R&M program elements discussed in Chapters 4 and 5 cannot be abandoned and replaced by incentive provisions in the contract. That would have little chance of success.

The overall R&M program, including contract incentive provisions, needs to be tailored to the specific equipment type and program objectives by the R&M staff specialists in the program or project office.

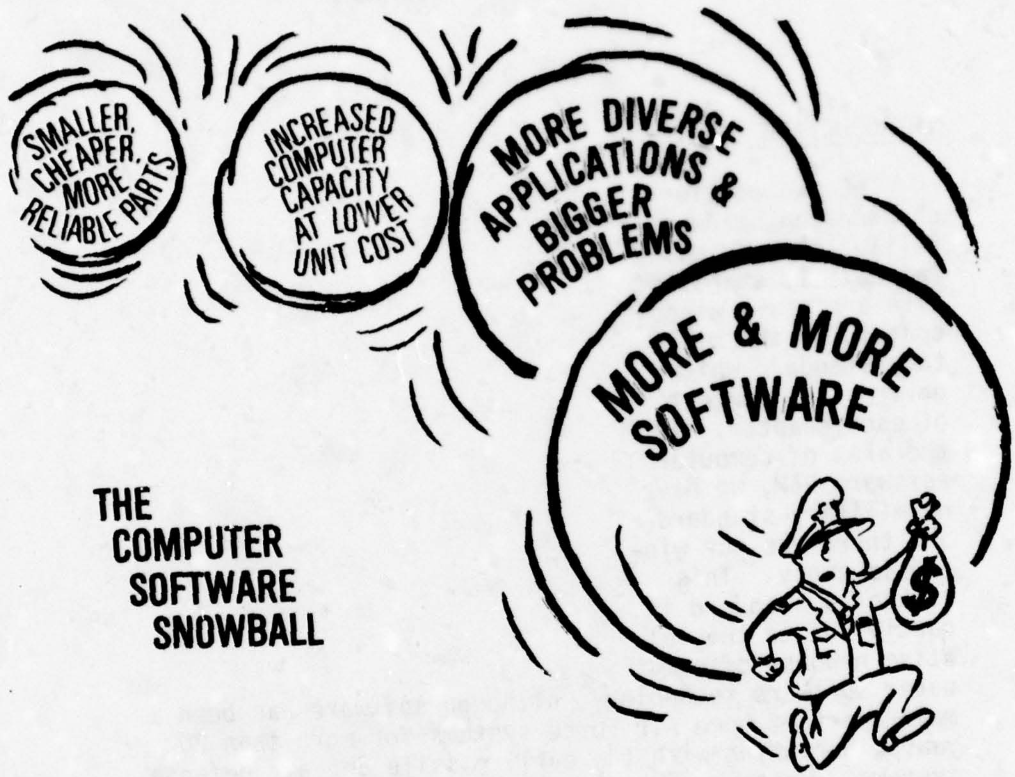
Chapter 7

RELIABILITY AND MAINTAINABILITY OF COMPUTER SOFTWARE

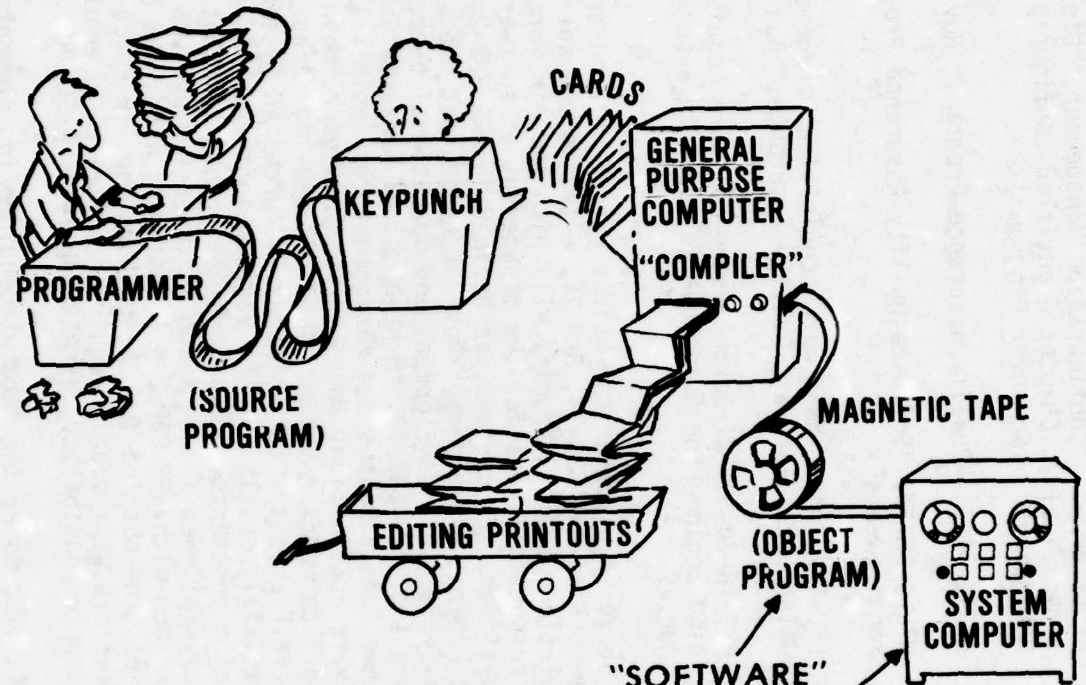
INTRODUCTION

The two earlier chapters on hardware reliability and maintainability start off with a picture window containing the military standard which governs the content of each chapter. In the area of computer software R&M, we have no military standard and therefore our window is empty. This lack of a standard is partly due to the relative newness of computer software technology, although software has been a major part of some Air Force systems for more than 20 years, beginning with the early missile and air defense systems. Whatever the reasons may be for not having software R&M standards, Government experiences with large systems over the past 10 years (Apollo, Safeguard, defense satellite system, etc.), and the mushrooming new uses of digital systems, have all shown that the software community needs to focus attention on R&M. Indeed, response to this need has been reflected in technical literature and in new Air Force R&D work in recent years.

Software in Air Force systems has been growing like a snowball rolling downhill. This has resulted from production of microscopic digital circuit devices that combine increased reliability, lower unit cost, and lower power requirements. These smaller, better devices have inspired many new applications which have in turn spawned the need for more and more software. The trade literature has claimed that the cost of new software ranges from two to ten times the cost of hardware on which it operates. Furthermore, estimates show that the Air Force now spends about a half billion dollars annually on its related software. Software is big business and is a major cost and risk segment of most new systems.



While we do not have any software standards which focus on R&M, other general regulations do have R&M implications. For example, we have the 300-series (Data Automation) regulations and manuals which for many years have governed procurement and management of data processing systems for support applications. This series, in varying degrees, has also governed research and development applications. In addition, various configuration management procedures have been applied to software development. Of course, those regulations and standards have benefitted R&M somewhat.



MAKING COMPUTER SOFTWARE

A series of standards and guidebooks, although not specifically dealing with software R&M, can provide guidance on the requirements for, and possible contents of, a software R&M program. Some of the more recommended ones are:

AFSCP 8ØØ-7, "Configuration Management," Dec 77 (specifically, Chapter 6 entitled Configuration Management of Computer Programs).

AFSCR 74-1, "Quality Assurance Program," Nov 78

MIL-S-52779, "Software Quality Assurance Program Requirements

ESD-TR-77-225, "Software Acquisition Management Guidebook: Software Quality Assurance," Aug 77

ASD-TR-78-8, "Airborne System Software Acquisition Engineering Guidebook for Quality Assurance," Aug 77

The above regulations and guides were developed around the framework of AFR 8ØØ-14, Sep 75, a two volume set of regulations dealing specifically with the Air Force policies and responsibilities for the management of software acquisitions for systems, as defined in AFR 8ØØ-2, "Acquisition Program Management," Nov 77, throughout the software life cycle (both development and operational useage). Volume I of AFR 8ØØ-14, "Management of Computer Resources in Systems," establishes the management responsibilities for software acquisitions among the various user, developing, and support commands. Volume II of AFR 8ØØ-14, "Acquisition and Support Procedures for Computer Resources in Systems," specifically spells out the various software life cycle events, planning documents, and management principles that must be rigidly followed in acquiring software for systems in accordance with AFR 8ØØ-2. In essence, then, AFR 8ØØ-14 provides the outline for the methods the Air Force and its contractors will use in acquiring software. The office of primary responsibility for AFR 8ØØ-14 is AFSC/XRF.

Before discussing the separate engineering elements of software development, let us review several terms. The meaning of "software" is well known. It is the set of written instructions which tell a digital computer what to do. Of course, these instructions have to be written in a simple and precise language which the computer can understand.

Usually, the instructions are first written in a "higher level" language such as FORTRAN IV, which is easy for people to work with. This set of instructions is called the "source program." The program is then translated via another computer program (called a "compiler") into machine language (the "object program") which is efficient for the system computer to read and execute.

Throughout this process of software development, many kinds of mistakes can be made which lead to system reliability problems. These mistakes can be grouped as follows:

* Problem definition

  In the system engineer's conception of the overall operational system problem to be solved, some task or situation has been misinterpreted or has been overlooked and left out of the problem formulation. Sometimes, as the definition of the problem proceeds into greater detail, interface and timing errors arise.

* Computation logic

  The computer program designer has made logical mistakes or misinterpretations in converting the problem statement into computational steps or unanticipated combinations of circumstances cause errors in execution.

* Grammar

  The programmer or the program translator (compiler program) have made mistakes in applying the grammatical rules of the programming languages.

* Typographical

  The keypunch operator, the keypunch machine, the card reader, tape unit, or other data transducers have made mistakes in converting symbols from one form to another.

Editing, debugging and system testing routines are designed to flush out these mistakes. The first category (problem definition) contains the kind of mistakes which are the most difficult to uncover and cause the most operational heartburn, since they might never be discovered until revealed by system failure during some unusual mission. By that time, computer program changes are very costly and disruptive, and of course mission failure could mean a disaster. This difficulty also applies in some degree to the second category (computation logic), since large computer programs may contain millions of possible logical flow paths with some never exercised during tests. Some paths may come into use only by chance, years after deployment.

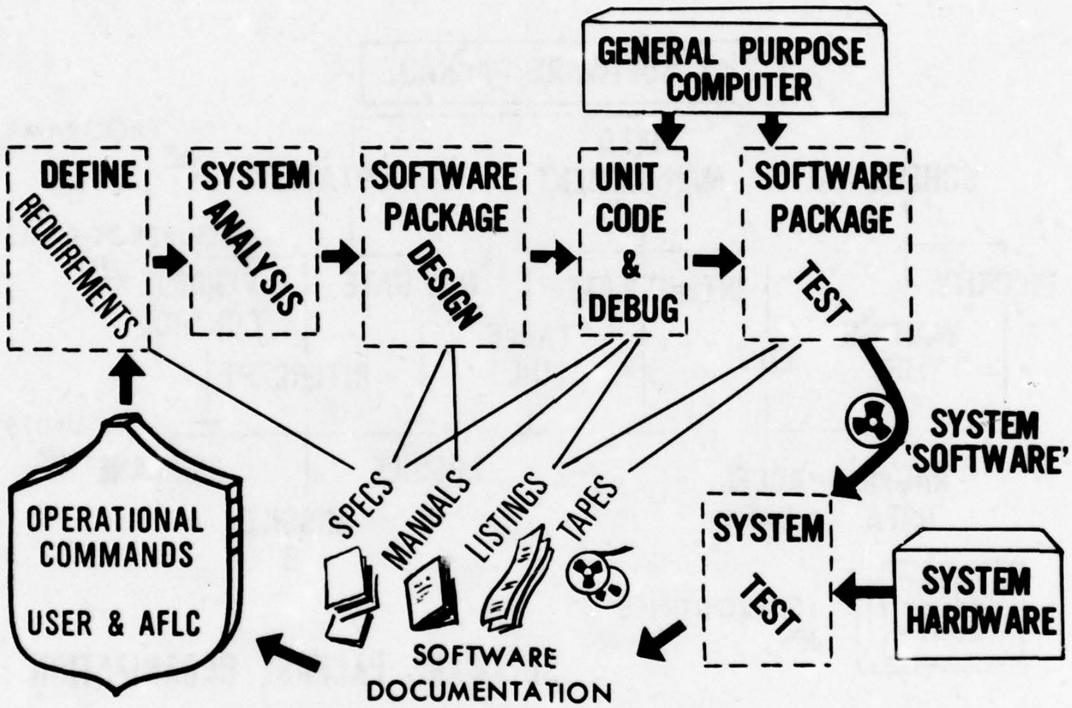
The term "software reliability" refers to the degree that a software package can be expected to perform its intended function according to expected mission profiles. While several numerical measures of software reliability have been proposed and used in some instances, no generally accepted measure of software reliability has been adopted for widespread useage.

The term "Software maintainability" refers to the degree a software product facilitates updating to satisfy new requirements or modification to correct mistakes. Again, no single method for measuring software maintainability has been adopted, even though the major portion (up to 70%) of software life cycle costs are for software maintenance.

The Information Sciences Division (IS) of Rome Air Development Center (RADC) is the focal point within the Air Force for software reliability expertise. An extensive program for establishing tools and procedures for improving software reliability has been underway for several years. This program has resulted in formulation of RADC Specification CP 0787796100, "Computer Software Development Specification," Mar 78, which is available for guidance and information. Of more importance to this manual is the forthcoming Oct 79 RADC handbook on software reliability prediction which will describe in detail the use of current methodologies for predicting software reliability. This handbook is intended as an interim product that will eventually become the software counterpart to MIL-HDBK-217, "Reliability Prediction of Electronic Equipment".

ELEMENTS OF SOFTWARE DEVELOPMENT

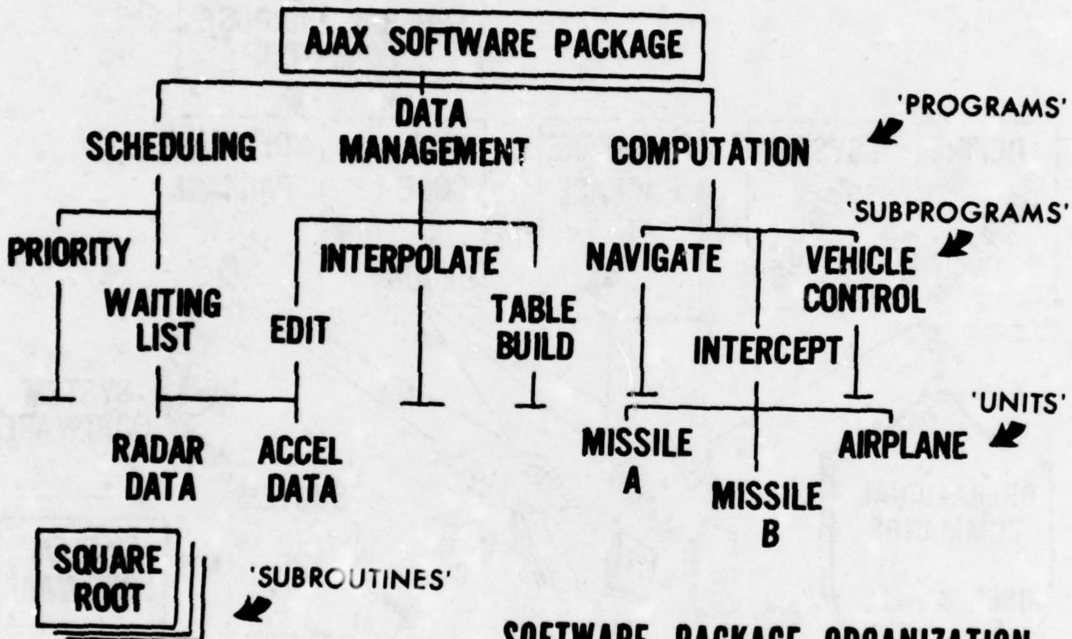
The following diagram shows the major elements of a software development cycle. Note that this is not a software R&M program, but a system software development program in general. Software R&M has simply not developed to the point where it can be discussed as a separate engineering discipline. However, each of the steps is described later emphasizing R&M considerations.



SYSTEM SOFTWARE DEVELOPMENT CYCLE

The diagram introduces some more terms that need explanation. The term "system" refers to the combined software/hardware system including the computer and everything that functions with it to provide and handle numerical data. The software "package" is the complete set of computer programs which govern the processing of system data. This package is organized into separate "programs," "subprograms," "subroutines," etc., with the smallest functional subdivision being a "module" or "unit."

It is desirable for this unit to be small enough to fit on one page of source code instructions, and junior programmers are assigned the job of designing, coding and debugging one or more of these units in a large system problem. Senior programmers or system analysts are responsible for organizing and interfacing the larger groupings of units (subprograms, subroutines, programs, etc.), and those programmers must be sure the code is written so that all units operate together in harmony.



SOFTWARE PACKAGE ORGANIZATION

The "subroutines" sitting on the sidelines are standard subprograms which the programmer can call into use at any level to carry out routine calculations such as square toot, standard deviation, sine function, etc. While the functional organization of the software package is charted from large subdivisions on the top to the smallest units on the bottom, the computational sequence might follow almost any path through the chart. Therefore, communications between programmers and documentation of coding rules and decisions must be highly disciplined.

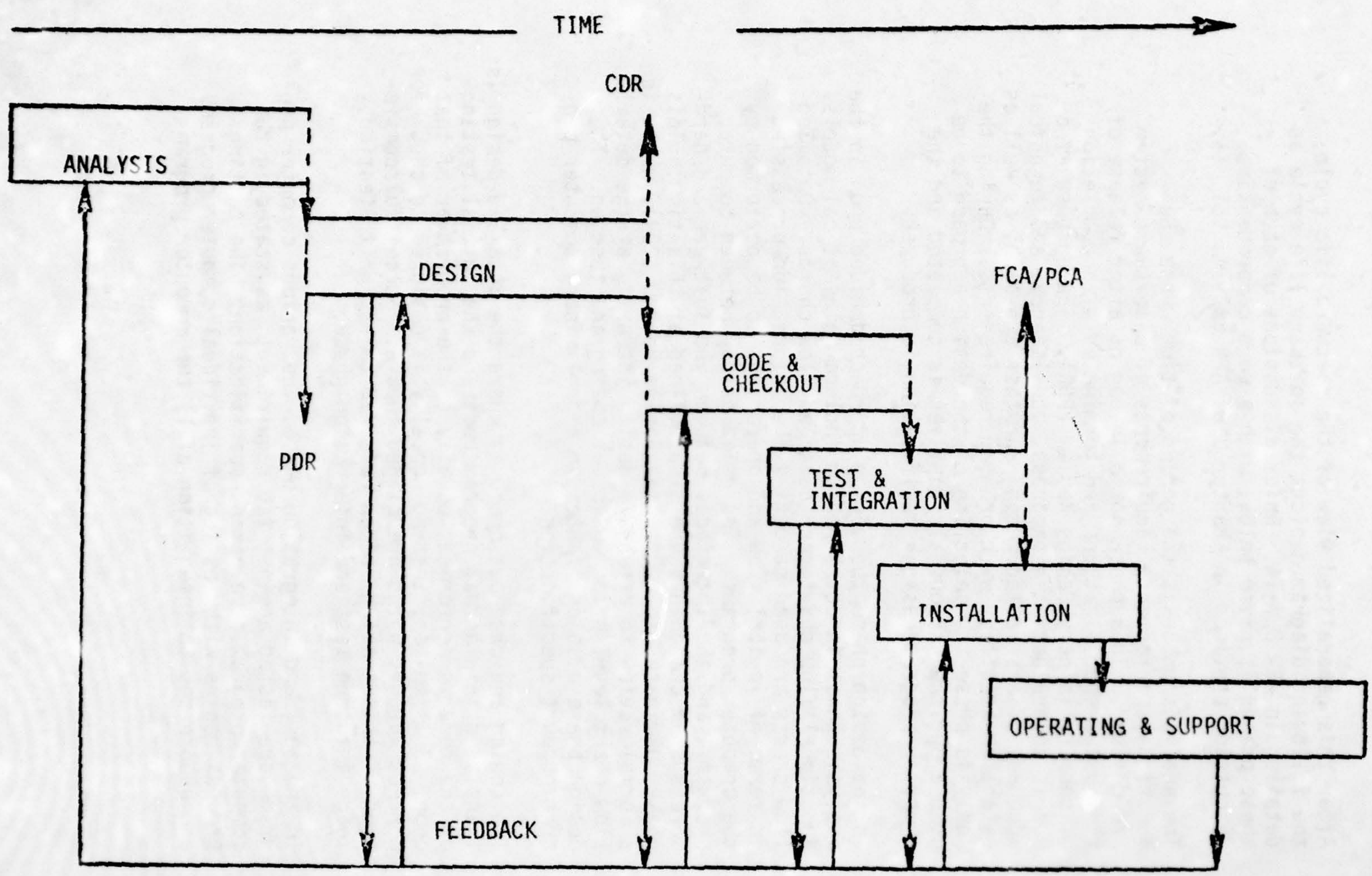
After this generalized view of the software life cycle, the following diagram depicts the software life cycle as detailed in AFR 8ØØ-14. Brief discussions of each of these phases is given below, with a more comprehensive discussion provided in Chapter 2 of AFR 8ØØ-14, Vol. II.

The analysis phase is the period of time where the functional performance requirements of a software system are defined. This phase normally begins after release of the system specifications and terminates with completion of the Preliminary Design Review (PDR). The purpose of a PDR is to evaluate the progress, consistency, and technical adequacy of a selected design and test approach, as well as establish stability with program requirements. During the analysis phase the selection of the design approach to be used among the various alternatives is completed and the computer program design specification is produced.

In the design phase the design approach decided upon in the analysis phase is developed to include mathematical models, functional flow charts and detailed flow charts. Detailed flow charts are used to define the information processing in terms of logical flow and operations to be performed by the computer programs. The relationship between computer programs, and the interfaces between the software and hardware system components are also defined at this time. This phase culminates in a Critical Design Review (CDR), which is a formal review to establish design integrity at the detailed flow chart level prior to actual coding and testing. The design phase also culminates in a preliminary computer program product specification.

The coding and checkout phase is where the detailed design is translated into actual program code and the initial testing of the code is performed, usually by the programmer of that code. This initial testing normally is designed to check for correct outputs using predefined inputs. Successful completion of this testing, often referred to as "unit" testing, leads into the test and integration phase.

In the test and integration phase, the various computer programs are tested against the requirements as stated in the computer program development specification. The testing process begins with testing of individual computer programs and progresses to integration of 1) the computer programs



COMPUTER PROGRAM LIFE CYCLE

into a total software package, and 2) the software and hardware components into a total system. This phase is concluded with a formal qualification of the software produced and development of the completed computer program product specification.

The installation phase includes the loading and running of the computer programs after successful completion of integration testing and formal qualification. During this phase the system is checked to insure its performance is within specified levels of confidence. The operational and support phase covers the time when the operational suitability of the system is assessed and the capability of the system to operate in an operational environment is evaluated. Support phases cover all the activities and resources required to insure that the software continues to meets its required operational capabilities. Included in this phase are the activities of software maintenance performed to either 1) correct software errors that were not detected during testing, 2) make changes in the software to maintain its operational capabilities at current levels, and 3) make changes in the software to upgrade or modify the operational capabilities of the system. Activities during this phase also include making changes in the supportive documentation, such as program listings and the product specification, to accompany any changes in the code or in the requirements. This phase is the largest in terms of life cycle costs, with an estimated 6Ø-7Ø% of the total software life cycle cost being accounted for during this phase.

The following chart lists the principal elements of a program to develop the software package for a large system. It also shows the phasings and relative importance judged reasonable for an "average" development program. The percentage distribution of contractor manhour effort gives some idea of what to expect, and can vary widely from one program to another depending on circumstances. A particular program would have to be planned by experienced system software people to fit those circumstances.

Notice how early the requirements and system analysis are expected to be complete--early in the validation phase. That's because software design cannot proceed very far until certain mission decisions are made. These include exact mission problems to be solved, data inputs and outputs, computer design, programming languages, etc. Any basic hardware

ELEMENTS OF SOFTWARE DEVELOPMENT

Element	%Effort	Life Cycle Phase: Conceptual	Validation	Full Scale Development	Production	Deployment
Requirements Definition	5	xxxxxxxxxAAA	A.........	....		
System Analysis	10	xxxxxAA	Axxxxxxxxxx	xxxAAA.....		
Package Design	10	---oooo	xxxxxxxx...	....	....	....
Unit Design, Code & Debug	15		---oooooooo	xxxx........	....	....
Package Integration & Test			---ooo	xxxxAAA...	....	....
System Integration & Test	30			xxAAAAx	x...........	....
Acceptance Test				xxxAA	A...........	
Program Plan		---oooooo	xxxxxxxxxxx	xxxxxx....	....	
Specifications		xxxxxxxxx	xxxxxxxxxxxx	xxxxxxxAAAAA	....	
Data System		oooooo	oooooooooooo	oooooxxxxxx	....	....
Program Review	30	oooooo	xxxxxxxxxxx	xxxxxxxAAAAA	....	
Test Plan			----oooxxx	xxxxAAAA...		
Technical Manuals				oooooxxxxxx	xAA.........	....

First contract

KEY

-----------ooooooooooooooxxxxxxxxxxxxxxxxAAAAAAAAAAAAA.............

- ----- Desirable activity (for highest success probability)
- ooooo Necessary activity (errors seldom disastrous)
- xxxxx Very important activity (errors often disastrous)
- AAAAA Critical activity (errors usually disastrous)
- ..... Low key activity (to update previous results)

changes which come later can cause big pieces of software effort to be scrapped leading to cost overruns and schedule crises. The software-related hardware and mission parameters have to be identified and pinned down early.

Notice also that the software design, code and test work trail off into the deployment phase. While not a desirable circumstance, it is almost inevitable with large software systems because of their size, complexity and the relative ease with which changes can be made. Planners must recognize this reality and set up a documentation and approval system which will keep the changes under control.

Definition of Requirements

Software requirements define the overall mission problem to be solved by the software, the operational constraints, and any fixed interfaces with system hardware and people. Requirements must cover the following kinds of information:

* Mission problems to be solved by the software system

* Software-related system hardware design decisions not subject to tradeoff studies

* Software design contraints imposed on Air Force systems

* Input data sources, rates and formats (if established)

* Output data destinations, rates, and formats (if established)

* Adaptability required for system modifications in operational use

* Software-dependent maintenance concepts and plans

* Security needs

* Operational hazards and environment

* Reliability and maintainability needs

Requirements are determined, so far as possible, by the System Program Program Office as an in-house task. The work is done before the first contract, depending heavily upon inputs from the using command and AFLC. After the first contract, the contractor will further refine and define the requirements through systems analysis and discussions with the System Program Office. As mentioned earlier, requirements must be pinned down by the early part of the validation phase, otherwise subsequent software effort will have to proceed on the basis of assumptions. This can cause a lot of waste, if the assumptions do not come true later on. Requirements are documented in the program plan, system specifications and interface specifications.

System Analysis

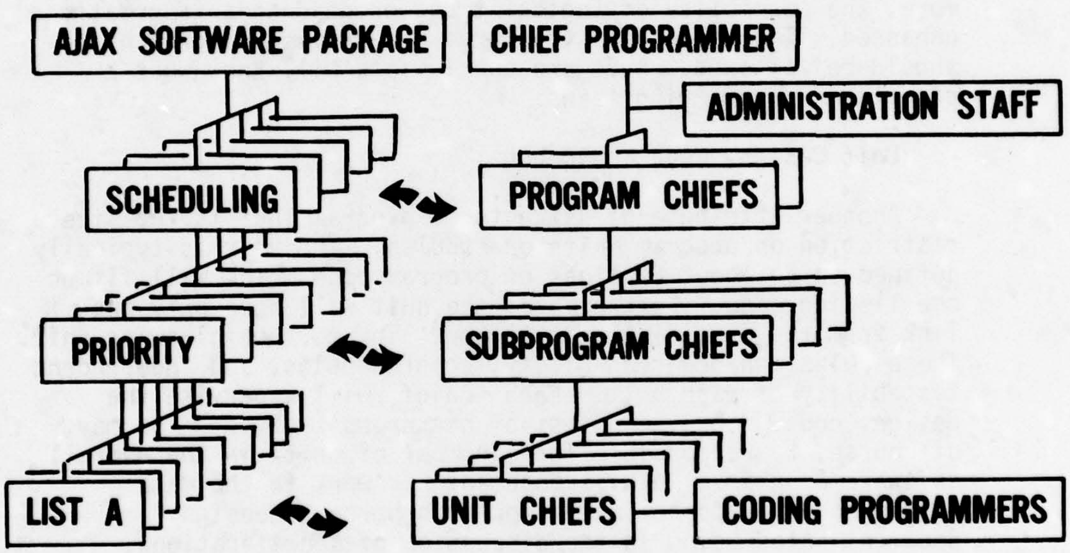
System analysis proceeds in parallel with requirements definition, and evaluates the system design tradeoffs between hardware and software. It considers computer hardware options, maintenance options, and in general, all of the software-related hardware alternatives. The objective is to design the hardware/software system so as to maximize the chances of success at the lowest life cycle cost. These chosen design options are documented in system and interface specifications used by the software designers. The first set of A's on the chart refers to delivery of these hardware parameters to the specification writers.

Another important area of system analysis which continues through the middle of full scale development, is the development of schemes for system testing and acceptance. The thoroughness of these schemes directly affects the verification of software R&M. Test schemes are documented in the system test plans and acceptance specifications. The second set of A's on the chart refers to delivery of this test planning information to the test plan writers.

Package Design

Package design refers to the development of the complete software system functional organization. That is, the overall task of the software system is broken down into functional categories and subcategories all the way to the unit level. (The process is analogous to organizing a large group of people with diverse skills to carry out a project). To enhance R&M of a large software system, this software functional organization must be thorough, well documented, and all interface rules between functional elements must be precisely defined and their application carefully controlled.

A "chief programmer" or a senior software system engineer must be assigned to oversee and manage this whole process. Subordinate programmers responsible for the separate programs in the functional categories will be assigned to him. In other words, there will be a hierarchical organization of people (programmers) with supervisors and subordinates that pretty much parallels the functional organization of the software system. The chief programmer must not only be an engineer experienced in development of large software systems, but must also be skilled in applying the traditional management tools to plan, organize, man, lead, and control his people and project.



THE PROGRAMMER'S BUREAUCRACY

In turn, the subordinate manager of each program or subprogram will plan, organize, lead and control the detailed coding, testing, and documentation of programming within his domain using the ground rules laid down by the chief programmer. At the same time, each subordinte manager will devise schemes for testing to insure quality. The results of this work are documented in the test plan, data system and specifications discussed below.

In addition to organizing the whole operation, the chief programmer must identify the source program langaugues to be used (from system analyses documented in the system and interface specifications) and the general rules for program structure and progress documentation throughout his organization. The programming rules should be documented in one of the computer program design specifications.

To enhance the readability and testability of the computer programs, "structured programming" techniques should be employed. In part, this means that the programmer is restricted to a small set of standard language constructs which prevent him from skipping to some remote segment of the computational sequence. Unbridled use of "go to" instructions can lead to a maze of possible computational flow paths making the program very difficult to comprehend, document and check out. Furthermore, the possiblity of logical traps or dead ends is greatly enhanced. Therefore, a "structured programming" approach should be followed. Software specialists will know what structured programming means.

Unit Design, Code and Debug

Another attribute of "structured programming" is the size restriction on program units or modules. The unit is typically defined to be about 50 lines of program code which will fit on one listing page. Furthermore, the unit will have only one link from the preceding unit and one link to the following unit. These rules enhance readability, comprehension, and independent testability of each unit. Each "Chief" will supervise the design, code, debug, and test of his group's output. He may, of course, be responsible for a number of units in the overall software program. He will document his work in the data system and the appropriate computer subprogram design document noted below in the discussion of specifications.

Package Integration and Test

Package integration and test means that units, subprograms, subroutines, etc., and programs are assembled and tested in groups of increasing size until the entire software package is put together. This assembly and testing is usually done with the aid of general purpose computers, since the operational hardware computer may not be available until late in full scale development. The Test Plan is used throughout this process, and results are documented in the data system. The thoroughness of this element of the software development process is critical to software reliability.

System Integration and Test

System integration and test means that the software package is inserted into the operational hardware, and complete system tests are run to insure that hardware and software are compatible and that operational requirements can be fulfilled. This element is also critical to verification of operational suitability. It occurs in the final phases of full scale development, and hopefully, only minor changes will be necessary then. The Test Plan is used to conduct these tests.

Acceptance Test

The software acceptance test is defined in the Test Plan and possibly in an overall system acceptance specification. This test is the final test which formally establishes acceptability of software products for delivery under the development or production contract.

Preparation of numerical acceptance criteria is hampered by the lack of any widely accepted measures of software R&M. Nevertheless, the Air Force Program Office must be sure that acceptance criteria are developed during the conceptual and validation phases. This is partly an in-house task using help from Government software engineers, but is also a task for the contractors under system analysis and package and unit design. Criteria are documented in the Test Plan and acceptance specifications.

Program Plan

The Program Plan outlines and explains all elements of the software development effort. It shows requirements, interfaces, organization, task breakdown, responsibilities, schedules, and the approach to solving all the software development problems so as to fulfill the requirements on schedule and within projected cost. This plan is developed mostly by the contractors during conceptual and early validation phases, but must be continuously updated.

For program planning purposes, several documents explaining all elements of the software development effort are prepared in accordance with AFR 8ØØ-14. The major documents are the program management directive (PMD), program management plan (PMP), computer resources integrated support plan (CRISP), and the computer program development plan (CPDP). The PMD is used by HQ USAF to identify the technical and managerial expertise responsible to the program manager (PM) for managing the acquisition of computer resources for systems being acquired per AFR 800-2. The PMD focuses on both the computer program development and the total system integration. The PMP is prepared by AFSC in conjunction with AFLC and the using command. Its purpose is to document the complete planning for the acquisition management of the computer resources, including computer program requirements, major project milestones, identification of required total system interfaces and configuration management concepts to be used on that particular project.

The CRISP identifies the organizational relationships and responsibilities for the management and technical support of computer resources. The CRISP is used during the development phases to identify the computer resources necessary to support the system after management responsibility has been transferred from AFSC to AFLC and the using command. During the preparation of the CRISP the Computer Resource Working Group (CRWG) is formed, with members from AFSC, AFLC and the using command. The CRWG is responsible for preparing and updating the CRISP and insuring its proper implementation in the program management responsibility transfer (PMRT) plan. The CPDP is developed generally by the contractor and is used to identify those activities needed to develop and deliver a computer software package, including all necessary support resources. The CPDP addresses such items as the development schedule, procedures for monitoring development status, the approach to developing all necessary documentation, and any required engineering practices, such as the use of structured coding.

Specifications

Specifications formally and precisely document all requirements and design decisions. They may be grouped into several categories:

* System Specification

  Defines the system requirements and the overall hardware/software system design in top level detail.

* Software Performance Specification

  Defines the software requirements, software design ground rules, selected software-dependent hardware parameters, interface identification, and overall structure of the software system. This specification goes into a second level of detail below the System Specification.

* Interface Specifications

  Defines the interface design details between software and hardware elements and between software subdivisions. It goes into a second level of detail below the preceding Software Performance Specification.

* Software Design Specification

  Defines and describes the computer programs that will meet the Software Performance Specifications in functional flow diagram detail. It also defines the programming scheme and rules which will be used by programmers to implement the functional elements in computer code.

* *Subprogram Design Document*

  Gives a detailed technical description of each subprogram including input, output, functional flow, narrative description, limitations, interfaces, and mathematical equations solved or operations performed. It also describes the tests used to check it out.

* Common Data Base Design Document

  Gives a detailed technical description of all data items used by the software system. This includes constants, variables, and tables. Details include data name, table index, purpose, dimensions, units, initial values, range of values, exact format, etc.

* Acceptance Specification

  Defines the criteria to be used in judging formal acceptability of software products under contract.

Data System

The data system also called the program support library, is designed to provide management control information and documentation discipline. It will consist of some kind of periodic reporting procedure where every programmer will be required to submit at least a weekly report on his effort. The reports might include estimates of coding completion on assigned units, numbers and classifications of errors found in debugging and testing, information shortages which hamper coding progress, specification errors discovered, manhours spent on separate units, documentation contributions, etc. Listings of each run are also collected and stored in this system. The chief programmer will have an administrative staff to compile the reports into composite summary charts, graphs and narratives for use in management reviews. The data system must also cover status of the documentation, and some very disciplined scheme must be devised to insure that documentation keeps up with changes in requirements, system design and software design.

Notice in the chart of software development elements presented above that the data system continues through production and deployment. This means that the Air Force must adopt a data system for use throughout the software life cycle. In contrast to hardware, software is relatively easy to change in the field and documentation changes must be thoroughly disciplined.

Program Review

The contractor will have frequent in-house program reviews, and the Air Force less frequent reviews. In the Air Force program reviews, overall program progress is reviewed and compared with the CPDP. Also, a technical review of the software is performed by the Program Office backed up by software specialists from Government laboratories or specialists from some other advisary organization. These Air Force reviews are formally documented with action items assigned to the Air Force or contractor for resolution by specified dates.

AFR 800-14 requires at least four formal reviews; the systems requirements review (SRR), the system design review (SDR), the preliminary design review (PDR), and the critical design review (CDR). The PDR and CDR were described earlier. The SRR is conducted after a significant portion of the system functional requirements have been established and is used to evaluate contractor responsiveness to the statement of work and the contractor's interpretation of the system requirements. The SDR is conducted prior to the beginning of preliminary design by the contractor and is used to review system documentation and assess the degree of accomplishment of the engineering management activities. It is advisable that the contractor arrange informal design reviews prior to PDR and CDR with the Air Force technical specialists, so that minor problems can be ironed out in advance to permit PDR and CDR to focus on the most important matters. The following figure illustrates the relationship of these reviews to the software development process.

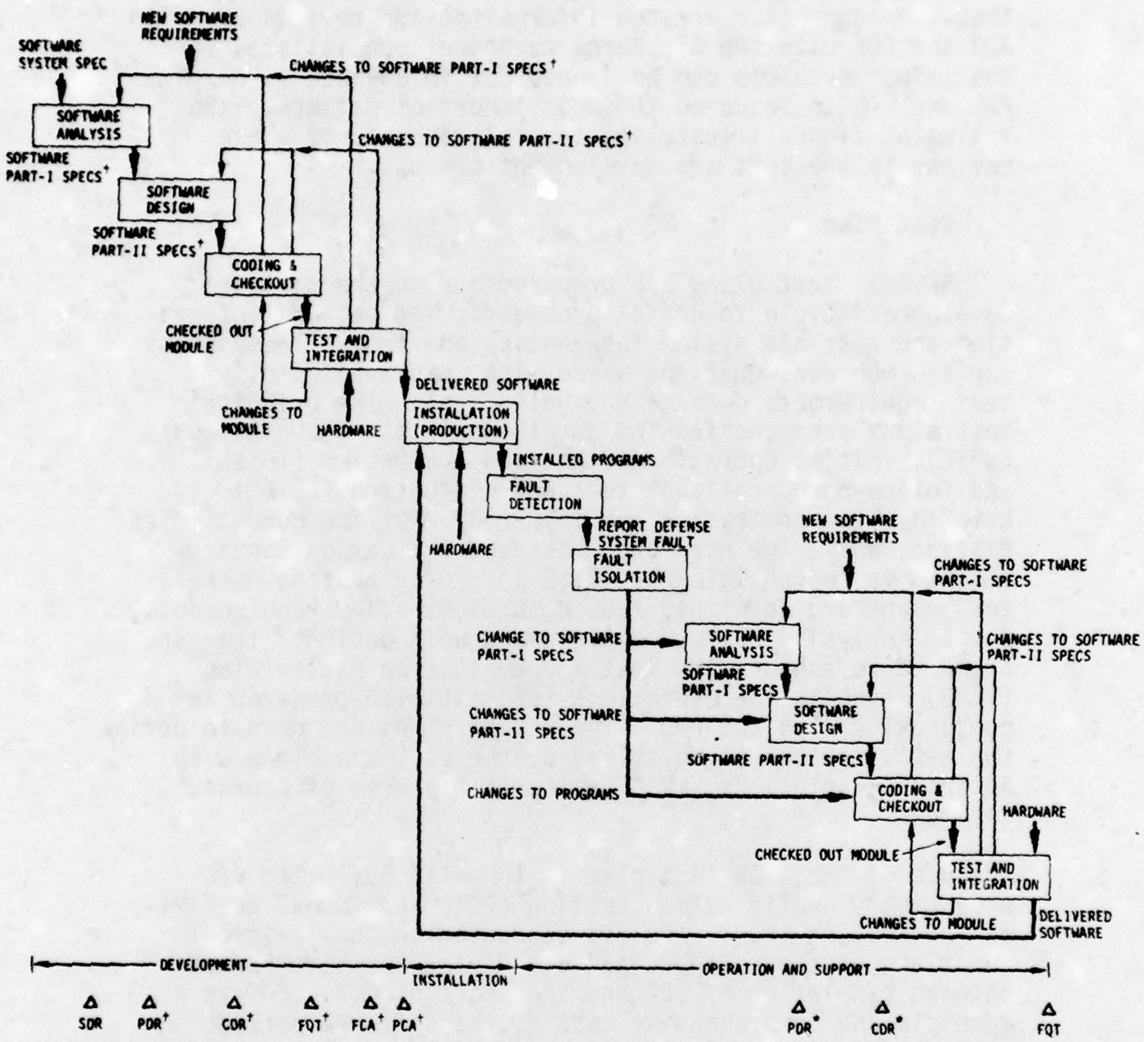
Test Plan

Several test plans are prepared during the software development cycle to define procedures for package integration and test and system integration and test. These plans explain who does what and when. They may also specify test requirements down to the unit level. The principal test plans prepared are for development test & evaluation (DT&E), initial operational test and evaluation (IOT&E) and follow-on operational test and evaluation (FOT&E). Note that the contractor and the Program Office conduct DT&E testing, while the Air Force Test and Evaluation Center (AFTEC) is responsible for IOT&E and FOT&E testing. These test plans are developed from data provided by requirements, system analysis, package design, and unit design. They are prepared to support the Test and Evaluation Master Plan (TEMP) which is the overall master test plan prepared in conjunction with the PMD. These test plans are used to define the test problems to be solved by the software along with acceptable solutions. R&M test criteria are, of course, included.

The use of the DT&E test plan is formally evaluated via preliminary qualification testing (PQT) and formal qualification testing (FQT). PQT is conducted on the "critical" functions of the software package during the time period between completion of CDR and the start of FQT. FQT is a complete and comprehensive test of the software package performed after completion of the design, and which culminates in a functional configuration audit (FCA).

Technical Manuals

While the various specifications and design documents described above document the exact structure of the software, those documents are not necessarily suitable for field use in training and operations. The technical manuals are



* MAY NOT BE FORMALLY HELD

† EACH CPCI HAS A SEPARATE SET OF SPECIFICATIONS AND SEPARATE REVIEWS

SOFTWARE DEVELOPMENT PROCESS

written using those specifications and documents, but are written by people who know how to convey that information to field personnel in the most effective way. The manuals normally include the following types:

* User's Manual
* Computer Operator's Manual
* Software Maintenance Manual
* System Maintenance Manual

All types may not be needed for a particular system. As mentioned before, the contractor's and Air Force data systems must include administrative procedures to insure that these manuals reflect all changes in specifications and design documents throughout the software life cycle.

RESOURCE REQUIREMENTS

At least 95% of the software engineering work described above will be done under contract. The brief comments to follow apply to the other 5% or less which is in-house Air Force work, but is critical to program success.

Technical Manpower

The Air Force Program Manager responsible for a system which includes a major software subsystem, should have a software specialist assigned to his staff. At the very least, he should make arrangements with one of the Government R&D organizations which specialize in software work to provide engineering support for preparation of statements of work, requirements and specifications, and to review design and test results. Software groups are located in the *Information Sciences Division of Rome Air Development Center*, in the Air Force Avionics Laboratory, and in the Directorate of Information Systems Technology at Electronic Systems Division. Of course, the captive corporations such as Aerospace Corporation and MITRE Corporation have software people, and other corporate groups could be employed as advisors assuming no conflict of commercial interest is present.

Reference Publications

There are numerous commercial books and journals which describe all aspects of software engineering. The Program Office library should include some recent publications on the implementation of modern programming practices on large systems, such as the RADC Structure Programming Series, which any software engineer can locate through standard reference sources such as the National Technical Information Service.

The following documents, among many others, would be useful:

* Record, 1975 International Conference on Reliable Software, Los Angeles CA, 21-23 Apr 75, published by the Institute of Electrical and Electronic Engineers, Inc., 345 East 47th St., New York, NY 10017.

* Record, Software Quality and Assurance Workshop, San Diego CA, 15-17 Nov 78, published by the Association for Computing Machinery, P.O. Box 1205, Church Street Station, New York, NY 10249.

* "Structured Programming Series," IBM Corp., RADC-TR-74-300, Vols. I - XV, available through the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

* "Software Reliability Study," TRW Systems Group, RADC-TR-76-238, Aug 76, also available through NTIS. (A030798)

* Record, Second Software Life Cycle Management Workshop, Atlanta, GA, 21-22 Aug 78, available through IEEE.

In addition the Program Office library should include:

* AFR 800-14, Vols. I & II, "Management of Computer Resources in Systems," Sep 75.

* AFSCP 800-7, "Configuration Management," Dec 77.

* AFSCR 74-1, "Quality Assurance Program," Nov 78.

Note: RADC-TR-74-300, Vols I - VI (A016771)(A018046)(A013255)(A015794) (A003339)(A007796) Vol VII & VII Addendum (A008639)(A016414) Vols VIII - XV (A016415)(A008640)(A008861)(A016416)(A026947) (A020858)(A015795)(A016668)

* MIL-S-52779, "Software Quality Assurance Program Requirements."

* MIL-STD-1521, "Technical Reviews and Audits for Systems, Equipment, and Computer Programs."

* MIL-STD-483, "Configuration Management Procedures for Systems, Equipment, Munitions, and Computer Programs."

Facilities

The Air Force Program Office does not need any special facilities for software engineering management. The contractor, of course, will need access to data processing facilities adequate to handle the scope of his project.

SYNOPSIS

Software reliability and maintainability have begun to develop into an organized body of knowledge and ideas in only the past several years. There is no military standard focused on this area, but an Air Force manual is being written that may adequately encompass software R&M. Software costs in systems development are snowballing, because of the expanding use of digital technology and system data processing computers.

The most critical elements in development of a large software system to achieve adequate R&M are the use of logically developed and carefully controlled organization for both the problems being solved and the people doing the computer programming, the use of a restrictive set of programming rules to prevent the growth of a computation logic maze, development of thorough test procedures, and special emphasis on documentation and overall program management.

The Air Force Program Office needs to arrange for expert consultants to help plan and monitor software development.

APPENDIX A

RELIABILITY AND MAINTAINABILITY TRAINING SOURCES

There are a variety of means for obtaining R&M training ranging from Master's Degree programs to lectures sponsored by local R&M professional groups. These are described by categories below:

MASTER's DEGREE PROGRAMS

Starting September 1979, the Air Force Institute of Technology will begin a program leading to an MS in Electrical Engineering, Reliability option. Further information can be obtained from:

AFIT/ENG
ATTN: Dr. T. Regulinski
Wright-Patterson AFB OH 45433

Another program leading to an MS degree with a Reliability Engineering option is offered by the University of Arizona. Information may be obtained from:

Dr. Dimitri Kececioglu
Aerospace & Mechanical Engineering Department
Building #16
The University of Arizona
Tuscon, Arizona 85721

SHORT COURSES IN R&M

AFIT offers two short courses in R&M. Reliability QMT 372 is a 15-day course designed to provide an understanding of R&M principles and basic skills. System Reliability/Maintainability QMT 576 is a 50-day graduate level course designed to provide the attendee with the ability to carry out the functions of a reliability/maintainability

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engineer. Information on these may be obtained from:

AFIT/LS
Wright-Patterson AFB OH 45433

Other courses are offered by various sources. The R&M trainee will find training courses listed in R&M newsletters and, if he joins an R&M professional society, will receive many course announcements by direct direct mail. A listing of agencies who have sponsored recent R&M courses are as follows:

The Reliability Analysis Center
RADC/RBRAC
Griffiss AFB NY 13441
(Sponsors a four day training course, "Reliability Design Guidelines", held in various locations throughout the country).

Arizona State University
Reliability Engineering and Management Institute
Dr. Dimitri Kececioglu, Director
Building #16
The University of Arizona
Tuscon, Arizona 85721
(Periodic five-day courses at Tuscon)

Short Course Program Office
UCLA Extension
10995 LeConte Ave
Los Angeles CA 90024
(Various five-day R&M courses at UCLA)

ARINC Research Corporation
2551 Riva Road
Annapolis MD 21401
(R&M seminars of various lengths and locations)

University of Wisconsin - Extension
Dept of Engineering
432 North Lake Street
Madison WI 53706

Office of Business Extension
215 Business Building
Oklahoma State University
Stillwater OK 74074

University College of Syracuse University
610 East Fayette Street
Syracuse NY 13202

Stat-a-Matrix Institute
P.O. Box 2021
Menlo Park Station
Edison NJ 08817

Continuing Engineering Education
George Washington University
Wash DC 20052
(Various courses in Washington, DC)

TUSTIN Institute of Technology
22 E. Los Olivos Street
Santa Barbara CA 93105
(Short courses on vibration, shock and noise effects, measurement and design guidance)

R&M SYMPOSIUMS

The Annual Reliability and Maintainability Symposium is a three-day conference held each year in January, alternating in location between the east and west coasts. It is jointly sponsored by all the R&M professional societies and its technical program includes tutorial sessions for R&M trainees. Every paper presented (75 at the 1979 R&M Symposium) is printed in the proceedings. A copy is given to each attendee and the IEEE Reliability Society also sends a copy to each of its members. Past conference proceedings are available at $18.00 a copy from:

Order Department
IEEE Service Center
445 Hoes Lane
Piscataway NJ 08854

Information on the symposium may be obtained from any of the R&M professional societies listed under R&M Professional Societies below.

The Institute of Environmental Sciences sponsors seminars on R&M topics such as testing, and offers a variety of seminar proceedings. A listing of available proceedings and prices, as well as information of future seminars may be obtained from the Institute, at the address listed below under R&M Professional Societies.

Other annual national symposiums include the Reliability Physics Symposium sponsored by the IEEE Reliability Society, and the Product Liability Conference. Information on the latter may be obtained from:

Richard M. Jacobs, PE
23 Rumson Road
Livingston NJ 07039

There are also various national symposiums on R&M specialty areas, such as Software Reliability, sponsored by the R&M professional societies, Industrial concerns and Academic Institutions either annually or on an ad-hoc basis.

R&M professional societies also sponsor local symposiums, such as the Annual Spring Reliability Seminar in the Boston area, and local meetings featuring topics of current interest. One need not belong to the sponsoring society to attend. The chief source of information about these affairs are the various society newsletters and local announcements.

PERIODICALS

R&M technical papers are published in the IEEE Transactions on Reliability, which also serves as the Journal of the Electronics Division of the American Society for Quality Control. Copies are provided to members of these organizations and are available in many technical libraries. Copies may also be purchased from the IEEE.

Evaluation Engineering Magazine also publishes R&M articles. Subscriptions are available from:

A. Verner Nelson Associates
The Nelson Building
1282 Old Skokie Road
Highland Park IL 60035

The RAC Newsletter provides information on the operations of the Reliability Analysis Center, RADC R&M activities, R&M symposiums and conferences, and general items of R&M interest. Subscriptions are free from:

RADC/RBRAC
Griffiss AFB NY 13441

Finally, each R&M professional society provides a newsletter to its members. Local chapters often provide their own newsletter listing all local conferences of interest.

R&M PROFESSIONAL SOCIETIES

As indicated above, membership in an R&M society can be a fruitful source of information. The major R&M professional societies are:

The IEEE Reliability Society
Institute of Electrical and Electronic Engineers
345 E. 47th Street
New York City, NY 10017

The Reliability Division and the Electronics Division
American Society for Quality Control
161 West Wisconsin Ave
Milwaukee WI 53203

The Institute of Environmental Sciences
940 East Northwest Highway
Mount Prospect IL 60056

The Society of Logistics Engineers
3322 South Memorial Parkway, Suite 2
Huntsville AL 35801

The Society of Reliability Engineers
P.O. Box T31
Crum Lynne PA 19022

The System Safety Society
Box A
Newport Beach CA 92663

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Rome Air Development Center

RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.