R&M 2000
The Engineering Connection

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Reader Aids —
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Special math needed for explanation: None
Special math needed to use results: None
Results useful to: Planners, managers, design engineers, quality engineers, manufacturers, R&M engineers

Abstract — This paper introduces 5 principles and 21 associated building blocks representative of successful approaches used within industry to produce reliable and maintainable systems. Several building blocks are singled out for discussion because of recent initiatives undertaken by the Air Force. These topics include modularity, technician transparency, simplification, computer-aided tools, and environmental stress screening. The 21 building blocks provide a strong foundation upon which to build weapon systems with increased combat capability. The requirement to maintain the designed-in reliability and maintainability (R&M) attributes through careful attention to quality control issues also receives emphasis. Those factors which most strongly influence variability in the desired system performance must be identified. Finally, the paper emphasizes the crucial role of education in truly integrating the design aspects of R&M into engineering disciplines.

1. INTRODUCTION

Lieutenant General Leo Marquez [1] describes the four trends that affect combat forces and has demonstrated the potential for generating quantum leaps in combat capability through precise attention to system reliability and maintainability (R&M). With these observations design engineers, managers, corporations, and the Department of Defense (DOD) must explicitly recognize and act on the well known fact: reliability and maintainability are inherent attributes of a system. As inherent attributes, R&M characteristics are established in the design phase of system development. Once the design becomes fixed, subsequent testing and production will not increase R&M unless a design change is precipitated. Unfortunately, in the past R&M has not been considered coequal with cost, schedule, and performance parameters and as a result has not always received the necessary emphasis.

The Air Force now recognizes that a resource-constrained environment dictates that R&M as well as its corollary, quality, must attain coequal status with cost, schedule, and performance. With this elevation R, M, and Q, as crucial design parameters, require up-front integration into the design process in an orderly, disciplined fashion. Attainment of this goal requires the interactive efforts of design, system, logistics, and manufacturing engineers. These people are in the best possible position to apply basic principles leading to R, M, and Q enhancement.

The requirements of the manufacturing process should be considered during the design phase. In this way quality assurance techniques, which minimize the degradation of the inherent R&M during production, will receive proper attention.

Fig. 1. The 21 Building Blocks of Reliable and Maintainable Systems

In my interactions with both industry and DOD organizations, I’ve noted certain recurring practices which lead to systems which break infrequently and are easy to fix. This paper details some of the more important considerations which the total engineering team must consider in designing weapon systems. Many of the approaches are well known to the reading audience. My intent is to present those fundamental approaches gleaned from across industry, and which now should be uniformly adhered to by all of industry.

The overall structure leads to enhanced weapon system R&M through 5 R&M Principles and 21 Building Blocks. Figure 1 shows that the structure flows from and is driven by management involvement. In order for management to appreciate the emphasis the Air Force places upon R&M, the motivation principle is used; it consists of three building blocks: source selection, incentives and warranties, and performance based programs. Then along the timeline of system development and employment, there are the principles of: needs and requirements, design and growth, and maturation and preservation. It is within these
principles where the engineers exercise their discipline. In this paper I discuss just a few of the building blocks under each principle. The Air Force is preparing a guidebook which will discuss at length each of the building blocks.

2. MOTIVATION — Source selection

The source selection process constitutes the strongest motivating factor to the contractor competing for a contract award. Historically contractors received ratings and rank orderings based upon cost, schedule, and performance parameters. Recently a revolutionary change has been made to the source selection, driven by a fundamental truth expressed by General Marquez that, "... once a system is fielded there are limited options to improve R&M" [1]. Today if the source selection is for a new design or system, then reliability, maintainability, and producibility shall be singled out as a specific evaluation criteria. In the source selection process this criteria grouping is the first listed in the highest ranked area as basis for an award.

General Marquez, Deputy Chief of Staff for Logistics and Engineering, discusses [1] the rationale for this change and the implications for the system engineering design process. A few examples emphasize the absolute dedication to this new approach. The first example deals with a major program which, by definition, involves at least 200 million dollars for R&D and/or 1 billion dollars for procurement.

The Air Force recently selected the Northrop and Lockheed Corporations as primes to build and fly two prototype ATF's. The Northrop and Lockheed groups will build two planes which will be flown starting in 1989. Edward C. Aldridge, Secretary of the Air Force, stated [2]:

"Our fly before buy prototype approach, combined with tough-minded streamlined management, continued vigorous competition with an emphasis on reliability and maintainability, will make the ATF program a model for future weapons systems acquisitions."

Further, Thomas E. Cooper, Air Force Assistant Secretary for Research, Development, and Logistics, indicated the importance R&M played in the selection when he stated [3]:

"... the Air Force chose the best two designs and the priority given to R&M kept two of the losing companies from being more competitive."

In the category of major programs the Air Force has thrown down the gauntlet; R&M has become and henceforth will be a primary decision factor in the selection of competing engineering designs.

On the other side of the coin, one should not fall into the trap of concluding that the dollar size of a program determines the degree of emphasis on R&M in source selection. Recent decisions on four non-major programs managed by the Electronics Systems Division located at Hanscom Field emphasize this point. I will not specifically name the programs, only state the results. In all four cases, the winning corporations had excellent R&M technical approaches. Only one out of the four winning corporations was the low bidder, and they had the best technical proposal.

The conclusion to be drawn from the major and non-major program source selections is inescapable. Corporations which fully and aggressively integrate the goals of the R&M 2000 initiative [4] into their proposed designs will maintain their competitiveness. Those who don't — won't.

3. SPECIFYING THE CUSTOMER'S NEEDS AND REQUIREMENTS

3.1 Technician Transparency

Requirements for technician transparency flow from demographic changes in the available manpower pool, the drive to eliminate intermediate test shops, and improve maintenance actions at the combat unit level. Systems must be designed to make them transparent to the technician, as to allow technicians to easily, accurately, and repeatedly diagnose and repair a wide variety of system/subsystem failures. This approach will help reduce the manpower and multiplicities of specialties required to service increasingly more capable systems. By incorporating technician transparency into system design, the average technician will be able to service several subsystems. The requirement for transparency will be stated in the operating commands statement of need (SON).

At present electronics technology offers the potential for implementing this approach. Engineers must consider designing future electronic systems with built-in-test & fault-isolation-test to the shop replaceable unit (SRU) or the line replaceable module (LRM). This concept is called repeatable fault isolation. During peacetime operations the system design will facilitate computerized maintenance analysis by generating automated signal outputs. However, for combat conditions the maintainer requires very simple non-volatile, visual fault indicators using "white for failed" and "black for functioning". With this approach the Air Force can reduce base level logistics support while maintaining combat capability.

3.2 Simplification

Designing for system simplicity should be a given for all design engineers. Intuitively, the fewer the parts and interconnections, the smaller the propensity for system failure. However, a disciplined approach to achieve simplicity in aerospace weapons design has, until now, not received industry attention. When industry receives proper
motivation, the innovative improvements are impressive. The cleanness of design now seen in the LANTIRN system and new jet engines now being tested testify to industry's capabilities. Applying this precept will result in increased reliability, ease of maintenance accessibility, and decreased system costs. Why decreased costs? The system will be simpler to build, simpler to produce, simpler to upgrade, and simpler to support; the money saved can buy combat capability.

Some basic guidelines for simplification include:

- minimize the number of parts and interconnections
- minimize the number and simplify the design of support tools
- make all equipment items & test points accessible.

If the overall design mandates inaccessibility of some item, then that item must be highly reliable. In general the best system is the simplest system that supports technician transparency and on-equipment repeatable fault isolation without external test equipment.

In the final analysis a simpler system builds higher reliability while appreciably increasing the efficiency of that two stripe described by General Piatoski, Vice Chief of Staff of the Air Force, in his paper on Air Force R&M Policy Letters [5]. Increased productivity of the maintainers means faster turn arounds, higher sortie rates, more systems on alert, and hence increased combat capability.

3.3 Modularity

Ample precedents exist which illustrate the utility of designing subsystems to be self-contained units. This approach is now taught and used regularly in computer software design, reducing the chance for logic errors and allowing for portability between routines. Modularity of jet engines, such as designed by General Electric and Pratt & Whitney, has allowed the development of families of engines for a wide range of environments and functions. Although modularity is nothing more than designing a self-contained unit according to its function, it provides several benefits. Because specific functions reside in one location, system updates are much easier. Anyone who has ever dealt with spaghetti software code appreciates this fact.

The same parallel exists in updating hardware. In particular when dealing with electronics, engineers should move toward sets of generic modules (data processors, bulk memories, bus controllers, etc). Complementing this development, an architecture must be designed which includes interfaces, packaging conventions, electrical parameters, and protocols to which all connected modules must comply. By this approach new modular technologies and designs can be introduced while maintaining the physical and interface architecture. Programs such as PAVE PILLAR, the Common Signal Processor, and the High Speed Data Bus are embracing this approach with great promise [6].

Modularity supports repeatable fault isolation, decreases development costs and effort, and reduces spares requirements. Good modular design for electronic modules segments the circuitry into easily tested portions, while concurrently setting aside a portion of the on-module resources for Built In Test & Fault Isolation Test (BIT/FIT) control. The modular design should allow for recording fault isolation detection data to assist in post-mission failure analysis.

Lieutenant General Bernard Randolph, Military Deputy for Acquisition, Office of the Assistant Secretary of the Air Force (Acquisition) discusses [7] the Air Force's ongoing programs to reap the rewards of modularity. In particular, for the F-15 VHSIC MIL-STD-1750A computer, he states:

"The new computer will also be designed to make technology increases in the years to come by simply swapping out modules instead of redesigning a whole new computer."

As these generic modular components are developed, the result will be a reduction in the number of item types to be procured and spared while increasing production volume; all of which will reduce final system costs.

Modularity also assists in realizing reliability growth as system failure mechanisms become more readily apparent. In general the contractor would partition a system into functional modules which then define the software or hardware configuration. During reliability growth testing in concert with Test Analysis and Fix (TAAF), modularity will accelerate redesign efforts and replacement of hardware supporting lagging functions. Modularity will also assist the goal of graceful degradation, as modularly integrated systems can be designed which provide on line sparing for all crucial functions. This approach results in higher reliability by diffusing redundancy throughout a small fraction of all modules. For example, sensor processing and electronic warfare circuitry could provide backup for critical capabilities lost to failures or combat damage. Selected replacement processors would replace failed and deactivated units after being loaded with instructions from a central memory. This process would proceed automatically without the operator's explicit intervention or even awareness [6].

4. DESIGN AND GROWTH FOR R&M
A Formula for Success (What, Why, When, How)

4.1 Analysis

R&M analysis has one overriding goal: the reduction of risk. There are many techniques for evaluating and reducing the risk associated with system development, operation, reliability, maintainability, and safety. These approaches have been extensively discussed in the literature and for the most part are being applied. Some
approaches which are tools to be used in the engineering design process are:

- Stress/strength analysis
- Fault tree analysis (FTA)
- Criticality analysis
- Thermal stress analysis
- Sneak circuit analysis
- Worst case tolerance
- Logistic support analysis (LSA)

The critical point is that all design engineers must be aware of and in many case have a working knowledge of these approaches. We cannot afford the luxury of applying these and other analyses at the tail end of the design process. For example thermal stress analysis provides absolutely no value when applied solely toward the end of the design process. The logic implied by thermal stress analysis should be invoked as soon as the system or subsystem functional configuration takes shape.

Increasing availability of software packages on both personal computers and mainframes along with RAMCAD will make these processes accessible for real-time integration into the design process. Software packages for both PC and miniframe applications have appeared, allowing for stress/strength analysis, thermal analysis, VHSIC sneak circuit analysis, etc. Reliability growth and TAAF computerized approaches will be used in conjunction with the analysis tools. The end result will be the ability to compress the time required for design and full scale engineering development.

4.2 Computer Aided Tools

With today’s emerging technologies, the pressure to rapidly produce, and the complexity of Air Force weapon systems, industry must carefully consider automation of the design and manufacturing process. A 1984 National Academy of Sciences study indicated that companies using Computer Aided Design & Computer Aided Manufacturing (CAD/CAM) reduced engineering design costs by 15 to 30 percent [8]. Concurrently the National Academy estimates that the adjunct to CAD/CAM, Computer Aided Engineering (CAE) increases productivity by 30 times and will be used in 90 percent of American designs by 1990.

The final step, Computer Integrated Manufacturing (CIM), brings it all together and is already being employed by some sectors of industry with good results. Allen-Bradley represents a case in point [9]. Their futuristic assembly line, which started up in 1985, produces industrial controls. The line has the capability to make different versions of a product at mass production speeds in lots as small as a single unit. With CIM, Allen Bradley entered a highly competitive world market and established itself as a leader. The company decided against using cheap offshore labor as there were hidden costs, and adopted the long term approach. The secret to success hinged on an innovative application of bar codes which provided necessary assembly information. All operations are fully automated using an IBM mainframe and require only four technicians to monitor the process. The bottom line is that Allen-Bradley became number one in the markets it serves [9].

In a corollary to the automotive process, Allen Bradley significantly enhanced the quality of its product — which brings me to R&M and CAD/CAE. As discussed by Major General M. T. Smith, AFSC [10], R&M as design attributes must also be part of the CAD/CAE process to provide the Air Force with the highest quality at time zero. The Air Force has demonstrated the value of RAMCAD in a Ground Launch Cruise Missile (GLCM) turbine system redesign. The turbine system was a Government Furnished Equipment (GFE) item which was packaged for the GLCM in a sniper-proof enclosure. Unfortunately during operation, the internal temperature reached levels which resulted in an MTBF of 50 hours, and the steel enclosure forced a Mean Time To Repair of 7 hours. Using computerized accessibility and thermal design analysis, 21 R&M design changes increased the MTBF to 500 hours and significantly reduced the MTTR.

Both the National Security Industrial Association and the Institute for Defense Analyses recognize the need to integrate R&M with CAE. A national consortium has been formed to accelerate the development and use of RAMCAD ensuring wide application by 1990. The resulting RAMCAD /CAE environment will allow the design engineer to assess alternate designs rapidly for R&M and support issues in consonance with cost, schedule, and performance considerations. With the speed-up in analysis afforded by paperless transfer of databases, design engineers can quickly gauge the impact of these design trade-offs on the R&M 2000 weapon system goals.

4.3 Growth Curves

In new-system development the Air Force considers reliability development and growth testing (RDGT) to be an essential part of system development. By definition, RDGT is planned improvement in equipment reliability during development through redesign efforts that eliminate failure sources discovered during the analysis of test results. Depending upon the system, an RDGT plan may be relatively expensive, but as MacDiarmid & Morris [11] point out, the customer typically has only four options upon discovery of non-compliance:

- Accept the deficient hardware
- Require correction of defects
- Contract to another supplier
- Cancel the program.

None of these alternatives is acceptable and hence the Air Force requires RDGT. By doing so the Air Force guarantees
that it knows the system reliability throughout the engineering development phase and can redirect resources if needed. The planner should establish a budgeted growth curve at the start of development, which will form the basis for program decisions aimed at achieving the desired reliability growth. RDGT, in concert with TAFF, forms the foundation for smart engineering to insure developmental advances in R&M. The models and mechanics of RDGT are amply discussed in many sources. An excellent overview with additional references can be found in MacDiarmid & Morris [11].

5. MATURATION AND PRESERVATION
(R&M 2000 Environmental Stress Screening)

As pointed out by General Piotrowski [5], the Air Force is requiring R&M 2000 Environmental Stress Screening. The cost benefit of applying ESS early in the production process has been well documented. For example, Fiorentino & Saari [12] illustrated the significant increases in repair cost with repair at the part level all the way to field replacement. Specifically they gave multiples of 30, 250, 500, and 5000 as we repaired at the assembly level, unit level, system level, and field level, respectively. In general, cost savings from ESS accrue from at least two sources: repair cost avoidance and (although not a major objective of ESS) design changes improving the overall reliability resulting in lower rework and warranty costs [13]. To be fully effective the production engineer and manager must integrate ESS into the manufacturing process. As the system grows, ESS should be applied incrementally from component to the final subassembly. At different stages of the assembly process, latent defects may be introduced requiring different screening equipment configurations to perform the temperature and quasi random vibration screens. The effectiveness of these screens must be carefully analyzed to insure that they are performing their function. Care must be taken to avoid either under or overstressing the elements of the system [12, 13]. The question of screen effectiveness includes both cost effectiveness implications and the ability to determine how well the screen reduces the system infant mortality [14]. Given the essential quality implications and the potential cost benefits of an effective ESS program, a competitive, prudent manufacturer will integrate ESS into the production process.

6. MANUFACTURING QUALITY
(If You’ve Got It, Don’t Lose It)

6.1 The resurgent quality ethic

General Piotrowski, former Vice Chief of Staff of the Air Force and currently Commander United States Space Command, emphasized the revitalization of American industry which is taking place with the resurgence in the quality ethic in his speech to the Second NASA Symposium on Quality and Productivity [15]. The Air Force as a customer has a direct stake in this process and must have military equipment as good as seen in the commercial market place, certainly not less. The Air Force has not always asked for such quality in clear terms. In fact, as stated in General Piotrowski’s recent speech, “... the disincentives were more apparent: rigid adherence to specifications, micro-managing project offices, and lack of reward for those companies who incorporated extra reliability, maintainability and producibility into their products. As a result contracts were going to lowest bidders without carefully considering performance over time, ease of maintenance, or economic yield off the factory floor.” [15]

The Air Force has set a course to change this state of affairs and is making the quality message crystal clear. The Air Force will emphasize quality in the source selection process, and expects to see quality designed in and built in from the inception of a system through its production and deployment. Finally the Air Force will buy off-the-shelf items, where it makes sense to do so and when the commercial market place offers the needed high quality.

6.2 All factors are not equal

The variability of product performance can be traced to three effects: variability due to environmental factors, variability due to internal changes of the product over time, and variability due to manufacturing deviations. The goal of quality engineering is to reduce the deviation of product functional characteristics from a target value. To this end, efforts should be expended in both the design process and manufacturing process to identify those factors which most strongly influence product variability.

Specifically in the United States there has been a tendency to use tolerance levels as a means to cull out units which do not sufficiently conform to acceptance standards. This approach insures that unacceptable units do not reach the consumer. However, hidden costs accrue due to scrap and rework costs. A more reasonable approach involves identifying those factors which have the greatest influence on the variability of product characteristics. Reduction in the variability of these factors and/or making the design so that the product performance is relatively insensitive to variations in underlying factors, can catch quality imperfections up front in the design of the system and its manufacturing process. This approach can use experimental design techniques [16] which have been used in Japan for some time, and are receiving interest in the USA. Attention to this approach, along with statistical process control, will help realize constant improvements in the quality of Air Force weapon systems.

7. EDUCATION AND INDUSTRY
A WINNING COMBINATION

7.1 Research and Engineering Scholar Program

In this paper I have stressed the need to attack deficient product $R$, $M$, and $Q$ at the point of greatest return:
during the design process. During the process of institutionalizing \( R, M, \) and \( Q, \) the Air Force has noticed that the majority of US academic institutions do not include these attributes in normal engineering curricula. This circumstance arises because the vast majority of US college and university engineering faculty do not receive coursework containing reliability design. Hence, these topics do not appear in the courses they teach.

The Air Force has developed an R&M Research and Engineering Scholar Program designed by Dr. T. Reguliniski, Senior Associate Editor of this Transactions and hosted by the USAF R&M Center of Excellence at the Air Force Institute of Technology during the mid-summer of 1987. This program presented generic R&M engineering design concepts to a select group of 40 professors from leading engineering institutions. The object of the program was integration of the R&M concepts by the professors into their own design-course materials. Integration by the professor develops a sense of idea ownership and results in optimal integration of the generic reliability concepts. The expectation is that the professors who teach design courses will impart a strong awareness of R&M considerations in the design process. Such institutionalization of R&M concepts should yield students cognizant of the need to design systems whose performance characteristics do not degrade over time and are easy to maintain if failures do occur. The Air Force hopes to generate additional research into the Unified Life Cycle Engineering approach as discussed by Major General M. T. Smith [10].

7.2 USAF R&M Academic Center of Excellence at AFIT

Within the United States, productivity and quality centers can be found at several academic institutions providing a forum to surface and spread topical productivity and quality issues. A system of R&M academic centers could perform much the same function for R&M, as engineering design for R&M becomes engrained in the engineering design disciplines. Recently such a center was established at the Air Force Institute of Technology at Wright-Patterson AFB. Because R&M actually embraces many disciplines, the Center's core consists of resident faculty and research facilities both in the School of Engineering, School of Systems and Logistics, and the School of Civil Engineering. The institute has implemented a post Master's level Professional Specialized Education program in R&M, one academic quarter in length and aimed at approximately 30 selected AFIT graduate engineers. Four new faculty are being added with R&M engineering design expertise. These four, in conjunction with professors already on the faculty in the various schools, will form the Center's nucleus. The added faculty, along with improvement in laboratory facilities, will allow AFIT to take a strong lead in R&M through engineering design.

Other institutions, such as the University of Maryland, have also formed R&M Centers of Excellence. The University of Maryland has established a curriculum which leads to a Master's degree in reliability engineering and the faculty performs research in R&M related areas. The University of Arizona has a strong mechanical reliability program. A good initiative would be to form additional academic R&M centers at engineering institutions. From the perspective of international competition in the world market place and from a national defense perspective, it is imperative that our academic institutions integrate performance over time into their engineering curricula.

SUMMARY

The Air Force has pushed the performance of weapon systems to new plateaus. However, the successful operation of modern Air Force systems in today's global environment depends upon systems that break infrequently and require minimal support. R&M 2000 was instituted to realize this requirement. As General Randolph stated:

"The Air Force cannot afford to trade R&M as a matter of course to obtain a little more performance or to improve the schedule or to get marginal gains in cost. We pay in the long run when we do that." [7]

The Air Force is convinced that the road to success depends upon R&M through engineering design. The manager, developer, and engineer must ensure that R&M technology advances along with operational performance, must relate those advances to user needs, must ensure that R&M enters the design, and must maintain it during manufacturing.

I have highlighted just a few of the 21 building blocks which will lead to weapon systems with enhanced combat capability. Attention to these crucial elements, coupled with quality enhancements through identification of important production factors, will generate the necessary leverage to meet the challenges of the 21st century.

REFERENCES


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