AFHRL-TP-89-28

AIR FORCE

HUMAN RESOURCES

AD-A221 771

FILE COPY

DESIGN FOR MAINTAINABILITY: WHAT MILITARY STANDARDS DO AND DON'T SAY

Donald R. Loose, Capt, USAF

Air Force Acquisition Logistics Division
Wright-Patterson Air Force Base, Ohio 45433-5000

LOGISTICS AND HUMAN FACTORS DIVISION
Wright-Patterson Air Force Base, Ohio 45433-6503

May 1990
Interim Technical Paper for Period April 1986 - May 1989

Approved for public release; distribution is unlimited.

LABORATORY

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235-5601

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The Public Affairs Office has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This paper has been reviewed and is approved for publication.

BERTRAM W. CREAM, Technical Director
Logistics and Human Factors Division

JAMES C. CLARK, Colonel, USAF
Chief, Logistics and Human Factors Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
May 1990

3. REPORT TYPE AND DATES COVERED
Interim - April 1986 - May 1989

4. TITLE AND SUBTITLE
Design for Maintainability: What Military Standards Do and Don't Say

5. FUNDING NUMBERS
PE - 62205F
PR - 1710
TA - 00
WU - 18

6. AUTHOR(S)
Donald R. Loose

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Acquisition Logistics Division
Wright-Patterson Air Force Base, Ohio 45433-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Logistics and Human Factors Division
Air Force Human Resources Laboratory
Wright-Patterson Air Force Base, Ohio 45433-6503

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFHRL-TP-89-28

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

→This literature survey consolidates and evaluates already existing Department of Defense guidance on Design-For-Maintainability (DFM), which is typically used for Air Force weapon system acquistion. DFM expertise is scattered among references from several engineering and logistics disciplines. Application in the acquisition process therefore tends to be equally fragmented.

Consolidation of this information serves two functions. First, the information will be more readily accessed and applied. Second, the information may then be analyzed in total to determine which parts of DFM expertise are still weak within the Air Force; these areas should become the focus of the acquisition logistics research community.

14. SUBJECT TERMS
human engineering
human factors engineering
maintainability
manpower
standards
training

15. NUMBER OF PAGES
99

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-0'-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

AFHRL Technical Paper 89-28 May 1990

DESIGN FOR MAINTAINABILITY: WHAT MILITARY STANDARDS DO AND DON'T SAY

Donald R. Loose, Capt, USAF

Air Force Acquisition Logistics Division
Wright-Patterson Air Force Base, Ohio 45433-5000

LOGISTICS AND HUMAN FACTORS DIVISION
Wright-Patterson Air Force Base, Ohio 45433-6503

Reviewed by

Bertram W. Cream, Technical Director
Logistics and Human Factors Division

Submitted for publication by

James C. Clark, Colonel, USAF
Chief, Logistics and Human Factors Division

This publication is primarily a working paper. It is published solely to document work performed.

SUMMARY

This technical paper summarizes and analyzes the Design-For-Maintainability (DFM) guidance contained within Department of Defense (DOD) references typically used for Air Force weapon system acquisition.

I surveyed diverse military standards (MIL-STD) and Air Force Systems Command design handbooks (AFSC DH), and included all information I judged to be DFM-relevant in the Appendix. I had to exclude the two largest references due to size -- MIL-STD-1472, Section 5-9 (24 pages), and AFSC DH 1-3, Section 2G (39 pages) -- but I included their tables of contents. Both of these large references address human factors engineering. The appendix thus consolidates the aggregate Air Force DFM expertise under one cover for easy access and analysis.

The main body of the paper provides an overview of the Appendix and assesses how completely this data base addresses typical systems engineering requirements. One chapter each addresses the following questions:

1. What approaches, tools, or guidelines do military standards offer the system designer to:

   * design a new system from the beginning to meet maintainability specifications, or

   * fix a previous design which fails its maintainability specifications?

2. What approaches, tools, or guidelines do military standards offer the system evaluator to:

   * quantitatively estimate the effects of system design on system maintainability,

   * predict the effects of system design and its resultant maintainability on manpower and training requirements, and

   * quantitatively estimate the effects of system design and maintainability on system readiness and life cycle costs?

3. How does maintainability formally relate to human engineering?

I offer suggestions as to where and how this information should be improved. A summary of my findings appears on pages E-6 to E-8.

PREFACE

"Reliability and Maintainability" (R&M) is the chief focus of acquisition logistics to improve readiness. "Manpower, Personnel, and Training" (MPT - a consolidation of the integrated logistics support elements of "Manpower & Personnel" and "Training & Training Equipment") is the Air Force's largest life cycle cost driver. Design For Maintainability (DFM) determines the former and predominantly drives requirements for the latter.

Any activity in logistics systems technology transition should therefore start with an understanding of the current DFM state-of-the-art and its relationship to R&M and MPT. I undertook this project to support my assignment as technology transition manager between the Air Force Human Resources Laboratory/Logistics and Human Factors Division (AFHRL/LR) and the Air Force's Acquisition Logistics Division (ALD).

The size of this report may intimidate the reader. It needn't. Over half its volume is the appendix, intended to be used as a reference as needed. The report body is accessible if read hierarchically:

* First, read the introduction, references, conclusions, and recommendations (pages E-1 to E-8) as an executive summary.

* Second, read the individual chapter introductions and summaries (pages 1-1, 1-11, 2-1, 2-17, 3-1, & 3-4) for more in-depth findings.

* Third, read the 10- and 12-pitch text, skipping the quotes in 15-pitch to follow the flow of logic.

* Finally, include the 15-pitch quotes to verify the report's assertions.

ACKNOWLEDGEMENTS: Aeronautical Systems Division (ASD/ENES) provided camera-ready copies of the reprinted design subnotes. Ray Erickson at ALD and Al Herner at WRDC provided considerable editorial assistance.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

The Impetus

The Air Force Chief of Staff has stated that reliability and maintainability will be <u>at least</u> as important as cost, schedule, and performance in weapon system acquisition.[1] Although logisticians applaud this new emphasis, they are at a loss to effectively implement it for maintainability (<u>M</u>).

Formally an item's "reliability" is the probability that it will perform satisfactorily for a specified period of time under a stated set of conditions (usually stressful). Reliability is typically measured in some form of expected operating time between failures. Formally an item's "maintainability" is the probability that it will be retained or restored to a given operational condition within a specified period of time. Maintainability is typically measured in some form of expected time to repair or expected probability of correct repair.[2]

Reliability is a "hard" engineering discipline with its causes and effects well understood; in contrast, maintainability is a "soft" discipline relying predominantly on human performance and its inherent variability. Predicting the consequences of a specific design feature on deployed system mean time between failures, for example, is considerably more straightforward than predicting its consequences on deployed system mean time to repair with 3-, 5-, & 7-skill-level enlisted personnel.

In a related issue, the Department of Defense is attempting to lower its Manpower, Personnel, and Training (MPT) requirements for new systems.[3] Congress is now requiring credible manpower predictions on all major weapon system acquisition programs 90 days prior to Milestones II, Full Scale Development, and III, Production.[4] Maintenance produces the largest Air Force MPT requirement. A large portion of designing for lower MPT requirements is hence really designing for <u>M</u>. Intuitively, an easy-to-fix system requires fewer skills from fewer people, but how many fewer? And just how much easier will the system be to fix as a result of a specific design feature?

So there's impetus from several directions to better design new systems for maintainability and to better predict the consequences of such design.

---

1. Combat Support And The Air Force, Acquisition Logistics Division (ALD) Videotape # SAVPIN 604380 DF.
2. Acquisition Logistics Division's Deputy Program Manager For Logistics course definitions.
3. Office of the Secretary of Defense Directive 5000.53, Manpower, Personnel, Training, and Safety Integration in the Defense System Acquisition Process.
4. National Defense Authorization Act for Fiscal Year 1987, pages 165-166.

Air Force Influence On Maintainability Design[5]

The ideal approach to acquiring maintainable new systems would be to trust the competency of the contractors for M design. (Standard acquisition slogan: "We should tell contractors what to build, not how to build it.") The Air Force would give contractors bottom-line M requirements in system specifications, then back up these requirements contractually with financial incentives. Contractors would remain totally independent in their approaches while being highly motivated and resourceful during system design. The Air Force would learn of contractors' successes or failures during M demonstrations of system prototypes. This approach would offer a quick, efficient development program with a considerably reduced administrative burden for both the contractor and the Air Force.

Unfortunately, this approach is hard for the Air Force to accept: If for any reason contractor design efforts would be inadequate, the Air Force would remain ignorant of these failures until after prototypes were built -- late in system design. At this stage remedial system redesign causes significant cost and schedule overruns.

Thus the Air Force usually takes the opposite approach: It chooses not to fully trust contractor competency for meeting M specifications. It, rather, monitors contractor activities throughout system design. It evaluates not only the end products of design efforts, but contractor management and technical approaches to them. Inevitably the Air Force imposes its own Design-For-M (DFM) perspective on contractors. It suggests how to conceptualize the maintenance process, what M determinants to consider, where to look for M data, and specific design guidelines to consider. It also critiques the contractors' ideas in these areas.

By not giving contractors complete independence while they design for M, the Air Force in essence provides them with its own baseline "corporate memory" on the subject. While not necessarily providing detailed design criteria, the Air Force nevertheless imbues all contractors with its own perspective on M design. Although not ideal, this could be beneficial. After all, the Air Force should have a larger corporate memory on designs which work/do not work than any contractor would.

However, without M design expertise at least equal to that of its contractors, Air Force monitoring of the design effort could be more harmful than helpful. Assuming Air Force scrutiny of contractor design efforts, therefore, that scrutiny must be competent. And even if contractors would be permitted a completely independent design effort, accumulated Air Force wisdom in M design would provide valuable supplemental information for contractor consideration.

---

5. These next two sections reflect my personal opinion, based on 8 years' acquisition experience serving on both engineering and logistics staffs.

Information Needed By Program Managers

From a requirements perspective:

* Given manpower (M), training (T), and maintainability (M) requirements for a new system which have never been achieved before on predecessor systems, OR given old requirements on already deployed systems which have so far never been realized, how can one estimate whether a proposed new design will achieve them, before prototypes are built?

* What other design options are available to achieve these same requirements at perhaps a lower cost?

From a design perspective:

* Given a specific design option with a specific cost of implementation, how much of an improvement in M will result (in terms of decreased repair time or increased probability of effective repair)?

* How much of a decrease in system M and T requirements will result?

* How much improvement in system readiness will result?

* Finally, how will all this affect the life cycle costs of the system, in comparison to the above cost of implementation?

The Scope Of This Survey

To summarize: The Air Force as a whole requires better DFM, both in its own right and because of its effects on MPT. The Air Force must understand M design approaches and their consequences as long as it insists on overseeing contractor design activity. Program managers inside and outside DOD require tools to trade off M design features with their consequences on system readiness, M & T requirements, and life cycle costs. I will distill these information requirements thusly:

1. WHAT APPROACHES, TOOLS, OR GUIDELINES DO MILITARY STANDARDS OFFER THE SYSTEM DESIGNER TO:

   * DESIGN A NEW SYSTEM FROM THE BEGINNING TO MEET M SPECIFICATIONS, OR
   * FIX A PREVIOUS DESIGN WHICH FAILS M TESTING?

2. WHAT APPROACHES, TOOLS, OR GUIDELINES DO MILITARY STANDARDS OFFER THE SYSTEM EVALUATOR TO:

   * QUANTITATIVELY ESTIMATE THE EFFECTS OF SYSTEM DESIGN ON SYSTEM M,
   * PREDICT THE EFFECTS OF SYSTEM DESIGN AND ITS RESULTANT M ON M & T REQUIREMENTS, AND
   * QUANTITATIVELY ESTIMATE THE EFFECTS OF SYSTEM DESIGN AND M ON SYSTEM READINESS AND LIFE CYCLE COSTS?

3. HOW DOES M FORMALLY RELATE TO HUMAN ENGINEERING IN THE SYSTEM ENGINEERING PROCESS?

This paper is organized according to these questions. As I survey the information/resources found, I will assess their adequacy for meeting system engineering requirements. Specifically I will comment on their accessibility to the designer/evaluator and describe what I consider to be essential omissions.

NOTE 1: The M of any equipment involves two discrete functions: the ability to diagnose and measure equipment status, and the ability to repair the failed equipment. The net M of a system is then determined by the design of its mission equipment, its location within higher levels of assembly such as an airplane (on-equipment M), its diagnostic equipment capability, the design of its repair tools, and its maintenance instructions. This paper focuses on the M aspects of mission equipment designs.

NOTE 2: For this survey I assume M allocation, analysis, modeling, and prediction are basically synonymous. They relate specific M task/subtask times to overall M objectives (e.g., time to unscrew a fastener, to time to repair a component, to time to repair the system). Likewise, M design criteria and design guidelines are basically synonymous. They manipulate determinants of the task times (e.g., requiring quick-release fasteners).

NOTE 3: This survey assesses only DOD resources currently available to the system designer or evaluator. Assessing the potential contributions of future resources while still in the Research and Development (R&D) pipeline is beyond the scope of this effort.

REFERENCES

This survey found relevant information in the following military documents:

	See Herein:
AFR 173-13 USAF Cost And Planning Factors	Section 2D
MIL-STD-415 Design for Testability	Page A-2
MIL-STD-454 Design Criteria for Electronic Equipment	Page A-3
MIL-STD-470 Maintainability	Throughout
MIL-STD-1388-1 Logistics Support Analysis	Section 2B
MIL-STD-1472 Human Engineering Design Criteria for Military Systems, Equipment, and Facilities	Page A-5
MIL-H-46855 Human Engineering Requirements for Military Systems, Equipment, and Facilities	Section 3
MIL-HDBK-472 Maintainability Prediction	Section 2A
Readiness Improvement through System Engineering (RISE) Handbook from Electronic Systems Division (ESD)	Page A-1
Operating And Support Cost Estimating, A Primer by the Aeronautical Systems Division (ASD)	Section 2D
AFSC Design Handbook 1-3 Human Factors Engineering	Page A-35
AFSC Design Handbook 1-6 System Safety	Page A-6
AFSC Design Handbook 1-8 Microelectronics	Page A-10
AFSC Design Handbook 1-9 Maintainability (for Ground Electronic Systems)	Page A-12
AFSC Design Handbook 2-3 Propulsion and Power	Page A-24
AFSC Design Handbook 2-6 Ground Equipment and Facilities	Page A-26
AFSC Design Handbook 2-8 Life Support	A-33
AFSC Design Handbook 3-2 Space Vehicles	A-34

CONCLUSIONS

* There exists a substantial set of M design criteria and guidelines in the sources reviewed. (The Appendix reprints it all except MIL-STD-1472, Section 5.9, and AFSC DH 1-3, Section 2G, which are too large.) However, this knowledge is widely scattered and buried among several publications used by different segments of the acquisition community within the Air Force; reliability and maintainability (R&M) logisticians typically use only a very small subset. Furthermore, much of it exists in design handbooks, which are rarely if ever quoted as binding in the system specification. I believe this knowledge base -- as well as the responsibility for using it -- must be consolidated in order to be useful to a contractor during system design or to the Air Force during system evaluation.

* Additionally, military publications have yet to systematically assimilate the considerable body of expertise resident in senior Air Force flight line maintainers or senior contractor R&M engineers. Military standards should also periodically assimilate the M experience in the Air Force lessons-learned data base.

* Because the Air Force seldom allows contractors to pursue M design efforts independently; it attempts to lead contractor efforts indirectly via suggestions on where to look for data, what M determinants to consider, and how to conceptualize the maintenance process. This guidance -- as found in MIL-STD-470, MIL-STD-1388-1, and the ESD RISE HDBK -- appears to be sound and useful.

* The standards contain detailed instructions for both the contractors and the Air Force to trade off M design with availability, supportability, manpower and training (M & T) requirements. But I found little guidance as to HOW.

    * * They offer no approaches for estimating specific repair times or probabilities of effective repair from specific design features.

    * * They offer no approaches to developing a new optimum maintenance manpower structure for a new, more reliable and maintainable design.

    * * They offer little help in predicting the life cycle cost implications of M, M & T requirements under conditions of new design approaches, new deployment concepts, new training technology, differing aptitude requirements, or differing manpower structures, as compared to current "baseline" systems.

In short, still missing are techniques to rigorously translate between "micro human factors" (detailed human engineering design) and "macro human factors" (system-level people requirements).

* The standards do call out comparability analyses, failure modes and effects analyses, M allocation and prediction, choice of diagnostic approach, graphic depiction of maintained components, or human engineering function/task analyses, all of which attempt to drive the contractor to better conceptualize M tasking.

  * * Comparability analyses are in essence a structured lessons-learned approach using current systems, addressing the relationship between design features and M requirements. However, their accuracy is a function of how similar the new design is to old ones.

  * * Reliability-centered maintenance and failure modes & effects analyses predict theoretically which components will fail when, and hence which components to pay most attention to while designing for M. But they will not predict component repair time or difficulty.

  * * M allocation and prediction techniques transition between system and component M measures. They do not, however, quantitatively estimate the effects of specific design features on these M measures.

  * * The ESD RISE Handbook uniquely asks the acquisition program to choose a repair philosophy, either "troubleshooting" or "theory of operations." It is a general decision dealing with trends in system design but not with precise M consequences.

  * * Illustrations of maintainable components show accessibility for testing and removal, allowing early evaluation of a major M determinant.

  * * Human engineering function/task analyses, if done properly, could provide a transition between system design and M & T requirements via a common task inventory and selected human engineering research.

* LCOM -- the official Air Force manpower prediction technique -- allows tradeoffs between M, manpower, and operational readiness for a specified operational scenario using a specified manpower structure. But it is only as good as the maintenance task times fed into it, which are usually derived from comparability analyses. LCOM will not address system design effects on task times, system design effects on probabilities of correct fault isolation/diagnosis/repair, or M & T effects on system life cycle costs. A comparatively simple M tradeoff model also exists in AFSC DH 1-9; I believe that its simplifying assumptions strain its credibility.

* Within the documents I surveyed, the human engineering discipline offers the best single source of both M design criteria and insights into M design effects on M & T requirements. DOD standards regularly stress the connection between M and human engineering. Yet R&M, M, T, and human engineering issues are handled independently by separate communities within the typical AF weapon system acquisition program.

RECOMMENDATIONS

Thus the Air Force still requires:

* A more comprehensive knowledge base in DFM, particularly a way to encapsulate the experience of senior AF maintainers and senior contractor R&M engineers.

* Consolidation of the current DFM knowledge base and its application; i.e., a condensation and restructuring of all material referenced in Appendix A into a single, handy reference.

* Any analysis technique to rigorously estimate probabilities of successful repair and mean repair times from component M design.

* Any analysis technique to define optimum AF specialties based on trading off weapon system turnaround, manpower, aptitude, training, skill retention, and personnel retention requirements, for a design with specific R & M characteristics.

* Any technique to compute life cycle cost implications of system M and M & T requirements when the new system significantly differs from the "baseline."

* Formal, embedded ties between logistics and human engineering experts within the acquisition community, to better comply with the interdisciplinary requirements of these standards, and to better implement the M design guidance and evaluation techniques which human engineering already offers.

1. DESIGN-FOR-MAINTAINABILITY (DFM) GUIDANCE

WHAT APPROACHES, TOOLS, OR GUIDELINES DO MILITARY STANDARDS OFFER THE SYSTEM DESIGNER TO:

* DESIGN A NEW SYSTEM FROM THE BEGINNING TO MEET M SPECIFICATIONS, OR
* FIX A PREVIOUS DESIGN WHICH FAILS ITS M SPECIFICATION?

Leaving aside design aids currently in the Air Force R&D pipeline, I will first survey the Department of Defense (DOD) knowledge base that exists today in regulations, standards, and handbooks typically used by the Air Force. How extensive is it?

I will then survey less direct ways in which the Air Force guides the contractor's management and technical approaches.

A. DOD-Published Maintainability Design Criteria

What currently exists in the DOD knowledge base on Designing-For-M (DFM)? I surveyed military documents which would be commonly available to contractors -- standards and handbooks. However, I excluded second-tier references from industry sources which are beyond DOD authority to print and distribute. Besides searching for explicit M design criteria, I searched for guidance about related design goals: accessibility, fault diagnosis, design for testability, replace versus discard, etc.

This section and the attached Appendix collect all such information I found, into one document for easy reference and comparison. The only exclusions are the two human factors engineering DFM resources -- MIL-STD-1472, Section 5.9, and AFSC Design Handbook 1-3, Section 2G -- which are relevant in total but too large to reproduce here.

The obvious place to start searching for DFM guidance is in the M standards themselves and, more generally, in logistics standards. The only such insights I found were in MIL-STD-470, MAINTAINABILITY:

40.2.6.2 General design criteria relate to the achievement of various goals or targets, for example

40.2.6.2.d to minimize the complexity of maintenance by designing for:

(1) Compatibility among systems equipment and facilities.
(2) Standardization of design, parts, and nomenclature.
(3) Interchangeability of like components, materials, and spares.
(4) Minimum maintenance tools, accessories, and equipment.
(5) Adequate accessibility, work space, and work clearance.

(40.2.6.2.a,b,c,e,f all list as many criteria, but they do not give the designer insight on how to meet them. Only d, above, lists things a designer should already have experience doing.)

206.2.2 ... Criteria to be considered for inclusion for all levels of maintenance are

206.2.2.3 guidelines and policies regarding:

a. General accessibility, work space, and work clearance.
f. Number of personnel and skill levels.
i. Use of access panels for inspection.
j. Training requirements and needs.
k. Handling, mobility, and transportability.

40.2.6.4 ... Some examples of M design criteria appropriate for some equipment programs are:

a. All repair part items having the same part numbers shall be functionally and physically interchangeable w/o modification or adjustment of the items or system or equipment in which they are used.

b. Maintenance adjustment or alignment shall not be required.

c. Preventive maintenance requirements, including calibration, shall be eliminated.

d. Physical and functional maintenance access shall be provided to any active component ... and shall not require prior removal or movement of other components except access entries.

e. Devices securing access entrances and maintenance replaceable items shall be the captive quick-release type with positive locking features.

f. Special (system or equipment peculiar) tasks shall not be required in the performance of user or intermediate level maintenance tasks.

MIL-HDBK-472, MAINTAINABILITY PREDICTION; MIL-STD-1388-1, LOGISTICS SUPPORT ANALYSIS; and the remainder of MIL-STD-470 contain no other direct M design guidelines.

By extending into engineering standards, however, I found considerably more guidance. The following excerpts are referenced to the attached appendix.

MIL-STD-415, DESIGN FOR TESTABILITY, contains advice on marking and color coding which will improve M [Page A-2]. MIL-STD-454, DESIGN CRITERIA FOR ELECTRONIC EQUIPMENT, contains design requirements covering many areas. Four have direct impacts on M: Requirement 28 Controls, Requirement 36 Accessibility, Requirement 63 Special Tools, and Requirement 67 Marking [Pages A-3 to A-4]. The Electronic Systems Division Handbook on READINESS IMPROVEMENT THROUGH SYSTEM ENGINEERING (RISE) contains a compact set of DFM criteria [Page A-1]. Each of these sets of requirements may be called out as binding in the system specification.

The most thorough collections (by far) of design criteria and guidelines appear in two human factors engineering references. MIL STD-1472, HUMAN ENGINEERING DESIGN CRITERIA FOR SYSTEMS, EQUIPMENT, AND FACILITIES, Section 5.9 is titled, "Design For Maintainability," and contains 24 pages covering 18 relevant subject headings. Too large for reprinting here, I listed its table of contents on page A-5 of the Appendix. Likewise, AFSC DESIGN HANDBOOK 1-3, HUMAN FACTORS ENGINEERING, Section 2G is titled, "Maintainability Design," and contains 39 pages of guidance over seven design notes. I reprinted its table of contents on pages A-35 to A-37.

More insight is available from the remaining series of Air Force Systems Command Design Handbooks (AFSC DH). Their primary purpose is to document Air Force technical knowledge for use in support of acquisition programs. They are almost never called out as binding in the system specification, but can be listed for guidance. Twenty-six design handbooks currently exist; still others are approved but not funded. Aeronautical Systems Division (ASD/ENES) manages the program for AFSC for all but a few handbooks related to ballistic missiles. I surveyed their entire collection on file and reprinted the relevant guidance in the appendix, beginning with page A-6.

It is worth noting that most handbooks contain no information on DFM. Some handbooks (electromagnetic compatibility, aerospace materials, reliability, transportability, etc.) are discipline-oriented so one would not expect to find DFM information inside. Others are system-oriented, however, and specific DFM criteria would be helpful. Conspicuous in their failure to address DFM were handbooks on environmental engineering, airframes, crew stations and passenger accommodations, electronic warfare systems, armament, and space ground equipment/facilities.

On the other hand, M has its own handbook. Three chapters of AFSC DH 1-9, MAINTAINABILITY (FOR GROUND ELECTRONIC SYSTEMS), contain the second most comprehensive set of DFM guidance in the design handbook series. (AFSC DH 1-3, HUMAN FACTORS ENGINEERING contains the largest set.) Chapter 5 of AFSC DH 1-9 features a concise table of DFM guidelines similar to those appearing in the RISE handbook. Chapter 4 contains guidance on designing for system test, laying out schematic diagrams to be user-friendly, and overall system construction. Chapter 8 deals with non-destructive-inspection (NDI), an important fault detection and isolation technique for mechanical, fluid, electronic, propulsion, and ordnance systems. [Pages A-12 to A-23]

The third most comprehensive set of DFM guidance in the design handbook series appears in three chapters of AFSC DH 2-6, GROUND EQUIPMENT AND FACILITIES. Although DH 1-9 is primarily concerned with ground electronic systems, DH 2-6 is primarily concerned with ground mechanical systems. General DFM topics include maintenance access doors and panels (section 2B); bearings and gears (section 2C); and maintenance equipment lubrication, adjustment, and repair (section 4F). More specific DFM topics include test equipment maintenance (section 4G), snow and ice removal equipment maintenance (section 4F), and radio communications equipment (section 3A). [Pages A-26 to A-32]

A fourth collection of DFM guidance exists in AFSC DH 1-6, SYSTEM SAFETY. Section 3H addresses aerospace vehicles, and section 4E addresses aerospace ground and ancillary equipment. [Pages A-6 to A-9]

I also found guidance on specific systems. Section 6B of AFSC DH 1-8, MICROELECTRONICS, addresses some DFM considerations for microelectronic circuits [Pages A-10 to A-11]. Section 2A of AFSC DH 2-3, PROPULSION AND POWER, addresses some DFM considerations for propulsion and power systems [Pages A-24 to A-25]. Section 3A of AFSC DH 2-8, LIFE SUPPORT, contains a little DFM guidance for oxygen systems [Page A-33]. Section 13B of AFSC DH 3-2, SPACE VEHICLES, contains some general DFM guidance for ground maintenance of space vehicles [Page A-34].

The Air Force Lessons Learned Data Base housed at the Acquisition Logistics Division can be searched for M lessons. The index alone for M lessons is over 50 pages in length. These can certainly give insights and general design guidelines, but until these lessons are translated into concise design criteria and used in system specifications, they will have little influence.

The Aeronautical Systems Division's MIL-PRIME program routinely incorporates lessons learned into its specifications and standards. As of the date of this publication, however, no MIL-PRIME standard addresses how to design a system to be maintainable.

ASD/ENES attempts to periodically review the lessons for translation into appropriate design handbooks. However, their small staff must cover over 20 different subject areas besides M.

All these references together form a substantial set of DFM criteria and guidelines. However, this knowledge is scattered and buried:

* Only the MIL-STD-470 section and possibly the MIL-STD-415 section are commonly used by the R&M community; in my experience the rest is used primarily by the engineering community, with little attention paid to it by the logisticians.

* The RISE handbook criteria are used only at Electronic Systems Division; RISE is strictly an ESD approach.

* MIL-STD-454 is to be applied only to electronic systems.

* Design handbooks contain a substantial, useful set of DFM criteria; however, citing design handbook sections as binding, according to ASD/ENES, is generally considered bad practice. Furthermore these criteria must be distilled from six handbooks (or 26, if the M engineer hasn't read this report first) -- even when covering a single subject like ground equipment or communication electronics.

* The M lessons from the Air Force Lessons Learned Data Bank are mostly inaccessible in their present form due to their volume.

By my observation there is a similar scattering of focus and responsibility for DFM throughout the Air Force. There are, however, sources of expertise which can view a proposed design, perceive the potential repair problems, and intuitively know downstream implications.

One source of DFM expertise is experienced AF maintainers. Another source is senior contractor reliability and maintainability (R&M) engineers who have worked on industry design teams for many years. Both should have a good personal experience base about what is maintainable and what is not. However, the Air Force strongly needs the former in the field; so, they are not always available for acquisition advice. And the Air Force has yet to systematically tap the expertise of the latter. An encapsulation of this expertise via data bases or expert systems could provide the framework on which to consolidate and prioritize the scattered DFM knowledge base.

In summary, the core of an Air Force M design knowledge base exists in various standards and design handbooks, and still more could be culled from experienced maintainers and senior contractor R&M specialists. But, in my opinion, this base must be consolidated and given a single Air Force office of primary responsibility in order to be useful for system design and evaluation.

B. DOD Perspective On Design-For-Maintainability.

Despite a substantial, though scattered, knowledge base on DFM within military publications, the M standards task contractors to develop or choose their own approaches. Nevertheless, the DOD seldom risks allowing the contractors to DFM completely independently. Military standards attempt to lead the contractors' efforts in the right direction via suggestions on where to look for data, what M determinants to consider, and how to conceptualize the maintenance process. I will survey this guidance next.

Note that this section is not referring to M prediction techniques, which will be covered in the next chapter. M prediction deals with analyzing system M specifications into component M specifications, and vice versa. M prediction techniques can pinpoint which components need improving, but they are not intended to indicate how to design components or systems to meet M specs. The published information surveyed in this section, rather, is.

I will begin with DOD suggestions for M determinants.

MIL-STD-470, MAINTAINABILITY:

40.1.4.4 ... maintainability influencing factors to be considered at this review [preliminary design review] are adherence to specifications, form, fit, function, human engineering factors, packaging, and compatibility with other specifications.

104.2.4 The data collection system used during demonstration shall be used as a means for identifying maintainability design problems and errors, and for initiating corrective actions. Such corrective action can take the form of modifications and changes to equipment fault detection and isolation subsystems (hardware and software), packaging, assembly, training, manuals, etc.

Where might someone find information about these M determinants?

MIL-STD-470:

205.1 ... The purpose of Task 205 is to translate data from contractor's studies, engineering reports, ... , and information available from the CA into a detailed design approach and to provide inputs to ... the logistics support analysis.

40.1.5.4 Both engineering and qualitative analysis of the system or subelements should be initiated on each item which fails to comply with specified requirements. This consists of determining the causes leading to noncompliance and the changes required....

40.1.5.4.1 Qualitative analysis consists of review of specifications, design drawings, and examination of prototype or production hardware....

40.2.3.3 The detailed design prediction technique (applied midway during full scale development) is appropriate once detailed functional block diagrams and a complete packaging philosophy are established for an equipment. ... The following information is required to implement the technique:

a. Maintenance concept, including status panels, operator control panel layouts, built-in test equipment operating interface data, and removal and replacement task definitions.

b. Functional block diagrams.

c. Equipment theory of operation.

d. Detailed parts lists and schematics or circuit diagrams for Removable Units.

e. Reliability estimates at each removable unit level.

f. Removable unit sketch and drawing.

40.2.5.6 Valuable and necessary inputs to the M analysis tasks are obtained from among the following

a. Reliability analyses and predictions.

b. Human factors studies which recommend skill levels and quantities of personnel required.

c. System safety analyses.

d. Cost analysis tasks.

e. Manufacturing process analyses.

Given a set of determinants and sources to find them, how might they be used to design for M? Without giving specific guidelines, the standards levy tasking which helps the designer to conceptualize the system and how various factors may interplay.

One such tasking is to perform a comparability analysis. One examines the relations between design approaches and resultant M on similar parts of other, already fielded systems.

MIL-STD-1388-1, LOGISTICS SUPPORT ANALYSIS:

Task 203 Comparative Analysis

203.2.1 Identify existing systems and subsystems (hardware, operational, and support) useful for comparative purposes with new system/equipment alternatives. ...

203.2.2 ... A Baseline Comparative System (BCS) may be developed using a composite of elements from different existing systems. ... Different BCS's or composites may be useful for comparing different parameters of interest. ...

203.2.3 Determine the operation and support costs, logistic support resource requirements, reliability and maintainability values, and readiness values of the comparative systems identified ... adjusted to the new system/equipment's use profile ...

203.2.4 Identify the qualitative supportability problems on comparative systems which should be prevented on the new system/equipment.

50.2.4.1 ... When a realistic comparative system can be established, information on the comparative system helps identify the following:

b. Major downtime contributors.

c. Design features which enhance supportability.

e. Design concepts with potential safety or human factors impacts.

50.2.4.3 ... When the performing activity is a contractor, the level of comparison must be specified, as well as data sources to be used. ...

Another such type of tasking is to perform a Failure Modes, Effects, and Criticality Analysis (FMECA) or a Reliability-Centered Maintenance (RCM) analysis. One uses the theory of operation of the new system and the reliability characteristics of its components to predict required maintenance actions. Knowing the components most likely to require maintenance will aid in designing for M.

MIL-STD-1388-1:

Task 301 Functional Requirements Identification

301.2.1 Identify and document the functions that must be performed for the new system/equipment to be operated and maintained in its intended operational environment for each alternative under consideration. ...

301.2.2 Identify those which are unique to the new system/equipment due to new design technology or operational concepts, or which are supportability, cost, or readiness drivers.

301.2.3 Identify any risks....

301.2.4 Identify the operations and maintenance tasks for the new systems/equipment based on the identified functional requirements ... by the following methods:

301.2.4.1 The results of the failure modes, effects, and criticality analysis (FMECA), or equivalent, shall be analyzed to identify corrective maintenance task requirements, ... using the Logistics Support Analysis Record (LSAR) or equivalent format approved by the requiring authority.

301.2.4.2 Preventive maintenance task requirements shall be identified by conducting a reliability-centered maintenance (RCM) analysis ... based on the FMECA data and documented in the LSAR or equivalent.

MIL-STD-470:

204.1 The purpose of Task 204 is to define the potential failure modes and their effects on systems, equipments, and item operation in order to establish necessary maintainability design characteristics....

Complementary to FMECA and RCM are human engineering task analyses involving "functional decomposition." Although mainly used for analyzing operator tasks, they can also be used for analyzing maintenance tasks.

MIL-STD-1388-1:

301.2.4.3 Operations and other support tasks not identified by the FMECA or RCM analysis shall be identified through analysis of the functional requirements and intended operation of the new system/equipment. ...

401.2.1 Conduct a detailed analysis of each operation and maintenance task requirement identified (Task 301) and determine the following:

a. Procedural steps required to perform the task to include identification of those tasks that are duty position-specific ... or collective tasks....

c. Task frequency, task interval, elapsed time, and manhours....

No matter what the approach, tasking the designer to visualize the system before building it, then to submit diagrams of the repairable components in situ, creates opportunities to catch M problems before they are built in. The RISE handbook suggests listing Data Item Description E-7031/T, "Maintainability Diagrams for Design Reviews," on the Contract Data Requirements List (CDRL) with the following extensive tailoring. This could be viewed as requiring a paper M demonstration before any prototypes are built.

RISE HANDBOOK, METHOD 18, Atch 1:

Block 4 - Tailor DD Form 1664, (Data Item Description) block 10, to change and add as follows ...

10.4 "List, Units and Assemblies which will be Replaced During On-equipment Maintenance" will identify each unit or assembly which will be functionally and physically isolable during on-equipment (i.e., organizational) maintenance. List for each unit or assembly, the functional title, part number, and the number of subassemblies which can be physically isolated without soldering or cutting wires.

10.5 "List, Assemblies which will be Replaced During On-site Off-equipment Maintenance" will identify each assembly which will be functionally and physically isolable during on-site off-equipment (i.e., intermediate) maintenance. List for each assembly, the functional title and part number.

10.6 "Diagram, Functional (Schematic or Logic) for Maintainability" will be provided for each newly developed or modified item (i.e., system, prime item, critical items) for which the contractor's design contemplates functional failure diagnostic procedures to be performed. The level of detail of each diagram will define each isolable unit and assembly by at least one symbol. Superimposed on the functional diagram will be the identification of each functionally isolable unit and assembly. Test points for measurements and for the introduction of stimulus signals will be identified for each functionally isolable unit and assembly. Test equipment for measurement and stimulus will be defined for isolation of each unit and assembly. ...

10.7 "Diagram, Physical (Pictorial) for Maintainability" will be provided for each newly developed or modified item (i.e., system, prime item, critical item) which is to be developed or significantly modified. The level of detail of each diagram will show at least each unit an assembly which will be physically replaced during maintenance. Further identification is desired of all subassemblies which can be removed without soldering or wire cutting. Superimposed on the physical diagram will be the indication of each unit and assembly which will be removed during maintenance. Test points, used for functional isolation of a failure in each unit and assembly, will be indicated. Indicate access to test points and to remove/replace each unit and assembly. Indicate test equipments to be used to isolate each unit and assembly. ...

C. Summary of DFM Guidance

1) There exists a substantive core of military DFM knowledge in various standards and design handbooks, and still more could be culled from experienced AF maintainers and contractor R&M specialists. But this core of knowledge is scattered among several disciplines and often buried in large documents.

2) Additionally, DOD standards attempt to lead the contractors' DFM efforts via suggestions about where to find data, what M determinants to consider, and how to conceptualize the maintenance process.

3) The standards' suggestions for M determinants appear to be sound: form, fit, function, human engineering factors, packaging, assembly, training, manuals, and fault detection/isolation systems.

4) The standards' suggestions for places to collect relevant information also appear to be sound: contractors' studies, engineering reports, specifications, design drawings, removable unit sketches, panel layouts, functional flow block diagrams, and discipline analyses (reliability, system safety, human factors, manpower, etc.).

5) The standards levy tasking which helps the designer to conceptualize how these determinants interplay:

A) The standards may task the contractor to do comparability analyses, which could be used as a formalized lessons-learned survey as to which design features have and have not helped M on older systems.

B) The standards may task the contractor to do RCM or FMECA to theoretically predict which components are more likely to fail, giving priority to designing those components for easy access and testability.

C) The standards may call out human engineering function and task analyses which will aid the designer to visualize M tasks with the proposed system configuration.

D) The ESD RISE handbook requires diagrams of the equipment from the maintainer's perspective.

All of these taskings appear to be useful for supporting DFM, be the contractor experienced or naive. They do not impose a specific DFM technical approach, but they do prod the designer to look at relevant information.

2. DESIGN FOR MAINTAINABILITY (DFM) CONSEQUENCES

WHAT APPROACHES, TOOLS, OR GUIDELINES DO MILITARY STANDARDS OFFER THE SYSTEM EVALUATOR TO:

* QUANTITATIVELY ESTIMATE THE EFFECTS OF SYSTEM DESIGN ON SYSTEM M,
* PREDICT THE EFFECTS OF SYSTEM DESIGN AND ITS RESULTANT M ON M & T REQUIREMENTS, AND
* QUANTITATIVELY ESTIMATE THE EFFECTS OF SYSTEM DESIGN AND M ON SYSTEM READINESS AND LIFE CYCLE COSTS?

In his address to the DOD Human Factors Engineering Technical Advisory Group Meeting #17, Dr. Harold R. Booher, Chief of the US Army's MANPRINT program, strongly requested techniques to translate "micro human factors engineering" into "macro human factors engineering"; that is, techniques to understand the system-level operability, maintainability, manpower, personnel, and training implications of specific detail design approaches. (For example, how much would pervasive use of quick-release fasteners actually change the mean time to repair, maintainer training costs, or the system manpower requirements?)

Furthermore, the bottom line of acquisition decisions rests on two foundations: system readiness and life cycle costs. How do system-level operability, maintainability, manpower, personnel, and training in turn influence them? Without this rigorous translation, design tradeoffs which include maintainability considerations are subjective and imprecise.

I surveyed military documents commonly used within the Air Force for guidance on performing this multi-layered translation from micro to macro human factors engineering:

A) The only specific effects of DFM features on times-to-repair which I found appeared in several SUB-NOTES of AFSC DH 1-9. The ratio of expected repair times between two design approaches is occasionally given. This information is strongly relevant, but rarely provided.

B) The standards do mention two major classes of analyses which serve M, and acquisition programs usually dedicate significant resources to both: M Prediction and Logistics Support Analyses (LSA). Both of these classes of analyses have qualitative and quantitative aspects. Both include a variety of analytical approaches. I review them in sections 2A and 2B, respectively.

C) Although not specifically called out by the standards, the Air Force has an official manpower requirements prediction technique called LCOM (Logistics COmposite Model), and the M design handbook (1-9) offers rudimentary manpower tradeoff graphs. I review them in section 2C.

D) Life Cycle Cost models and data address standard costs due to acquiring, training, and retaining maintainers. I review them in section 2D.

Do any of these tools answer the above questions? I graphically summarize my findings in section 2E.

A. Maintainability Allocation, Analysis, Modeling, & Prediction

MIL-STD-470A, MAINTAINABILITY:

40.2.2 The contractor will begin the maintainability design process with one or more specific M objectives ... i.e. MTTR, ratio of maintenance hours to operating hours, fault detection probability, probability of fault isolation to a given level, etc. ... these must be translated into M requirements for system components. This process is known as M allocation.

40.2.2.4 In the allocation process initial estimates of M must be made for each affected item ... in the same units of measure as the M objective ... derived from any of the following sources:

a. Predictions.
b. Data on similar components.
c. Experience with similar components.
e. Engineering estimates based on personal experience and judgement.

40.2.2.5 The allocation process should be initiated as soon as possible in the early acquisition phases ... to allow time to establish lower level M requirements....

Thus, strictly speaking, M allocation takes a specified mean time to repair or probability of correct repair for the entire system, and derives what all the component mean times to repair or correct repair probabilities must be in order to meet this overall specification. Of course, one cannot allocate downward from system to component level without some conceptualization of how component M combines into system M. Implicit in the allocation process, therefore, is an M model; i.e. some way to make system M predictions based on system design.

203.2.2 Predictions ... shall be made using one of the methods contained in MIL-HDBK-472, or alternatives which are approved or provided by the contracting authority (CA).

I will examine each of these two options in turn. Starting with MIL-HDBK-472, the only possibly design-related perspectives on repair time/success I could find were:

MIL-HDBK-472, MAINTAINABILITY PREDICTION, PROCEDURE 1:

Malfunction downtime according to this model includes: preparation time, malfunction verification time, fault location time, part procurement time, and repair time.

System time includes initial delay time, system repair time, system final test time, and system logistic time.

MIL-HDBK-472, MAINTAINABILITY PREDICTION, PROCEDURES 2 AND 5:

Corrective maintenance tasks according to this model include: localization, isolation, disassembly, part interchange, reassembly, alignment, checkout, and startup.

Task times are dependent on the functional levels of maintenance. According to this model these are: part, stage (2 or more parts, not a replaceable item itself), subassembly (2 or more parts, replaceable individually or as a whole), assembly (a number of parts perform a specific function and are replaceable as a whole), unit (parts mounted together capable of independent operations in a variety of situations, usually directly accessible), group (collection of units not capable of performing a complete operational function, not normally a replaceable item), equipment set (collection of units and cabling that can perform an operational function), subsystem, and system.

These techniques suggest perspectives for conceptualizing system repair and consequent time parameters which may affect M. The techniques actually drive the contractor to perform a detailed breakout of M tasks, prodding consideration, at least, of possible M design problems and M & T implications.

I should point out here that, although not explicitly acknowledged in MIL-STD-470, SECTION 3D of AFSC DESIGN HANDBOOK 1-9, MAINTAINABILITY (FOR GROUND ELECTRONIC SYSTEMS), cites four M prediction methods. One references procedure 3 from MIL-HDBK-472, one uses a set of 14 equations, one uses comparability analysis, and one breaks repairs into four time elements: preparation time, fault location time, fault correction and alignment time, and item obtainment time. I found no M design insights in any of them.

The Electronic Systems Division does not typically require M prediction, but it similarly prods the Air Force to consider M via requiring the program office to select between two diagnostic approaches.

RISE HANDBOOK, METHOD 18, SECTION 3.b:

(1) The basic maintenance concept decision is whether to require the prime mission equipment design, selection of test equipment, and description of failure isolation procedures to be done by "troubleshooting" or by "theory of operations," i.e., compare to a reference (e.g., scope photo in technical order) or think as guided by technical order "Theory of Operation." Considerable evidence and logic indicate troubleshooting to be more effective and less costly in required skill levels, test equipment and levels of isolation and sparing. However, practice often still dictates use of theory of operations. Therefore, no definite direction can be given to acquisition programs. However, the program manager has the authority to decide on the maintenance concept, with proper coordination. The program manager must therefore either direct the maintenance method on the contractors or leave it open to competitive definition and selection by the contractors.

The following is given as background for this decision. When systems become too complex for manual maintenance by theory of operations, the trend has been toward automatic test equipment, external (ATE) and internal (BIT). Note that automatic test inherently uses troubleshooting, in that a computer can only compare and cannot think. Also note that computers can compare only discrete inputs or simple patterns, while humans can easily compare complex patterns. Manual maintenance by troubleshooting, using common test equipment (e.g., scope) and comparing to references (e.g., scope photos) in technical orders has shown considerable potential.

(2) Disciplined "substitution" is an easy and effective method of isolating to lesser failed assemblies. However, it has been disallowed because lack of discipline can lead to "cannibalization" and because previous types of equipment failures could cause failures in other substituted assemblies. The latter is rarely the case with solid state electronics. Limiting the number of substitutions permitted per repair in accordance with "substitution" may result in less test equipment, lower skilled technicians, smaller spares assemblies, and in the authorization of what is commonly done in effective field maintenance practice. Because different maintenance users have different policies regarding "substitution," each acquisition program must coordinate and decide on their requirements.

The RISE Handbook Method 18 and MIL-HDBK-472 drive us to determine the type of M tasks to be required on the new system and to perform a detailed breakout of the tasking. This allows us to better visualize repair tasks and hence better estimate task timing and probability of success. But as yet there is no insight into how to rigorously link those estimated task times and probabilities of fault detection/isolation with proposed system design features, nor on how to derive M & T requirements.

I will next move to the second option cited by MIL-STD-470A, 203.2.2. What do the standards say about "alternative prediction techniques approved or provided by the Contracting Authority"?

MIL-STD-470A:

40.2.3.1 During the validation phase, ... M predictions are based largely on experience with predecessor systems....

40.2.3.3 The detailed design prediction technique (applied midway during Full Scale Development) is appropriate once detailed functional block diagrams and a complete packaging philosophy are established for an equipment. ... The following information is required to implement the technique:

a. Maintenance concept, including status panels, operator control panel layouts, built-in test equipment operating interface data, and removal and replacement task definitions.

b. Functional block diagrams.

c. Equipment theory of operation.

d. Detailed parts lists and schematics or circuit diagrams for Removable Units.

e. Reliability estimates at each removable unit level.

f. Removable unit sketch and drawing.

203.2.1 ... These predictions shall be made using the associated mathematical models and M prediction procedures approved by, or provided by, the Contracting Authority. ...

Thus, to develop one's own, possibly better, M prediction tools, this standard suggests three significant sources of relevant information: 1) at first, experience with similar systems or similar components, then 2) close examination of the proposed new system design including its functional organization, its theory of operations, and its detailed layout, and finally 3) M mathematical models. All these sources, unfortunately, are limited in the help they can provide:

1) The first source -- experience with similar systems or components -- ties in with comparability analyses as required in Logistics Support Analysis (discussed in chapter 1B). Comparability analyses, besides being a type of formal lessons-learned survey where one learns which design approaches worked and did not work on current systems, are also a good source of repair time and success probability estimates. They are very rigorous if components of the new system and the baseline comparison system are similar in design. If not, which is often the case, one must rely on subjective estimates about the impact of the design change from subject-matter experts (SMEs). SMEs also are basically rooted in current systems and procedures, hence lacking detailed expertise with major design changes:

AFSC DESIGN HANDBOOK 1-9, MAINTAINABILITY (FOR GROUND ELECTRONIC SYSTEMS):

DN 3B2 Basic Steps Of Allocation.

2.2.1 Difficulties in making estimates. Attempts to make M estimates for system components are most often frustrated by the following: ...

d. This sytem incorporates new design concepts whose impact on M is not known.

2) The design features listed as the second source can greatly influence component and system repair times and probabilities, but again there is no inference has to how, or better, how much. However, human engineering function and task analyses -- alluded to by references to functional block diagrams, removal and replacement task definitions, built-in test equipment operating interfaced data, and removable unit sketches and drawings -- can provide the foundation for scoping M & T requirements if properly called out in the contract Statement of Work.

3) Here is what MIL-STD-470 says about the third source, M modeling:

201.2.1 Appropriate M math models shall be developed based on:

201.2.1.a System design characteristics which impact maintainability (for example, fault detection probability, proportion of failures isolatable, frequency of failure, maintenance time and manhours required, maintenance plan, etc.).

201.3 The complexity of the model will necessarily vary according to the complexity of the equipment being procured. ...

40.2.1.2 ... The complexity of the model may range from a simple functional flow block diagram of few elements to a complex flow diagram depicting a total system operational flow to a mathematical form of relationship which relates system parameters to system performance. Models may be implemented manually or through computer programming....

Alas, there is no insight here. Functional flows have already been mentioned. Frequency of failure is really a reliability measure; it will help determine overall system availability, but will not yield insight on the duration or probability of success of maintenance actions. Probability of detection, proportion of failures isolatable, required manpower, and time to repair are not independent variables, but the dependent variables to be rigorously derived.

Thus it appears that all three sources of relevant information cited in MIL-STD-470 for finding or creating M prediction techniques (other than those in MIL-HDBK-472) fall short in their ability to estimate the effects of design features on mean times to repair, probabilities of fault detection/isolation, and M & T requirements.

To summarize what the standards say about M allocation/ prediction/models:

1) The contractor should begin the M design process with M allocation -- breaking overall repair time and probability requirements into component requirements.

2) These must be verified via M prediction techniques, for which there are two sources: MIL-HDBK-472 and "other."

A) MIL-HDBK-472 gives some insights into how to visualize M tasking on a detailed level, although it provides none for predicting M & T requirements, nor for translating qualitative design features into quantitative mean times to repair or probabilities of fault detection/isolation.

B) The ESD RISE Handbook, which does not call out MIL-HDBK-472, nevertheless asks the system program office to conceptualize maintenance tasks, in that the program office must choose between two diagnostic philosophies for the system. Again, this is insufficient for quantitative predictions.

C) MIL-STD-470 suggests that the "other" M prediction insights may be obtained through comparability analyses with similar systems and components, through close examination of the proposed new system design, or through M math modeling.

C-1) Comparability analyses give good M predictions when the new system is similar in design to older ones with operational experience. If the new system's design is very innovative, however, comparability analyses give valuable insight but are not mathematically rigorous.

C-2) Military standards properly imply that M is a direct function of system design. But the standards fail to describe how to predict M from the system design once system functional organization, theory of operations, detailed layout, etc. are available for study.

C-3) Comments about M math models yield no useful insight.

3) References to functional block diagrams, removal and replacement task definitions, built-in-test operating interface data, and removable unit drawings do allude, however, to human engineering "functional decomposition." This can serve as the foundation for scoping manpower and training requirements from the system design -- via a common task inventory accessible to human engineering research.

On the whole, established M prediction procedures, allocations, and modeling provide little insight into rigorously predicting design effects. Logistics Support Analyses cover a broader range of techniques. What might they offer?

B. Logistics Support Analyses

First, LSA task 101 requires the Air Force system program office to connect system design with supportability requirements:

MIL-STD-1388-1:

Task 101 Development of an Early Logistics Suppport Analysis Strategy

101.2.1 Prepare potential supportability objectives for the new system/equipment and identify proposed LSA tasks and subtasks to be performed early in the acquisition program ... based on the following factors:

a. The probable design, maintenance concept, and operational approaches for the new system/equipment and gross estimates of the reliability and maintainability, ... of each design and operational approach.

40.2.1 Manpower and Personnel Constraints. ... manpower and personnel shortages (both in terms of quantity, skills, and skill level) will continue for the next decade or more. The problem is of such magnitude that it must be approached through the design process as well as the more traditional manpower and personnel approaches of the Services. ...

40.2.2 System Readiness. Logistics-related design parameters (such as R&M), logistics support resources (such as spares and manpower), and logistics system parameters (such as resupply time) must be related to system readiness objectives and goals. ...

Task 205 requires the contractor to predict the life cycle costs, supportability implications, and the risks of achieving supportability goals of various design approaches, but it does not say how:

Task 205 Supportability and Supportability Related Design Factors

205.2.1 Identify the quantitative supportability characteristics resulting from alternative design and operational concepts for new system/equipment. Supportability characteristics shall be expressed in terms of ... R&M parameters, ... Both peacetime and wartime conditions shall be included. Conduct sensitivity analyses on the variables associated with the supportability, cost, and readiness drivers for the new system/equipment. ...

205.2.2 Establish supportability, cost, and readiness objectives for the new system. Identify the risks and uncertainties involved in achieving them. Identify any supportability risks associated with new technology.

205.2.3 Establish supportability-related design constraints for the new system/equipment for inclusion in specifications, other requirements documents, and contracts as appropriate. ...

Task 303 gives the contractor a more detailed and comprehensive "wish list," again with no clue as to how:

Task 303 Evaluation Of Alternatives And Tradeoff Analysis

303.2.1 b. Select or construct analytical relationships or models between supportability, design, and operational parameters....

303.2.5 Estimate and evaluate the manpower and personnel implications of alternative system/equipment concepts in terms of total numbers of personnel required, job classifications, skill levels, and experience required. ...

303.2.6 Conduct evaluations and tradeoffs between design, operations, training, and personnel job design to determine the optimum solution for attaining and maintaining the required proficiency of operating and support personnel. Training evaluations and trades shall be conducted and shall consider shifting of job duties between job classifications, alternative technical publications concepts, and alternative mixes of formal training, on-the-job training, unit training, and use of training simulators.

303.2.8 Evaluate alternative diagnostic concepts to include varying degrees of built-in-test, off-line-test, manual testing, automatic testing, diagnostic connecting points for testing, and identify the optimum diagnostic concept for each system/equipment alternative under consideration.

303.3.6 TASK INPUT [from DOD] Manpower and personnel costs for use in appropriate tradeoffs and evaluations which include costs related to recruitment, training, retention, development, and washout rates.

Similarly ...

Task 402 Early Fielding Analysis

402.1 PURPOSE ... identify sources of manpower and personnel to meet the requirements of the new system/equipment....

402.2.1 ... This assessment shall examine impacts on depot workload and scheduling, ... automatic test equipment availability and capability, manpower and personnel factors, training programs and requirements ... and shall identify any changes required to support existing weapon systems due to new system/equipment requirements.

402.2 Analyze existing manpower and personnel sources to determine sources to obtain the required manpower and personnel for the new system/equipment. Determine the impact on existing operational systems from using the identified sources for manpower and personnel.

Task 401, however, ties in closely with human engineering function and task analyses. One can generate a detailed task inventory based on the system design and its intended use. This task inventory can form the foundation of manpower requirements and training development. Furthermore, the task inventory and its skill requirements can be validated before design freeze through system mockups:

Task 401 Task Analysis

401.1 PURPOSE. To analyze required operations and maintenance tasks for the new system/equipment to ... identify new or critical logistic support resource requirements, ... identify support requirements which exceed established goals, thresholds, or constraints, ... provide data to support participation in the development of design alternatives to ... enhance readiness, ... and provide source data for preparation of required integrated logistics support documents (technical manuals, training programs, manpower and personnel lists, etc.).

401.2.1 Conduct a detailed analysis of each operation and maintenance task requirement identified (Task 301) for the new system/equipment and determine the following:

a. Procedural steps required to perform the task to include identification of those tasks that are duty position-specific ... or collective tasks.

c. Task frequency, task interval, elapsed time, and manhours.

d. Maintenance level assignment based on the established support plan (Task 303).

401.2.4 Based upon the identified procedures and personnel assignments, identify training requirements and provide recommendations concerning the best mode of training.... Document the results in the LSAR....

401.2.9 Validate the key information documented in the LSAR through performance of operations and maintenance tasks on prototype equipment ... using the procedures and resources identified during the performance of 401.2.1....

50.4.2 ... the following will be determined for each operations and maintenance task:

e. Training and training materiel required along with recommended training locations and rationale.

f. Procedural steps required to perform the task.

i. Interval for and the frequency of task performance in the intended operational environment.

The annual operating basis for task frequencies must be carefully selected and widely understood to prevent misuse of the information generated by this task.

Thus MIL-STD-1388-1, which governs logistics support analysis, repeatedly recognizes the requirement to translate design features into maintainability, manpower, personnel, training, readiness, and life cycle cost implications. It tasks both the Air Force and the contractor, although predominantly the latter. But it offers <u>no</u> quantitative tools to translate design features into repair times, manpower slots, training costs, etc.

C. Manpower Requirements Analysis

AFSC DESIGN HANDBOOK 1-9, MAINTAINABILITY (FOR GROUND ELECTRONIC SYSTEMS)

Sub-note 1(1) of chapter 1 is a block diagram of the M sphere of influence. It shows system M connecting through human factors to task analyses, safety factors, manning requirements, training, man-machine interface, skill requirements, and documents/manuals. It also shows system M connecting through DFM to malfunction analysis, repair versus discard, support equipment, and interchangeability, among others.

Yet section 2B of the handbook, Tradeoff considerations -- while exploring techniques for trading off M with cost, downtime, and reliability -- is silent about how to trade off M with manpower or training.

SECTION 2C of the handbook presents a series of tradeoff curves between manning, system availability, and the ratio of system failure rate to system service rate, given the maximum number of units simultaneously needing service and the number of spare units available. The curves are derived from a simple queuing model in which manning is equated to the number of simultaneous "service channels" available (i.e., it assumes one person is necessary, sufficient, and allotted to repair each system in the queue). There is no insight about how to predict the system service rate for new designs, and the effects of individual maintenance tasks cannot be taken into account. The graphs are therefore of very limited value.

The Logistics COmposite Model (LCOM)

(The first five paragraphs of this section summarize information from the Task Identification and Evaluation System survey of maintenance task data bases, by Walter Driskill, The Texas MAXIMA Corporation, 31 July 1986. The last three paragraphs present my analysis.)

LCOM is the official Air Force manpower prediction technique. It is a Monte Carlo simulation of aircraft maintenance turnaround in an operational environment. It is a detailed and complex simulation to run, but has proven to be the most accurate manpower prediction method within DoD. LCOM is currently being used by the operational commands, Aeronautical Systems Division, and several major airframe contractors.

First, the operational scenario is modeled, including the logic of the operation and any rules or constraints. Data describing the scenario for a flight operation would include such factors as sortie rate, sortie type, takeoff time, sortie duration, number of aircraft, weapon configuration, weather factors, and rules for scheduled maintenance. With this information the operational scenario can be simulated in Monte Carlo fashion. The simulation will calculate when and how many aircraft must be available for succeeding missions, and when these aircraft will return, requiring turnaround.

Next, the maintenance scenario is modeled, including when and how often each subsystem is likely to fail, what tasks are necessary to fix it, and the probable task times. These data are collected via comparability analyses using the Air Force Maintenance Data Collection System and subject-matter experts. When input to the Monte Carlo simulation, specific aircraft will return from sorties with specific failures and undergo a set of specific maintenance actions before being available for a succeeding mission.

The final input into LCOM is supply data including type of resource, cost, authorization, valid substitutes, failure rates, stock levels, support equipment, etc. During the simulation, use of maintenance resources and their costs are tracked. Furthermore, a shortage of a required rescurce will block the repair cycle in the simulation as it would in real life.

LCOM is basically a resource counter. It simulates a maintenance queue. Specific failures and fixes occur based on the probabilities fed into it. A post-processor computes statistics based on many accumulated failures and repairs as the operational scenario proceeds. LCOM's principal virtue is that the interactive effects of manpower, supply, support equipment, reliability, maintainability, basing mode, etc. on sortie generation can all be studied at once. Typically one runs many simulations with different combinations of all these variables to note when sortie generation falls below a threshold value. One can see the impact of changing the proposed R&M of each subsystem. LCOM is ideally suited to "what if" questions with regard to the operational or maintenance scenarios.

How well does LCOM address this chapter's questions? For specific operational scenarios and specific manpower structures, it can translate generalized maintainability statistics into predictions of manpower requirements and estimations of system readiness. It in essence converts mean times to repair and probabilities of correct repair into sortie generation capability and (via Air Force Occupational Measurement Center data on standard skills/career specialty code) trained personnel (M & T) requirements.

It cannot, however, define new optimum Air Force specialties; i.e. reallocate maintenance tasks among various maintenance specialists for an optimum tradeoff between turnaround times, T times, aptitude requirements, total M requirements, and skill retention. It cannot address the effects of M & T requirements on life cycle costs. It cannot address the conversion of specific design features into M statistics but rather starts with task times fed into it. Thus, it is only as accurate as the task times are. In fact, because LCOM's inputs are products of comparability analyses, it shares their dependence on the similarity between the new system and its predecessors.

LCOM is an important link in the required chain of transformations, but the neighboring links are still missing.

D. Macro Human Factors Engineering And Life Cycle Costs

M-related Life Cycle Costs (LCC), as opposed to reliability-related LCC, are the costs of the PROCESS of system maintenance, rather than the cost of the parts going into the system. This translates primarily into maintainer costs: the costs of acquiring, training, and retaining sufficient numbers of competent personnel to maintain the system within readiness requirements. It also translates into support equipment costs, which by tradition are only included in overhead.

DFM can lower M LCC by lowering the time to perform maintenance; by reducing requirements for multi-person maintenance teams; and by lowering the skill requirements of the maintainer to diagnose, remove, repair, and replace the faulty component. These measures, in turn, reduce the number of maintainers required, their aptitude requirements, and their training requirements. Because maintenance manpower typically consitutes the largest number of personnel in an aircraft squadron, and because personnel-related expenses are the largest cost in the AF budget, reducing skilled personnel requirements can greatly reduce LCC.

Are current cost estimating techniques sufficient to predict LCC consequences of various DFM approaches? First I will summarize information from the following two sources. Then I will offer my personal analysis about what is still needed for understanding DFM influence.

AFR 173-13, USAF COST AND PLANNING FACTORS; &

OPERATING AND SUPPORT COST ESTIMATING, A PRIMER FROM THE AERONAUTICAL SYSTEMS DIVISION

The AF estimates costs by using models and data bases. Cost data bases document costs on currently deployed weapon systems. Cost strategies and models attempt to extrapolate this information to new designs. I will present the models and strategies first.

Models and Strategy

The primary AF cost estimating model is CORE (Cost-Oriented Resource Estimation model). This model is a series of formulas combining cost factors, mostly via summation and multiplication. AFR 173-13 lists the the formulas in tables 7-1 and 7-4, and covers the necessary cost factors in its first six chapters. (I will summarize the cost factors below.) The CORE model's cost structure is hierarchical in nature so that lower levels of indenture add to higher levels, allowing estimating techniques to vary as the program progresses and more detail becomes available.

A second class of models stem from the Logistics Support Cost model, but these have very detailed input data requirements and therefore are not often used. Complexity is not a desirable trait in cost modeling; the cost, labor, and schedule required to set up data for a complex model often prohibit its timely use.

Three categories of cost estimating formulas given in tables 7-1 and 7-4 are relevant to M: 1) Unit Mission Personnel (including unit maintenance personnel), 2) Depot Maintenance, and 3) Acquisition and Training of Personnel.

Unit Maintenance Personnel are the sum of organizational-level maintainers, intermediate-shop-level maintainers, ordnance personnel, and "other." Aircrew, except for the E-3 and E-4 maintenance stations, are not relevant. The "other" unit personnel are not affected by design for M.

The CORE model estimates unit maintenance personnel requirements using maintenance manhours/flighthour. The maintenance manhours include the time spent servicing, inspecting, and repairing aircraft components, both on and off the aircraft. at base level. AFALDP 800-4, Acquisition Management Historical Reliability And Maintainability, provides maintenance manhours/flighthour estimates for inspection and correction, while the using command estimates the maintenance manhours/flighthour for servicing. The CORE model multiplies these numbers by typical costs per hour of appropriately skilled maintainers, yielding maintainer cost/flighthour. Finally, the CORE model multiplies these costs by the total anticipated flight hours per year, yielding maintainer costs per year. Although this approach is simplistic, most organizations do not prefer to use more sophisticated and cumbersome cost estimating relationships.

These cost estimates are based on peacetime maintenance data, but the AF must also staff maintenance organizations to meet wartime requirements. There is therefore some planned slack in these estimates because 1) the expected maintenance manhours/person-month will increase from 144 to 244, 2) the 75% peacetime maintainer efficiency may also increase if not directly affected by the enemy, and 3) the required maintenance manhours/flighthour will decrease as flying rates increase.

Often cost analysts will use scaling techniques instead of starting from scratch with each new system. They will choose a baseline system in the current inventory and adjust its manpower documents for the new system. They will use subject-matter-expert knowledge for both baseline and new systems, and thoroughly document the rationale to enable comparison. Or they will scale upward or downward from the reference system, based on expected changes in maintenance manhours/flighthour, after separating the fixed portion from the variable portion of the reference's manning. Or they will use maintenance manhours/sortie for cyclical systems such as landing gear. Scaling takes expert opinion up one level of abstraction to maintenance manhours/flighthour, rather than maintenance manpower directly.

Depot Maintenance labor costs, similarly, are tabulated and predicted in labor hours times the hourly wage, rather than the number of whole people times the annual wage at base level. This is due to the fact that depots are large activities where employees are seldom dedicated to one particular system. Support equipment is periodically returned to the depot for repair; however, an adequate data base has not been developed to support an estimate, so it is simply included as overhead.

Acquisition and Training costs are based on AFR 173-13 data. These include the costs for recruiting, the weighted average cost of commissioning (Reserve Officer Training Corps Air Force Academy, Officer Training School, Airman Education & Commissioning Program), and/or the cost of basic training. The CORE model multiplies these numbers by the numbers of enlisted and officer personnel required, and by the turnover rates. These cost figures include specialty training.

Data Bases

Unit manning documents typically contain the number of authorized personnel by work center, position, Air Force Specialty (AFS), and rank.

The Maintenance Data Collection System, AFM 66-267, provides the primary source of operational and intermediate maintenance manhour data via the Maintenance Data Collection Record, AFTO Form 349, which is filled out for each maintenance action. It includes the work unit code of activity performed, the type of malfunction, and the manhours expended.

The H036B system provides the primary source of depot maintenance manhour data. It includes the frequency with which reparable items are returned to the depot, and the average labor and the average material costs to repair these items. Unlike the AFM 66-1 system, which collects data by individual weapon system, the H036B system collects data by the national stock number of the hardware item, as the vast majority of items are common to two or more systems. Simple allocation techniques to individual weapon systems have proven inadequate.

The Weapon System Cost Retrieval System (WSCRS) is a formal, state-of-the-art Air Force Logistics Command reporting system covering 174 weapon systems, solving many problems in using data from other systems. It collects and allocates historical depot maintenance and item condemnation costs to individual weapon systems using sophisticated allocation techniques.

AFR 173-13 summarizes information on existing systems and is updated annually. Averaged costs are provided for, among other things: crew composition, typical squadron manpower, support equipment, depot maintenance, base maintenance supplies, civilian standard composite pay and allowances by grade and category, civilian standard composite pay rates by AF Major Command (MAJCOM) and Separate Operating Agency, enlisted personnel acquisition costs by Air Force Specialty, officer personnel acquisition costs by source, military AF-wide standard composite rates by grade, military pay rates per month/week/day/hour by grade, turnover rates and reassignment costs, simulator costs by aircraft type, life cycle costs per flying hour by aircraft type, and initial training costs.

The most important data source to the cost analyst is the functional area expert. MAJCOM manpower organizations house the manpower estimation expertise. System program office engineering shops house R&M expertise.

What's Missing?

To predict the effects of DFM on life cycle costs using the above resources, one must first convert a proposed design to its repair time implications, its required skill implications, and its multi-person maintenance task requirements. One must next translate these into manpower, aptitude, and training requirements.

If these manpower, aptitude, and training requirements are similar to those of existing systems, the above models and data bases provide excellent cost estimations. Suppose, however, that a new system under development will result in any of the following conditions:

A maintainer will perform each maintenance task less frequently because of increased system reliability, so that s/he has less practice to maintain proficiency and must take refresher training.

A maintainer will be responsible for repairing a larger number of subsystems (for example, all avionics-related or all engine-related repairs), made possible by increased system maintainability, so that s/he must be proficient in a greater breadth of skills.

Fewer total maintainers are used because of increased system reliability and maintainability, lowering personnel acquisition requirements but amortizing training costs over fewer students.

New technology requires new maintenance skills for which there is no experience base (for example, repairing composites, reconfigurable avionics, or advanced digital flight controls).

New deployment modes will change overseas rotation requirements, which will, in turn, change retention rates of skilled maintainers.

New training technology is available for which we have no effective data on AF enlistees as yet.

How could one predict the manpower, aptitude, and training requirements along with their life cycle cost implications in these cases without strong precedents? Current cost analyses are based on extensive empirical data, not theoretical understanding of weapon system cost cause-and-effect. Thus, extrapolations to new design approaches, new training technology, new operation or deployment concepts, differing aptitude requirements, or differing manpower structures are very difficult.

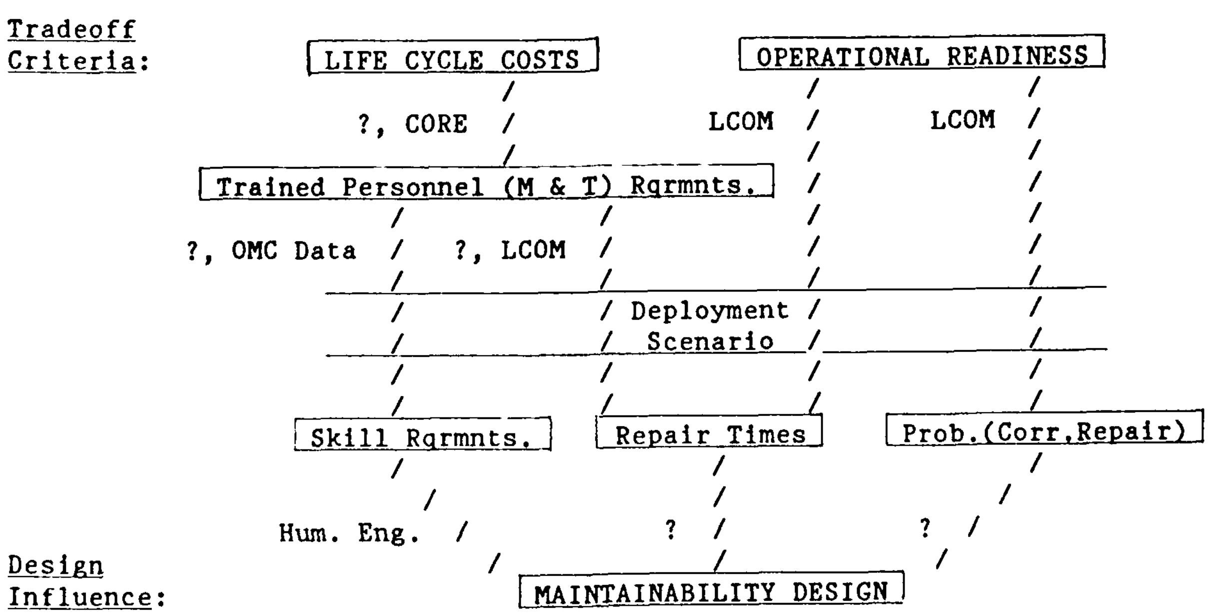
E. Summary of DFM Influence

Logisticians use two principal evaluation criteria for performing system design tradeoffs: operational readiness and life cycle costs. The first criterion essentially measures how long/often the system is capable of performing its mission. The M design contributes to readiness by minimizing system downtime between fully-mission-capable states. The second criterion measures the system's total resource requirements for development, purchase, and ongoing operation. The M design lowers system life cycle costs, among other ways, by reducing system requirements for skilled maintainers - the Air Force's most expensive resource. The influence of a specific design approach on readiness or life cycle cost is determined by the deployment scenario.

The following chart shows my conception of the paths of influence (vertically upward) between the M design and these tradeoff criteria. Only shown are the paths of interest to this chapter - those for which the Air Force currently has a critical lack of understanding. The M design will also influence readiness and life cycle costs via provisioning requirements, support equipment requirements, and maintenance planning; but these effects are more straightforward to predict.

Any of these parameters may be firmly constrained prior to design. Trained personnel requirements are increasingly limited by Congress. The ability to acquire some skills may be limited by enlistee demographics. Repair times and the probabilities of correct fault detection/isolation/repair are limited by maintainability allocations. Sometimes even system life cycle cost and operational readiness are firmly specified prior to system development; usually, however, they are left open for optimization during design. These constraints all drive the M design, but only indirectly and after-the-fact unless the vertical links can be rigorously analyzed.

The questionmarks show which links I believe to remain poorly understood for significantly new design approaches.



3. DESIGN FOR MAINTAINABILITY (DFM) AND HUMAN ENGINEERING

HOW DOES MAINTAINABILITY FORMALLY RELATE TO HUMAN ENGINEERING?

In chapter 2 of this paper both MIL-STD-470 and MIL-STD-1388-1 were shown to tie into human engineering functional decomposition and the derivation of a detailed task inventory. MIL-STD-470 states that functional block diagrams, removal and replacement task definitions, built-in-test equipment operating interface data, and removable unit sketches were some of the information required to implement detailed M predictions. These are within the province of human engineering. MIL-STD-1388-1 Tasks 301 and 401 call for function and task analyses akin to human engineering functional decomposition.

This resulting task inventory can be part of the bridge between system design and system M & T requirements. Once functions and tasks are derived for a proposed design, their times to perform and their skill requirements can be scoped through 1) comparability analyses or 2) human engineering simulations in system mockups before a prototype is built. They cannot necessarily, however, provide feedback on how to rework a design whose task times or M & T requirements are too high.

In chapter 1, by far the biggest DFM references found were in the human engineering standard, MIL-STD-1472, and the human factors engineering design handbook, AFSC DH 1-3. Chapter 1 also contained references to human engineering, with suggestions on how the contractor may generate his/her own maintainability design guidelines.

Thus both preceding chapters found human engineering resources to be most useful in designing for M and predicting the consequences. This surprised me since I have seldom personally known human engineers and R & M engineers to collaborate in acquisition. I therefore investigated just how well the maintainability and logistics standards formally tied into human engineering contributions.

MIL-STD-470, MAINTAINABILITY:

101.2.1.f [A maintainability program plan shall be prepared and shall include the following:] ... (1) how M, testability, and diagnostic tasks will interface and be integrated with other system-oriented tasks (i.e. ..., human factors, personnel, ...), and (2) how duplication of effort will be avoided. ...

104.2.1 ... Data collection should be integrated as much as possible with similar data collection requirements, such as reliability, Logistics Support Analysis, etc.

204.2.2 Information (from Failure Modes Effects Analysis) shall be integrated with FMEA/FMECA efforts for related areas, such as reliability, LSA, safety, human factors, and technical manual preparation.

205.2.4.1 Tradeoffs between M design alternatives and equipment design parameters shall be made ...

205.2.4.2 Whenever design tradeoffs are performed in other areas which impact M, the effects ... shall be evaluated, documented, and reflected in the M analysis. ...

40.1.4.4 ... some of the M influencing factors to be considered at PDR are adherence to specifications, form, fit, function, human engineering factors, packaging, and compatibility with other specifications.

40.1.4.4.1 [At PDR:] ... design decisions may be required as to redundancy versus rapid fault isolation techniques, or redesign of inaccessible areas versus a search for high reliability parts. The latter is a typical example of the extensive interface between M and reliability.

40.2.5.6 Valuable and necessary inputs to the M analysis task are obtained from among the following:

a. Reliability analyses and predictions.
b. Human factors studies which recommend skill levels and quantities of personnel required.
c. System Safety Analyses.
d. Cost analyses tasks.
e. Manufacturing process analyses.

MIL-STD-1388-1A, LOGISTICS SUPPORT ANALYSIS:

4.1.1 Maximum use shall be made of analyses and data resulting from requirements of other system engineering programs to satisfy LSA input requirements. Tasks and data required by this standard, which are also required by other standards and specifications, shall be coordinated and combined to the maximum extent possible. ...

40.1.3 Interfaces. ...

a. Tradeoff Analysis (Task 303). Interfacing activities - design engineering, reliability, maintainability, safety, human engineering, cost estimating, and ILS element managers.

b. Task Analysis (Task 401). Interfacing activities - reliability, maintainability, human engineering, and safety.

c. Resource Requirements Identification (Task 401). Interfacing activities - design engineering, human engineering, and ILS element managers.

40.1.3.3 Task Analysis Interfaces. LSA includes the requirement for all task analysis; however, specific task areas (e.g., operator tasks or critical maintenance tasks) may be analyzed as part of the human engineering program to provide the required input. Additionally, detailed task analysis input data are generally supplied by reliability, maintainability, and safety specialists. ...

102.2.1 ... The LSA Plan shall include ...

3. a description of how LSA tasks and data will interface with other ILS and system-oriented tasks and data. This description will include ...

(3) System/Equipment Maintainability Program.

(4) Human Engineering Program.

(13) Training and Training Equipment Program.

Task 203 Comparative Analysis.

50.2.4.7 ... this task can be performed by specialty areas and the results consolidated under the LSA program. For example, manpower, personnel, and training analysis may be performed by human engineering and training specialists, and maintainability comparisons may be done under the maintainability program.

Task 301 Functional Requirements Identification.

50.3.2 ... other system engineering programs provide a significant input to the functional requirements identification process. For example, human engineering specialists may be best qualified to identify and analyze operations functions, transportation specialists may be best qualified to identify and analyze transportation requirements etc. ...

Task 401 Task Analysis.

50.4.2.3 Task analysis is probably the area of LSA program which requires the most coordination and interfacing in that it involves essentially every system engineering discipline and ILS functional element manager. ... When not properly interfaced, task analysis can be a very costly process which duplicates other analyses and generates incompatible ILS products. Design, reliability, maintainability, human engineering, safety, and others are all involved in satisfying the task analysis requirements of Task 401. ...

Task 501 Supportability T&E

50.5.1.2 ... Development of an effective test and evaluation [T&E] program requires close coordination of efforts between all system engineering disciplines to prevent duplication of tests and to maximize test program effectiveness. Reliability tests, maintainability demonstrations, ... and other tests shall be used in satisfying supportability assessment requirements. ...

When the AFSC design handbooks discuss DFM criteria they often cite the human engineering design standard, MIL-STD-1472, for anthropometry guidance such as access hole size and reach limitations. Curiously, however, I found no references to the DFM section (5.9).

In return, do human engineering documents cite logistics references?

MIL-H-46855, HUMAN ENGINEERING PROCEDURES FOR MILITARY SYSTEMS, EQUIPMENT, AND FACILITIES:

3.2.1.3.1 Gross Analysis of Tasks. The analysis shall provide one of the bases for making design decisions; e.g. ... assuring that human performance requirements do not exceed human capabilities. These analyses shall also be used as basic information for developing preliminary manning levels; equipment procedures; skill, training, and communication requirements; and as Logistic Support Analysis inputs, as applicable.

3.2.2.5 Equipment Procedure Development. ... the contractor shall apply human engineering principles and criteria to the development of procedures for operating, maintaining or otherwise using the system equipment. ... This effort shall be accomplished to assure that the human functions and tasks identified through human engineering analysis are organized ... for efficiency, safety and reliability, to provide inputs to the Logistics Support Analysis where required, and to assure that the results shall be reflected in ... operational, training and technical publications.

3.2.3.1 ... Human engineering testing shall be incorporated into the system test and evaluation program and shall be integrated into engineering design and development tests, contractor demonstrations, flight tests, R&D acceptance tests and other development tests. ...

In short, the ties among disciplines, particularly M, human engineering, and M&T, are comprehensively called out in all appropriate standards and handbooks. It is odd that these connections are not reflected in Air Force organizations. Air Force R&M specialists, manpower requirements analysts, training planning specialists, and human engineers each exist in separate communities, with their own regulations, jargon, and training. These underlying communities are logistics, tactical/strategic planning, psychology, and engineering, respectively. IMPACTS (Integrated Manpower, Personnel, And Comprehensive Training and Safety), a fairly new management initiative whose future seems uncertain at time of this publication, is the first comprehensive Air Force approach to integrating these disciplines. Whatever the approach, I believe the DFM process urgently needs a formal Air Force integration of these disciplines.

APPENDIX A

DEPARTMENT OF DEFENSE PUBLISHED DFM GUIDANCE

ELECTRONIC SYSTEMS DIVISION'S
READINESS IMPROVEMENT THROUGH SYSTEMS ENGINEERING (RISE)
HANDBOOK

Method 1, Atch 3, Specification Requirements for R & M

3.4.2.1.6 Maintainability Design Criteria. The design of each newly developed or modified item:

b. Shall be such that failure, damage, or removal of one item will not cause damage or failure of any other item.

c. Shall contain only one isolable function on a physically isolable item; it is desirable to have one module for each isolable function.

d. Shall require no special fixtures (e.g., extender cards) for functional isolation procedures; should be in the operational configuration during functional isolation.

e. Shall have items which are physically self-supporting during prescribed maintenance and which can be laid on a work bench without damage.

f. Shall have accessibility of physically isolable items in accordance with MIL-STD 454, requirement 36.

g. Shall have test points in accordance with MIL-STD-454, requirement 32.

h. Shall have easily removable items.

i. Shall have interchangeable replacement items.

j. Shall have easily and correctly replaceable items, which should not fit in the wrong location or orientation.

k. Shall have accessible adjustments; should have fewest possible adjustments.

l. Shall require the same or less storage and shipping requirements for each item as for the system.

m. Should represent reasonable design compromises to obtain the following:

(1) minimum required maintenance technician skill level and training.
(2) minimum tools and test equipment selected in the prescribed priority.
(3) discardable assemblies (i.e., standard modules).
(4) minimum number of different items (i.e., standard).
(5) minimum connections between the system and replaceable items.

5.3.2 Marking and color coding

5.3.2.1 Marking of test points. All test points shall be permanently labeled to provide the clearest designation possible, both in terms of identification and legibility. Particular attention shall be given to the environmental conditions under which the test point must be identified in the equipment installation. Where space permits, a complete word description of the test point shall be provided. Otherwise, carefully chosen abbreviations or reference characters may be used. If possible, the within-tolerance range to be measured at the test point shall be included in the label. Waterproof ink shall not be considered as a permanent marking unless suitably protected against all environments to which it will be exposed.

5.3.2.1.1 Multiple test points. When sequential testing is required, test points shall be grouped in a line or matrix reflecting the sequence of tests to be made. An outlined matrix array of test points shall also be used when multiple test points are associated with a single system. Each test point shall be assigned an alphanumeric designation and appropriately referenced in the applicable maintenance instructions.

5.3.2.2 Marking of meters. Meters shall be so marked that they may be read with ease, accuracy, and speed; and when a voltage or current is to be held within limits corresponding to a given sector of the meter scale, that sector shall be clearly marked for ease of observation. Meters used in conjunction with selector switch mechanisms shall be similarly labeled according to space limitations on the meter face. Otherwise, the subsystem or circuit designation and within-tolerance range shall be specified at each switch position.

5.3.2.3 Color coding of test points. All external test points shall be color coded for different voltage range to provide an indication of the type of signal to be obtained. Encirclement notes danger.
...

MIL-STD-454
DESIGN CRITERIA FOR ELECTRONIC EQUIPMENT

Requirement 28 Controls

4.2.2 Adjustment controls. Adjustment controls that are required for periodic alignment or calibration shall be mounted behind covered openings, such as access doors, on the faces of the equipment most accessible when installed. When not adjustable by hand, controls shall be designed to accept a common screwdriver blade tip. Controls which infrequently require adjustment need not be accessible from the operating panel, but shall be readily accessible for servicing when the equipment is opened for maintenance purposes. Unless otherwise specified, infrequently required controls should be screwdriver adjusted.

Requirement 36 Accessibility

4.1 Access. Each article of equipment and each major subassembly forming a part thereof shall provide for the necessary access to its interior parts, terminals, and wiring for adjustments, required circuit checking, and the removal and replacement of maintenance parts. Accessibility for testing replacement does not apply to parts located in nonreparable subassemblies or assemblies. For routine servicing and maintenance, unsoldering of wires, wire harnesses, parts, or assemblies shall not be required in order to gain access to terminals, soldered connections, mounting screws and the like. Inspection windows shall be provided wherever necessary. Sizes of openings, maximum reach requirements, and allowable sizes and weights of replaceable assemblies shall conform to limits established in MIL-STD-1472.

4.2 Connections. Connections to parts inside a removable container shall be arranged to permit removal of the container without threading connection leads through the container.

4.3 Parts. Parts which are identified as replaceable parts for the equipment shall be easily removable and replaceable. These parts shall not be mounted by means of rivets, spot welding, or hard curing compounds. If, in order to check or remove a part, it is necessary to displace some other part, the latter part shall, whenever practicable, be so wired and mounted that it can be moved without being disconnected and without causing circuit detuning or instability. No unsoldering or soldering of connections shall be necessary when the front panel or any subchassis is removed for maintenance purposes. Design shall be such that where plug-in modules or assemblies are used, they can be easily inserted in the proper location when correctly oriented without damage to equipment or parts being engaged. Plug-in modules and assemblies shall be designed to prevent insertion when incorrectly oriented.

4.4 Enclosures. Accessibility to chassis, assemblies, or parts contained within cabinets, consoles or other enclosures shall be provided from outside the basic equipment through the use of access doors, by mounting such items on withdrawal slides, swinging doors, through cable extenders and cable retractors, provisions for circuit card extenders which will allow part or module operation in the open position, or other arrangements to permit adequate access for properly servicing the equipment. Automatic or manually operated locks shall be provided to lock the chassis in the servicing position. When withdrawal slides are used they shall be of guided sectional construction with tracks and rollers. Complete removal and access for servicing of electronic equipment contained within cabinets, consoles or other enclosures shall be provided from either the front or rear of the equipment. Guide pins (or locating pins), or the equivalent shall be provided for mechanical alignment during mounting. Shipboard equipment shall have complete access for maintenance and servicing from the front of the equipment.

Requirement 63 Special Tools

4.2 Furnishing and stowing. Special tools needed for operation and organization level maintenance shall be furnished by the contractor and shall be mounted securely in each equipment in a convenient and accessible place, or in a central accessible location for an equipment array requiring such tools.

5. Information for guidance only. The design of equipment shall be such that the need for special tools for tuning, adjustment, maintenance, replacement, and installation shall be kept to a minimum. Only when the required function cannot be provided by an existing standard tool shall special tools be considered. Necessary tools shall be identified as early as possible. The use of any special tool shall be subject to the approval of the procuring activity.

Requirement 67 Marking

4.6 Fuse holders. The current rating of fuses shall be permanently marked adjacent to the fuse holder. In addition, "SPARE" shall be marked adjacent to each spare fuse holder.

4.7 Connections. Marking adjacent to plugs, jacks, and other electrical connectors shall identify the connected circuits to preclude cross-connections. ...

4.9 Controls and indicating devices. Markings shall be provided on the front of each exterior and interior panel and panel door, also on control mounting surfaces of each chassis, subpanel, etc., to clearly (though necessarily briefly) designate the functions and operations of all controls, fuses, and indicating devices mounted thereon, protruding through, or available through access holes therein. All markings shall be located on the panel or chassis in correct relationship to the respective designated items.

4.10 Sockets. The chassis shall be marked to identify both sockets and parts, modules, or assemblies to be plugged into the sockets. The side of the chassis upon which items are plugged into sockets shall be marked, adjacent to each socket, with the reference designation for the item. The reverse side of the chassis shall be marked, adjacent to each socket, with the reference designation used in the circuit diagram and table of parts to identify the socket itself. If space does not permit marking of reference designations for sockets and parts, modules, or assemblies mounted in sockets, a location diagram shall be placed where it is visible when viewing the chassis, and shall display the markings described herein.

4.11 Cables, cords, and wires. All cables, cords, and wires which require disconnection to remove units for servicing and maintenance shall be uniquely identified.

4.12 Modules. Replaceable modules shall be marked with the following data (listed in order of decreasing precedence as space permits): identifying number, terminal identification, ratings, and wiring diagrams, as applicable.

(There are also numerous references to other marking standards.)

Requirement 54 Maintainability & Requirement 63 Human Engineering

(Neither of these offer specific design criteria, but they reference other standards: MIL-STD-470, MIL-STD 471 (Maintainability Demonstration), MIL-STD 721 (Definitions Of Effectiveness Terms For Reliability, Maintainability, Human Factors, And Safety), MIL-HDBK-472, MIL-H-46855, & MIL-STD-1472.)

MIL-STD-1472
HUMAN ENGINEERING DESIGN CRITERIA FOR
MILITARY SYSTEMS, EQUIPMENT, AND FACILITIES

SECTION 5.9 Design for Maintainability

Table Of Contents:

CHAPTER 3 AEROSPACE VEHICLE SAFETY DESIGN

DN 3H2 Installation Safety Objectives

3. Maintainability considerations. The recognition of the maintenance impact on the electrical system of the vehicle is imperative in the design stage. Inherent M must be consciously established; it is difficult and costly to attain after development. Design has achieved a high degree of M when the maintenance operations can be performed safely, quickly, easily, accurately, and economically by personnel of average ability and aptitude.

3.1 Accessibility. Accessibility is a prime maintainability problem. The system safety impact centers primarily in the area of delayed or omitted periodic maintenance, operator error, and accidental damage to immediate or adjacent equipment because sight, reach, or manipulative functions are impaired. ...

3.2 Personnel. In design and development, include features for safety of personnel during maintenance, repair, interchange, or operation of electrical equipment. Give consideration to proper grounding, shielding, interlocks, safety guards, barriers, and warning markings. Minimize the hazards of electrical shock during routine maintenance; even small voltages can generate currents that are hazardous to health. Consider the limits of human strength in the various maintenance activities. When equipment is heavy, bulky, slippery, or unique in shape, provide mechanical guides, handholds, rails, slides, or other aids to make a safe and rapid installation or inspection. Generally, the recommended lift limits for one man are 6 kg (14 lb) for portable equipment, 18 kg (40 lb) for frequently lifted equipment, and 34 kg (75 lb) for infrequently lifted equipment. Further, design so that the maintenance tasks can be performed with minimum numbers and types of tools, and with minimum crew training commensurate with maintenance proficiency.

3.3 Equipment. Design replaceable equipment so that it cannot physically be installed improperly. Use proper connector keying, coded shapes, asymmetrical mounts, and other means to prevent inadvertent maintenance errors. Design for rapid positive identification of equipment malfunction and, further, for the rapid positive identification of the replaceable defective assembly or component. Simple design which permits rapid isolation and repair of the faulty item reduces the possibility of creating additional damage during the troubleshooting process. Minimize the complexity of maintenance tasks by employing a simple design which includes interchangeability and standardized components. Reduce excessive maintenance time and possible electrical malfunctions as a result of loose or lost hardware by employing captive components such as doors, covers, and fasteners where practicable. Where possible, design to permit system test functions without removing the component or using temporary (cheater) cables or external stimuli. As a design goal, eliminate the need for maintenance by using sealed components, self-adjusting, self-compensating, and self-calibrating equipment where possible and practicable.

DN 3H4 Inspection And Maintenance

2. Inspection and maintenance considerations

2.1 Accessibility. Where possible, determine that inspection for incipient malfunction or system degradation can be performed in areas not requiring removal of covers, access doors, or equipment. Utilize windows or other suitable visual access in frequently inspected areas. Ensure proper and convenient identification of the components requiring inspection. Locate displays on faces of equipment which are accessible from a normal position. Incorporate methods of protection from accidental contact with dangerous voltages. In the areas of frequent inspection, minimize the hazards of sharp edges, protrusions, adjacent hot exhausts and ducts, or the presence of toxic fumes.

2.2 Personnel and equipment. Where maintenance activities are performed, ensure that all required test equipment is compatible with the environment, and adequate instructions and procedures are readily available to cover all the areas of activity. Provide for means to isolate all power from the specific equipment to facilitate maintenance or removal and to ensure personnel safety. Ascertain that the removal of power does not adversely affect the remaining system components. Provide equipment in which potentials above 1000 volts peak are to be measured with voltage-divided test points so that such voltages can be measured at lower potentials relative to ground. Interlocks and safety switches may be required; however, consider the effects of disabling an electrical component by the interlock. Ensure that it does not create an abnormal condition elsewhere in the system (i.e.,. expended ordnance, loss of stores, interruption of critical flight functions). Avoid the requirement for maintenance or inspection in areas where vibration or noise reaches an unpleasant or annoying range in readiness or operation. The noise of generators, inverters, gyros, and similar equipment will degrade the performance of personnel because of increased irritability or fatigue. In addition, tools, dials, and controls may be hard to manipulate when vibrating, and errors can occur. Design to minimize any maintenance requirements in an area where equipment manipulation can constitute a fire hazard, or where toxic vapors may be liberated. Where possible, design so that internal adjustments and controls, or maintenance of complex circuitry requiring high degrees of skill and manipulations need not be accomplished while the vehicle is in a standby, readiness, or operational mode. Such inspection and maintenance functions belong more properly at higher service echelons.

DN 4E2 Installation And Maintenance

2. Accessibility. Design so that the removal or replacement of a unit requires opening of only one access unless the accesses are either the latched or hinged type. Locate items requiring visual inspection (e.g., elapsed time or similar readouts) so they can be observed without the removal of panels or other components. Ensure that visual access is provided for all operations requiring visual control and particularly where hazards are present within the access. Where accesses are located over unavoidably dangerous mechanical or electrical components, design the access door to actuate internal lighting, and provide a high visibility warning placard on the door to point out such hazards. For additional information, see ... MIL-STD-1472.

2.1 Access configuration. Design access doors to the shape necessary to permit passage of components and implements which must pass through the opening. Access openings need not necessarily be conventionally shaped such as square or round. If, for example, structural members in units prevent an access of conventional shape being made large enough for the function it must serve, design the access to whatever shape is required. Use a hinged door where physical access is required (instead of a cover plate installed with screws or other fasteners). On hinged access doors place the hinge on the bottom or provide a prop so that the door will stay open without being held. If lack of available space for opening the access prevents use of a hinged opening, use a cover plate with captive quick-opening fasteners. If a hinged access or quick-opening fasteners will not meet stress, pressurization, or safety requirements, use the minimum number of the largest screws consistent with these requirements.

2.2 Visual inspection areas. Use an opening without a cover unless it is likely to degrade system performance. Use a plastic window if dirt, moisture, or other foreign materials are a problem. Provide a break-resistant glass window if physical wear or contact with solvents will cause optical deterioration of the glass. Use a quick-opening metal cover if glass will not meet stress or other requirements. Where required, use materials for openings and windows that will provide electromagnetic interference protection for internal and external fields.

2.3 Personnel Safety. Provide edges of accesses with internal fillets, or with rubber, fiber, or plastic if the edges might otherwise injure the technicians' hands or arms. Provide safety interlocks on accesses which lead to equipment with high voltages. If the technician may need to work on the equipment with the circuit on, provide a bypass switch that automatically resets when the access is closed. ... Provide screwdriver guides to adjustment points which must be operated near high voltages. Provide handles even on small lightweight units which would otherwise be difficult to grasp, remove, or hold without using delicate components as grips.

2.4 Location. ... Determine which faces of the unit will be accessible in normal installation and place accesses on one of these faces. Place all accesses, displays, controls, and cables on the same face of a unit whenever possible. Locate access openings to permit maximum convenience in performing job procedures.

3. Maintainability. ...

3.1 Structure. Employ foldout construction of subassemblies whenever feasible. Position parts and wiring to prevent damage to them from opening and closing the assembly. Attach permanently only interconnecting wiring and structural members to the unit chassis. Provide a brace or some other means to hold hinged assemblies in the "out" position while they are being worked on. Provide rests or stands on which units can be set to prevent damage to delicate parts. If feasible, design the rests or stands to be a part of the basic chassis. Make stress members of units strong enough to withstand the usual blows received during handling and transporting for maintenance purposes. Ensure that units are small and light enough for one man to carry and handle, whenever this is feasible (see

SUB-NOTE 3.1(1)). Design units so individuals handling them are protected from sharp edges, points, heat, and electrical charges. Ensure that irregular extensions, such as bolts, cables, wave guides, and hoses, are easily removable before the unit is handled as such protrusions are easily damaged and make handling of the unit awkward. Provide handles on units weighing more that 4.5 kg (10 lb) to assist in removal, replacement, or carrying. Provide handles even on small lightweight units which would otherwise be difficult to grasp, remove, or hold without using delicate components as grips.

3.2 Mounting and assembly. Provide field replaceable assemblies and subassemblies such as electrolytic condensers, relays, and miniaturized throwaway circuits with plug-in rather than soldered connections. Use no more than four screws for mounting a major unit in an installation unless stress or electromagnetic interference considerations require more. Ensure that assemblies and units are replaceable with conventional hand tools. Mount units which must frequently be pulled out of their normal installed position for checking on roll-out racks, slides, or hinges. Provide guide pins on units and subassemblies for alignment during mounting. Provide limit stops on roll-out tracks and drawers to prevent their being dropped. Provide overrides on such limit stops to allow replacement of racks and drawers.

3.3 Component location. Locate delicate components where they will not be damaged while the unit is being worked on. Do not locate resistor boards in a position where personnel are likely to strike them with their hand or arm when making adjustments. Avoid locating components, which retain heat or electrical potential after the equipment is turned off, where technicians are likely to touch them while changing commonly malfunctioning parts such as tubes. Orient all miniature tube sockets with the gap (key slot) facing in one direction to expedite replacement. If maintenance procedures require tube replacement, avoid the necessity of removing units from their installation to make such replacements. Locate all fuses so that they can be seen and replaced without removing any other parts or subassemblies. Tools should not be required for replacing fuses. In general, locate components so that:

a. There is sufficient space to use test probes, soldering irons, and other required tools without difficulty.

b. Tubes can be replaced without removing assemblies and subassemblies.

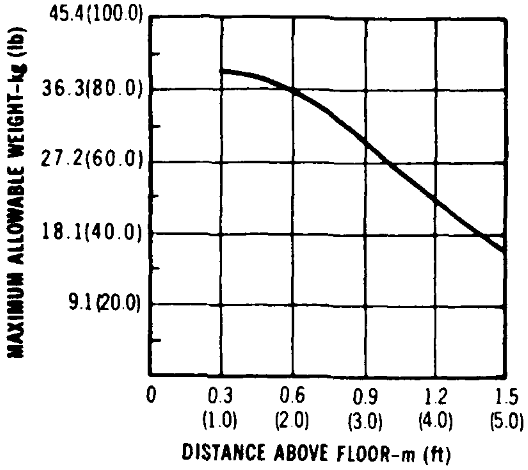
c. Resistors, capacitors, and wiring do not intefere with tube replacement.

d. Structural members of units do not prevent access to components.

e. All throwaway assemblies or parts are accessible without removal of other components.

3.4 Wire and cables. Provide cables long enough so that (1) each functioning unit can be checked in a convenient place (use extension cables where this is not feasible), (2) units in drawers and slide-out racks can be pulled out without breaking electrical connections, and connectors can be reached easily for replacement or repair, and (3) units which are difficult to connect when mounted can be moved to a more convenient position for connecting and disconnecting their cables. Ensure that the length of cables is the same for each installation of a given equipment if circuit functioning may be significantly affected by differences in cable length. Route cables so that they cannot be pinched by doors, lids, or covers, and cannot be walked on, abraded, chafed, or used for handholds. Flexible cables, when stored in their normal poistion, should have a means of retracting automatically. In addition, ensure that cables require no sharp bending and unbending when they are connected or disconnected. Provide guards or other protection for easily damaged conductors such as wave guides, high-frequency cables, or insulated high-voltage cables.

SUB-NOTE 3.1(1) Weight Lifting Capacity*



NOTE: THESE LIMITS ARE NOT APPLICABLE TO TASKS REQUIRING CARRYING THE ITEM MORE THAN A FEW STEPS

*Extracted from *MIL-STD-1473*

CHAPTER 6 MICROCIRCUIT APPLICATIONS

DN 6B2 Static And Electromagnetic Hazards

4. Static electricity

c. Many state-of-the-art microelectronic devices such as Complimentary Metal Oxide Semiconductors (CMOS), N-type Metal Oxide Semiconductors (NMOS), Field Effect Transistors (FET), certain linear and certain digital types are vulnerable to damage caused by static electricity. Sources of static charge or high electric fields which may lead to damage include the human body, machine handling, trioelectric effects involving the device itself and/or materials in the environment. Special handling and maintenance procedures are essential. See ... DOD-STD-1686 (Electrostatic Discharge Control Program For Protection Of Electrical And Electronic Parts, Assemblies, And Equipment), DOD-HDBK-263 (Electrostatic Discharge Control Handbook For Protection Of Electrical And Electronic Parts, Assemblies, And Equipment), MIL-H-3851 (Microelectronic Circuits), and MIL-STD-803 (Human Engineering Design Criteria FOr Aerospace Systems And Equipment) for more information.

6. Packaging and marking of electrostatic discharge sensitive (ESDS) items

d. ... Marking of the package is of paramount importance so that personnel who handle, store or stow these items are aware that they are ESDS and take the necessary ESD precautions ...

DN 6B3 Maintenance And Logistics

2. Disposal-at-failure. Microelectronic circuits should be packaged into replaceable modules of high reliability and of a cost that causes disposal-at-failure, rather than consideration of module repair, to be the cost effective and economical logistic support action. As a design goal those modules should incorporate built-in test so that they identify their own faults when they malfunction. Reliability, design complexity, functional use, functional groupings, minimum circuit path breaks, ease of fault location, ease of replacement, and supply support cost are typical tradeoff factors used to determine the number of integrated circuits the module should contain. The physical construction of integrated circuits and their eventual combinations into modular units legislates against replacement of individual integrated circuits. This replacement would entail unncessarily complex specialized test equipment to isolate the fault and to ensure functional performance after repair. In addition, specialized removal and insertion equipment for these integrated circuits would be required. Further, such maintenance practice tends to limit the rapidly advancing state of the art of microelectronics wherein individual microelectronic components are becoming increasingly complex, thereby decreasing the number of components to accomplish the same function.

5. Skill levels. The technical skills required at base-level maintenance can be limited to those necessary to remove and replace modules and functionally check the equipment. The number of maintenance personnel can be reduced due to the inherent reliability associated with microelectronics.

6. Design considerations. ... The design considerations are:

a. Each electronic subsystem will include an indication to the operator that the whole subsystem is or is not functioning satisfactorily.

b. An electronic subsystem will consist of one or more line (flight) replaceable units (LRU), each of which will have an elapsed time indicator to permit recording of hours or multiples of hours of LRU operation.

c. Each LRU will have a built-in go-no-go test capability. The design of the LRU will incorporate sound testability criteria to ensure that all critical paths are test point accessible and that logical isolation and identification of faults can be accomplished in a minimum amount of time.

d. The next lower assembly of the LRU is a module. An LRU can be one module or can consist of two or more modules.

j. Where discrete electronic component parts are combined with integrated circuits in a module, the module will be considered a microelectronic module.

k. Modules should contain, insofar as practical, complete functional circuits and must not require matching to other modules.

f. Replacement of defective modules would normally not be accomplished at the flight line; however, in the case of transport or bomber type aircraft, such replacement at failure during flight can be a design consideration.

i. Cost, physical configuration, and functional circuit complexity must be considered in the design of modules of microelectronic equipment. Until extremes of reliability are feasible, the normal module cost will be $1000 or less. As reliability of individual modules can be increased to above 10,000 hours mean time between failures, the optimum module cost can be increased to take advantage of the resultant decrease in connectors and circuit path breaks.

l. Circuit design should achieve maximum stability with minimum adjustments (minimum adjustments as to both quantity and frequency).

m. Electronic sybsystems, modules and circuit design specifications should include requirements for the use of circuit protection/protective devices, where appropriate, when it is necessary to use static-sensitive components or devices in areas of high susceptibility to electrostatic discharge damage.

n. Electronic subsystem components consisting of more than one module should include adequate provisions for Telemetry Data Acquisition Points (DAPs) or test points on critical signal paths to enhance fault-isolation capabilities.

CHAPTER 5 DESIGN CONTROLS

SUB-NOTE 5(1) Maintainability Design Guidelines

1. Design for minimum maintenance skills. Some technicians are neither well trained nor well motivated.

2. Design for minimum tools. Special tools and laboratory test equipment may not always be available.

3. Design for minimum adjusting. Adjustment for shift, drift, and degradation should not be necessary in most cases.

4. Use standard interchangeable parts wherever possible; special parts create problems.

5. Group subsystems (e.g., power supply components) so that they can be located and identified easily. (Use colors.)

6. Provide for visual inspection. Burned resistors, diodes, and broken terminals can be located quickly if they are visible. Visible tube filaments and heaters are helpful.

7. Provide troubleshooting techniques - panel lights, tell-tale indicators, built-in-test panels, etc.

8. Provide test points. Use plain marking and adequate spacing and accessibility.

9. Label units. The nomenclature of labels on top of components should agree with that of instruction manuals to aid in the location of suspected components.

10. Use color coding. (Choose colors carefully; about 6% of the population are color blind.) Use differently colored wires and tracers to facilitate the troubleshooting of wiring harnesses.

11. Use plug-in rather than solder-in modules. Ease of replacement avoids errors and mutilation of harnesses.

12. Orient all sockets in the same direction to eliminate the need for looking at each key position (especially tube sockets).

13. Use captive-type chassis fasteners that can be manipulated without tools and cannot be lost.

14. Avoid the use of large cable connectors where possible. Label connectors and key them so that they cannot be inserted improperly. Provide adequate separation between connectors. Wherever possible, follow the same letter from connector to connector (e.g. A-A-A-A-). Use "P" for plate, "C" for collector, etc.

15. Provide handles on heavy components for each handling.

16. Use BAD-GOOD meters, red-line meters, or tolerance bands. Where possible, avoid using meters that must be read and evaluated from a document or table. Place controls for metered parameters adjacent to meters. (Use colors.)

17. Design for safety. Use interlocks, safety covers, and guarded switches.

CHAPTER 4 FACTORS THAT INFLUENCE MAINTAINABILITY

SECTION 4C DIAGNOSTIC AND TESTING METHODS

DN 4C1 Selection Of The Test Approach

1. Introduction. ... The categories that will be considered are (1) no testing, (2) internal and external manual testing, and (3) internal and external semiautomatic and automatic testing. ...

2. No testing. The only factors other than maintenance time to be considered for the no-testing category are:

a. Cost - Is the system or equipment inexpensive enough to be discarded upon failure?

b. Logistics - Will the supply situation allow replacement equipments or systems to be available for use when failures occur?

3. Automatic, semiautomatic, and manual testing. Factors other than maintenance time to be considered in selecting from among the categories ... : development time for test equipment, test equipment cost, operational plan of deployment of end item, ... maintenance load, readiness requirements of prime equipment, maintenance echelon involved ..., simplicity or complexity of the test equipment, and training costs.

3.1 Necessary conditions. Automatic and semiautomatic testing should be considered only when ... :

a. Turnaround time or downtime must be held to an absolute minimum.

b. Many repetitive measurements must be made.

c. Maintenance loads are heavy.

(Note that missing is the rationale often cited today: restricted maintenance manpower or training time.)

3.2 Design choices. ...

a. How should the test equipment be programmed (punched tape, manual setup of parameter values by operator, magnetic drum)?

b. How should test results be displayed (go/no-go lights, meters, color-coded readout, etc.)?

c. ... should testing branch automatically into an isolation routine?

Worth noting is SUB-NOTE 4(1) Factors in Test Equipment Selection and SUB-NOTE 4(2) Advantages and Disadvantages of Built-In Test Equipment.

SUB-NOTE 4(1) Factors in Test Equipment Selection

FACTOR	ELEMENT	RATING		
		BUILT-IN	SPECIAL PURPOSE	GENERAL PURPOSE
Maintenance Technician	Personnel acceptance	High	Medium	Low
	Personnel safety	High	High-Medium	Medium-Low
	Complexity of test equipment operation	Low	Medium	High
	Time to complete tests	Least	Medium	Most
	Personnel training time	Least	Medium	Most
	Tendency to over-depend on test equipment	High	High	Low
Physical Factors	Limits on size of test equipment	Minimum limits; depends on prime equipment and application		Maximum limits; limited by portability
	Limits on weight of test equipment	Minimum limits; depends on prime equipment application		Maximum limits; limited by portability
	Complexity of "wiring in" test equipment	High	High	Low
	Need for additional test points in prime equipment	None	None	Many
	Wanted space in work areas	Least	Some	Most
	Storage problems	None	Medium	Many
	Need for traffic considerations	Low	Medium	High
Maintainability and Reliability	Probability of test equipment damage	Low	Low	High
	Probability of damage to prime equipment caused by testing	Low	Low	High
	Effect on prime equipment operation of repairing test equipment failures	Some	Slight	None
Logistics	Cost to incorporate test equipment	High	Medium-High	None
	Test equipment procurement time	High	Medium	Low
	Design-engineering effort	High-Medium	High-Medium	Low
	Compliance of test equipment to same specifications as prime equipment	Must	May	May
Application	Advantage of long duration and high-frequency usage is given location	High	High-Medium	Low
	Versatility of application	Low	Low	High
	Opportunity for incorrect usage	Low	Low	High
	System adaptability to new test equipment	Low	Medium	High

SUB-NOTE 4(2) Advantages and Disadvantages of Built-In Test Equipment

ADVANTAGES	DISADVANTAGES
1. Minimizes requirements for external support equipment.	1. Resulting hardware is heavier, larger, and requires more power. Requires compromise on part of designer as to minimum number and types of tests that could be performed on tactical equipments without exceeding weight and size limitations.
2. Minimizes downtime required to troubleshoot equipment. Also decreases service-induced failures and possible injury to repairman by allowing fault isolation to be performed without needless probing into interior of equipment.	2. Increases complexity of prime equipment, thus increasing development effort, cost, and time. Also increases maintenance to be performed on prime equipment and system.
3. Identifies performance degradation by operating personnel in sufficient time to avoid serious breakdowns.	3. Difficult to calibrate test facilities because of inability to separate these facilities from prime equipment.
4. Increases system confidence through availability of monitoring facilities.	4. Requires additional self-checking features to ensure that degradation of test facilities does not go unnoticed.
5. Assures that modifications of prime equipment are made concurrently with integral test facilities.	5. Requires extreme caution in selection of tests to be performed. Change in procedures of later date requires equipment redesign. Inflexibility in this area is limiting factor.

DN 4C2 Fault Location Requirements

1. Performance monitoring. Performance monitoring features in equipment and systems are not included for M. They are provided primarily to inform operating personnel of the operational status of sections of the equipment or system. Therefore, selection of the system parameters to be monitored and the monitoring technique to be used are not M design considerations. If performance monitoring features are included in a system design, they can be used by maintenance personnel to some extent for fault location. ...

2. Number of test points. ... A test point is generally required for each output from, and each input to, every unit that is replaceable ... (an output from one unit may be at the input to another unit; in such cases only one test point may be required). Test points may be either the signal sensing type or the signal injection type. Comments in this DN pertain to both types. In addition, if adjustment facilities are provided on a given unit, a test point must be provided that will permit direct observation....

SUB-NOTE 3.1(1) Data-Flow Patterns Encountered In Electronic Systems graphically summarizes the guidance in this DN.

DN 4C3 Implementation Requirements

2. Test point accessibility. The accessibility of test points is a major consideration only when the use of external test equipment is part of the selected test plan, since built-in-test equipment (BITE) ordinarily is connected permanently to the appropriate test locations. Maximum accessibility is achieved when all test points are brought to the outside of the item being tested. If manual testing methods are employed, logical grouping (from the viewpoint of signal flow) and clear marking are also required for the best accessibility. SUB-NOTE 2(1) shows desirable test point arrangements. With automatic and semiautomatic testing methods, the test points should interface with the tester through a minimum number of multiple-contact connectors located on the face of the item.... Less preferable, but acceptable, is the internal location of individual test points (for manual testing) close to the circuit elements for which they serve as input or output points. These locations should be easily accessible and system operation should not be interrupted to engage the test point. Similarly, connectors to be used with automatic and semiautomatic testers may also be located inside the item, under the same conditions....

3. Sensing. ... The sensing may consist of detecting the presence or absence of a voltage; detecting the magnitude of a passing signal; sensing the number of events, changes, or pulses during an increment of time; or determining the period of time necessary for a voltage to rise to a specific level. ...

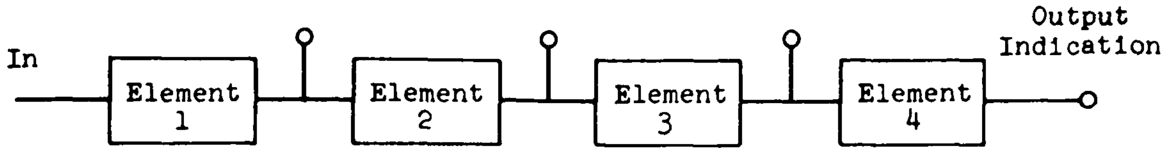
3.2 Sensors. ... Passive sensors perform their functions with unpowered circuits, e.g., voltage-divider networks and integrating circuits. Active sensors use powered circuits, e.g., amplifiers and flip-flops. Wherever possible, sensors used for testing should be passive. ...

3.3 Failure Effects. ... Although passive sensors are usually designed with high-impedance inputs to provide decoupling across the interface of sensor and prime system, the input components can fail in a manner that will transfer shorts, grounds, and various degrees of loading to prime circuits. ... special care should be exercised in selecting and derating the components of a sensor ... Since active sensors require the application of operating power, ... additional interfaces are involved ... with a power supply. In addition, active sensors can affect prime systems in more subtle ways - for example, if improperly designed, they can inject transients into prime circuits when inputs and outputs are switched.

SUB-NOTE 3.1(1) Data-Flow Patterns Encountered in Electronic Systems

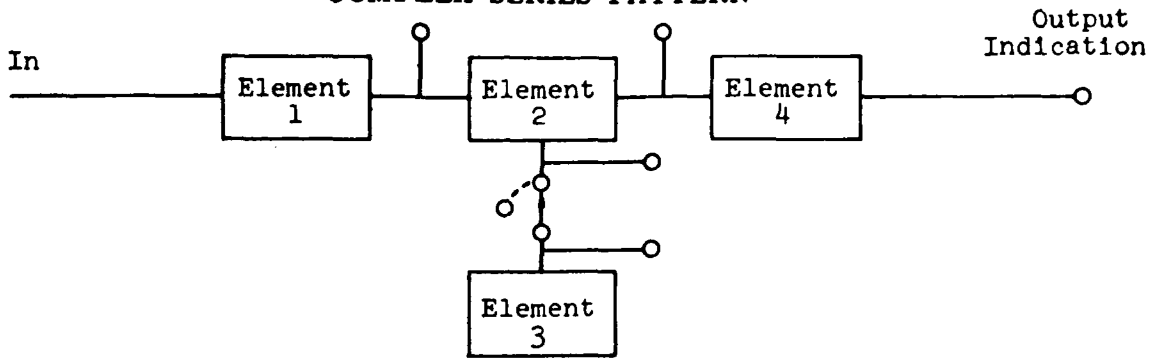
A

SIMPLE SERIES PATTERN



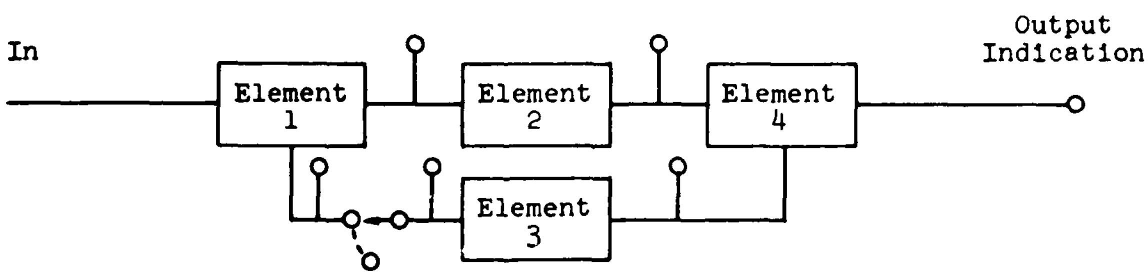
B

COMPLEX SERIES PATTERN

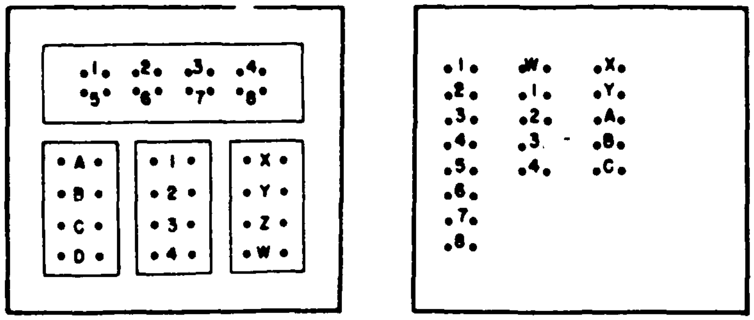


C

LOOP PATTERN

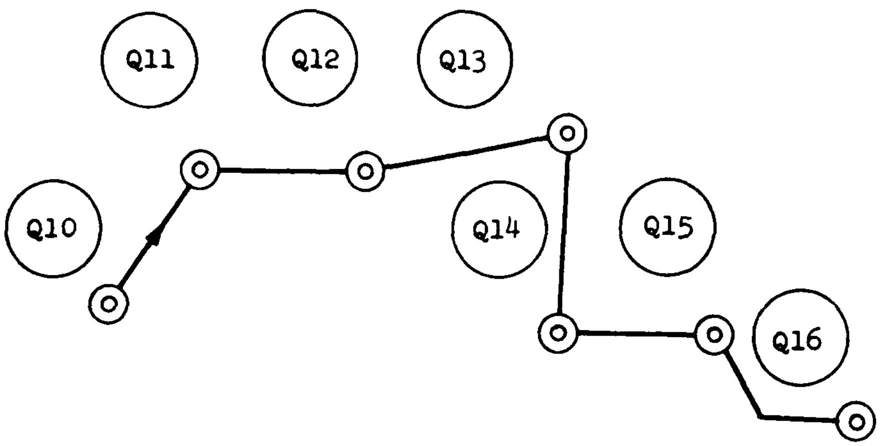


SUB-NOTE 2(1) Desirable Test-Point Arrangements *

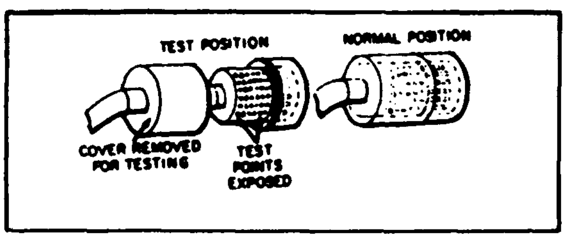


Use This Do Not Use This

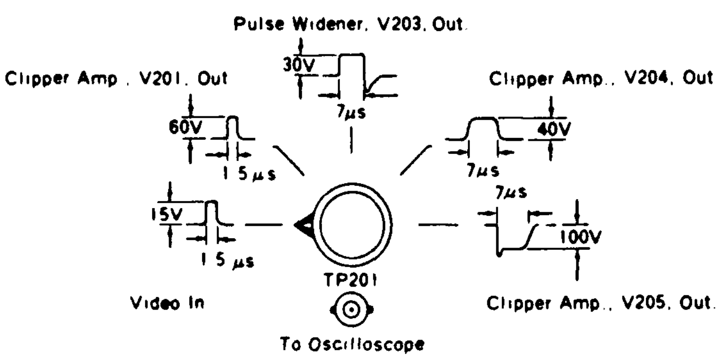
Grouping of Test Points [1]



Signal-Flow Test-Point Arrangement [2]



Test Points with Built-In Covers as Part of Connector Plug (for testing inputs and outputs that cannot be easily checked otherwise) [3]



Test-Point Selector Switch [4]

* Extracted in part from Ref 224(C)

4. Processing methods. After a parameter is sensed, it may sometimes be necessary to process the sensor output by converting from analog to digital, or vice versa ...

4.1 General conversion requirements. As a general guide, conversion should take place as near to the test point as possible for three reasons:

a. Analog signal leads in many critical situations can be kept short, thereby reducing the chance of unwanted radiation or pickup.

b. Each converter can tailor its output signal to match standard input acceptance characteristics of the switching matrix, which need not be located near the signal source.

c. Digital signals can be switched without the substantial losses sometimes encountered in analog switching. ...

4.3 Conversion parameters. The rate of change of the test signal, the number of signals applied over a period of time, and the magnitude of the signal required for resolution are the three basic parameters that must be accounted for in the design of the analog-to-digital converters. These parameters are expressed in terms of sampling rate, aperture time, and quantum steps of digital level.

4.3.1 Sampling rate. ... The rate must be adjusted to permit sampling of an analog sine wave at least twice per cycle of the highest significant frequency so the digital device can accurately interpret the signal. ...

4.3.2 Aperture time. Aperture time is the period between samplings. During this period the value of the sampled signal may increase, decrease, or remain stable. The equipment usually operates on the basis that the signal value has remained at the last sample's level. For a sine wave, the maximum error will occur as the signal passes through zero. For this case the percent error can be derived as 2 X pi X frequency X aperture time. In actual cases, aperture time and sampling rate have a direct bearing on the switching speed and the number of signals a converter can handle accurately.

4.3.3 Quantum steps of digital level. ... The quantum step can be considered as the smallest change in analog signal that will produce a change in digital output. This value is the least significant bit of information that the converter can handle; the digital output will be accurate to within one-half of that value.

5. Switching methods. Switching functions are common to all test approaches. ... the specific switch employed will represent a compromise among cost, convenience, size, weight, reliability, and accuracy. ... As the amount of testing increases, the switching function becomes more complex. As the number of switching devices increases to meet this increased complexity, it is convenient to arrange the switches in matrixes to simply control. ... Many mechanical and solid-state devices are available and can be used for any test application devised.

5.1 Electromechanical switching. ... Relays allow contacts to be operated simultaneously; when individual units are operated in parallel, the number of available contacts is practically unlimited.

5.2 Electronic switching. ... Transistors ... offer significant improvements in speed over electromechanical components and the advantages of small size and low power consumption. ... Solid-state devices are subject to leakage currents, which prevent the device from fully isolating the control signal from the switched signal. In addition, some leakage current is always flowing in the switched circuit. This leakage may be critical in certain designs. Electromechanical components, by contrast, offer true on/off switching.

SUB-NOTE 5(1) Typical Switch Device Characteristics is a table summarizing switch types and characteristics.

SUB-NOTE 5(1) Typical Switch Device Characteristics

CATEGORY	TYPE	SIZE (INCHES)	WEIGHT	RELATIVE COST*	POWER OR CURRENT HANDLING	PULL-IN TIME	RELEASE TIME	MAXIMUM NUMBER OF CIRCUITS	POWER REQUIRED	RELIABILITY (FAILURES PER MILLION HOURS)
Electro-mechanical Manual	Momentary Switch	½x½x1½	2 oz	$0.40	1000 VA	½ sec	½ sec	2	Human	9
	Toggle Switch	½x½x1¼	3 oz	$0.40	1000 VA	½ sec	½ sec	4	Human	9
	Slide Switch	½x1x1	2 oz	$0.20	500 VA	½ sec	½ sec	3	Human	9
	Rotary Switch	1½x1½x3	8 oz	$1	500 VA	½ sec	½ sec	20	Human	6.3
Electro-mechanical Automatic	Conventional Relay	1x1x2	5 oz	$3-$5	10 A	11 ms	3 ms	4	6 V	100
	Crystal-Case Relay	3/8x3/8x1-1/8	1 oz	$15	2A	5 ms	1.5 ms	2	6 Vdc	5.1
	Reed Relay	½x½x1	1 oz	$6	4 W (up to 250V)	1 ms	0.5 ms	1	6 Vdc	1
	Timer	5x5x3-3/4	½-5 lb	$10-$100	10 A	10 ms	10 ms	2	6-115 V	20
Electronic Automatic	Transistor	1x½x½	1 oz	$0.50-$50	20 A	1 ms	1 ms	1	5 V	8
	Silicon-controlled rectifier	1x½x½	1 oz	$5-$50	20 A	1 ms	1 ms	1	1 V at 1 mA	8
	Silicon-controlled switch	1x½x½	1 oz	$5-$50	20 A	1 ms	1 ms	2	--	8

* Costs for all three categories of switch devices are relative to the cost of a rotary switch.

6. Display characteristics. ... The M engineer has little or no control over display characteristics if external test equipment is to be used. If possible, the use of digital readout should be specified, since this type of display is easier to read and less subject to error. Other maintenance aids to be considered include scope overlays containing sample waveforms for comparison purposes, and the marking of test points with the value to be observed at that point. ...

Paragraph 6 references the human engineering design handbook for design of displays.

SECTION 4D HARDWARE AND CONSTRUCTION contains four good tables. SUB-NOTE 2(1) summarizes recommended equipment physical and visual access. SUB-NOTE 2(2) summarizes preferences for fastener types. SUB-NOTE 3(1) summarizes the preferences for mounting and interconnecting system components. SUB-NOTE 4(1) summarizes different strategies for grouping ccmponents within a circuit.

SECTION 4E MAINTENANCE MANUALS

DN4E1 Maintenance Manuals

2.1 Schematic diagrams. Conventional schematic diagrams are usually the product of drafting expediency, with accuracy and geometric symmetry the apparent objectives. Little thought is given to the actual needs of the technicians. SUB-NOTE 2.1(1) is a conventional schematic representation of a transponder assembly. Some limitations of the illustration are:

a. Functional Scheme - Circuit components are indiscriminately placed merely for efficient utilization of space on the page. There is little consideration of information flow or circuit configuration.

b. Line Complexity - A complex array of lines is required to represent power connections to functional elements and the connection of widely separated components.

c. Functional Definition - Components that are functionally dependent are not grouped or identified.

d. Depiction of Operation and Maintenance Features - Controls, indicators, test locations, etc. are often not clearly labeled or identified.

e. Signal Identity - Major signal flow, feedback, and gating-signal lines are often not identified. Signal tracing is difficult.

... In MIL-M-24100 (Manual, Technical, Functionally Oriented Maintenance Manuals For Equipment And Systems) an excellent technique is described. The diagrams show schematic circuitry superimposed on functional outlines, which in turn are superimposed on system-hardware boundaries.

SUB-NOTE 2.2(1) Preferred Method of Text Presentation illustrates the same transponder according to MIL-M-24100.

SUB-NOTE 2(1) Recommended Equipment Access

DESIRABILITY	FOR PHYSICAL ACCESS	RELATIVE ACCESS TIME	FOR VISUAL INSPECTION ONLY	RELATIVE INSPECTION TIME	FOR TEST AND SERVICE EQUIPMENT	RELATIVE HOOK-UP TIME
Most desirable	Pull-out shelves or drawers	(Quantitative Information Not Available)	Opening with no cover	(Quantitative Information Not Available)	Opening with no cover	(Quantitative Information Not Available)
Desirable	Hinged door (if dirt, moisture, or other foreign materials must be kept out)		Plastic window (if dirt, moisture, or other foreign materials must be kept out		Spring-loaded sliding cap (if dirt, moisture, or other foreign materials must be kept out)	
Less desirable	Removable panel with captive, quick-opening fasteners (if there is not enough room for hinged door)		Break-resistant glass (if plastic will not stand up under physical wear or contact with solvents)			
Least desirable	Removable panel with smallest number of large screws that will meet requirements (if needed for stress, pressure, or safety reasons)		Cover plate with smallest number of large screws that will meet requirements (if needed for stress, pressure, or safety reasons)		Cover plate with smallest number of largest screws that will meet requirements (if needed for stress, pressure, or safety reasons)	

SUB-NOTE 4(1) Circuit Layout Methods

LAYOUT METHOD	DESCRIPTION	RELATIVE FAULT LOCATION TIME
Component Grouping	All components of a similar nature are grouped together in one location. Within each group, all items performing a similar function are subgrouped.	0.74
Circuit Grouping	All similar or identical circuits are grouped together in one location.	0.71
Logical-Flow Grouping	Layout follows block diagram of electronic circuits, with components within each block grouped together.	0.50
Frequency Grouping	All circuits functioning in a particular frequency range are grouped together.	*
Standard Construction	Satisfactory circuit operation is the only criterion used for layout of components.	1.00

* No equipment has been built to this layout.

SUB-NOTE 2(2) Recommended Fastener Types

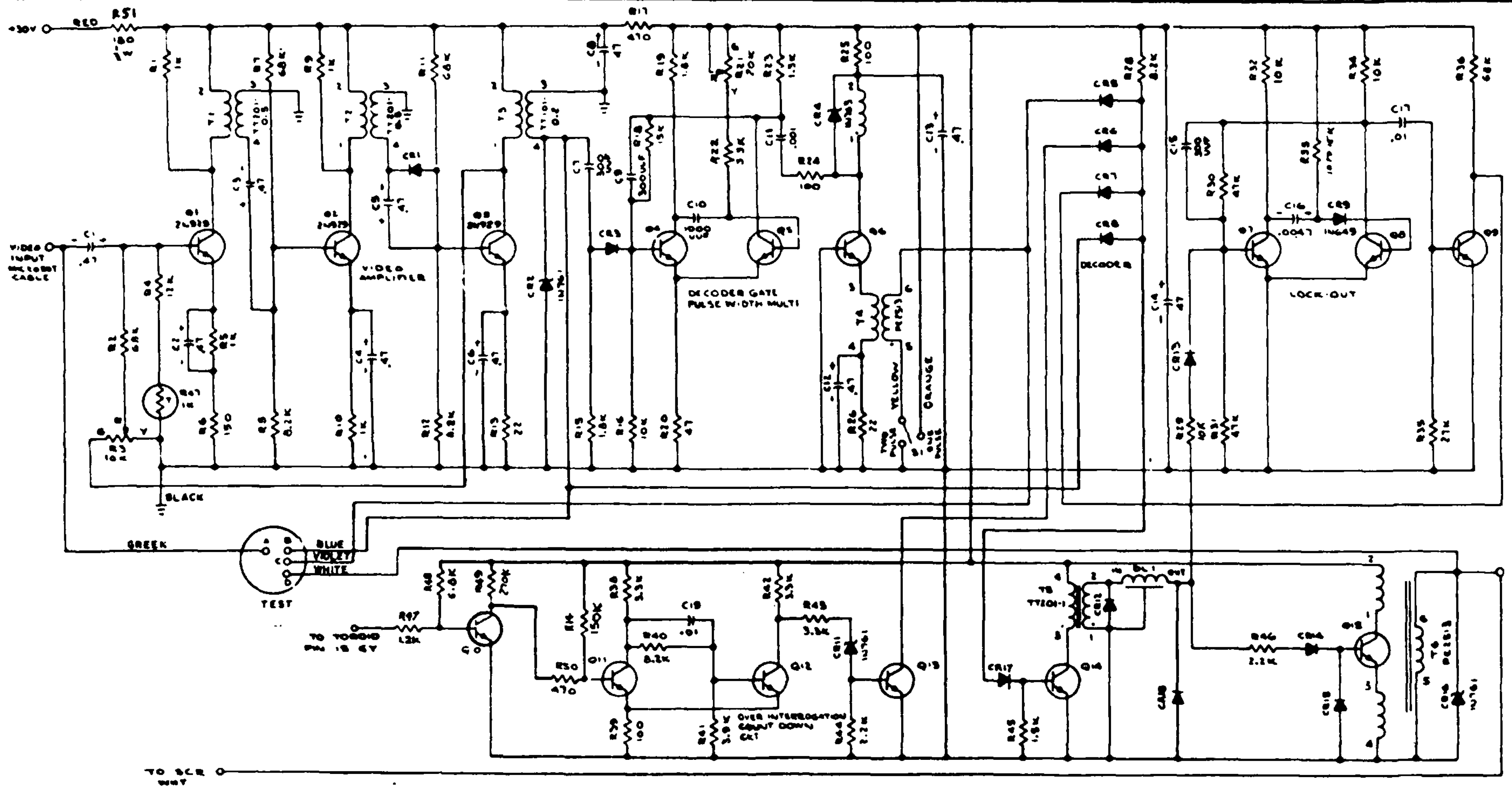
DESIRABILITY	TYPE OF FASTENER	RELATIVE TIME REQUIRED
Most Desirable	Quick Release, Captive	(Quantitative Infor-mation Not Available)
Desirable	Coarse-Thread Screws with Captive Nuts	
	Fine-Thread Screws with Captive Nuts	
Less Desirable	Screw and Non-captive Nut	
	Rivet or Eyelet	
Least Desirable	Melted Metal (Solder, Weld, Braze, etc.)	

SUB-NOTE 3(1) Methods of Packaging

DESIRABILITY	METHOD OF PACKAGING		RELATIVE REMOVAL/ REPLACEMENT TIME
	MOUNTING	INTERCONNECTION	
Most Desirable	(1) Items plugged in to socket on supporting member (chassis, circuit board, etc.) and clamped down	(1) Printed circuits point-to-point wiring, cabling, etc. soldered (or equivalent) to socket	(Quantitative Information Not Available)
Desirable	(2) Items fastened (screws, etc.) to supporting member; contacts completed by attaching a connector or connectors	(2) Same as (1), except to connector(s) instead of sockets	
Least Desirable	(3) Same as (2), except that contacts are completed by attaching individual lead to each contact	(3) Same as (1), except to item contacts instead of socket	

SUB-NOTE 2.1(1) Conventional Schematic Representation of a Transponder Assembly*

* Extracted from Integrated Maintenance Manual, System Sciences Division of Technical Operations Inc., Arlington, VA

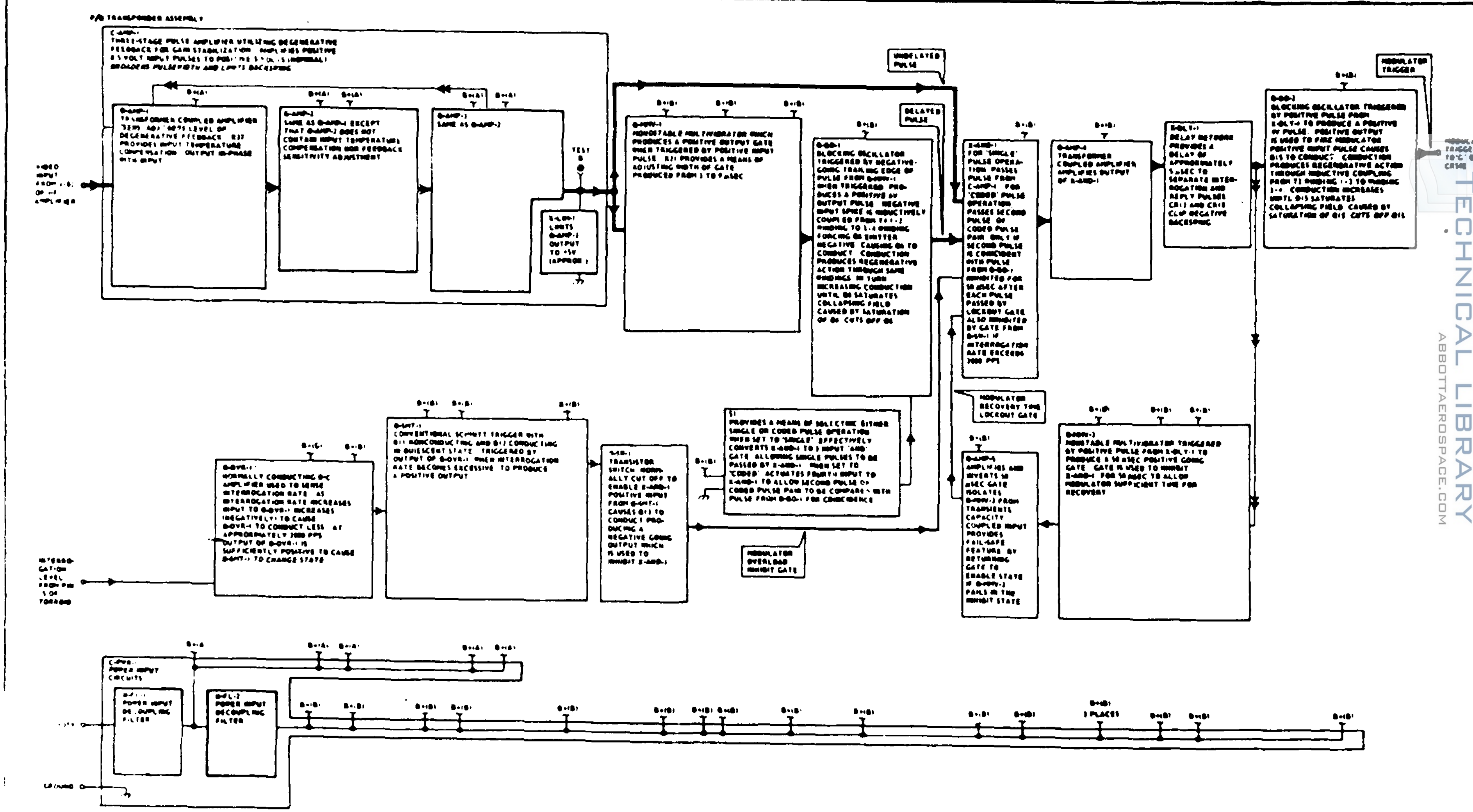


NOTES:

1. TEST
   - A – VIDEO AMPLIFIER INPUT
   - B – VIDEO AMPLIFIER OUTPUT
   - C – DECODER GATE
   - D – MODULATOR TRIGGER
2. EXTERNAL LEADS TO ENCAPSULATED ASSEMBLY ARE COLOR CODED.
3. UNLESS OTHERWISE SPECIFIED:
   ALL RESISTORS ARE IN OHMS, 1/4 W, ± 5%
   ALL CAPACITORS ARE IN UF.
   ALL DIODES ARE 1N916.
   ALL TRANSISTORS ARE 2N718.
4. \# SYMBOL ON R29 VALUE IS FROM 4.7K TO 10K.
5. ALL CKT SYMBOLS PROCEEDED BY 200 EXAMPLE (R240, C220, Q201 ETC.)

SUB-NOTE 2.2(1) Preferred Method of Text Presentation*

* Extracted from Integrated Maintenance Manual, System Sciences Division of Technical Operations Inc., Arlington, VA



CHAPTER 8 NONDESTRUCTIVE INSPECTION (NDI) AND ON-CONDITION MAINTENANCE

SECTION 8A NDI DESIGN CRITERIA

DN 8A1 General Information

1. Purpose. To reduce maintenance and downtime on aeronautical systems during their service life, it is necessary that the methods of nondestructive inspection (NDI) be utilized to their fullest. ... The use of NDI as an on-condition maintenance inspection tool also reduces maintenance costs and virutally eliminates the possibility of maintenance-induced system failures or malfunctions. The application of NDI cannot, however, be done haphazardly. Adequate provisions must be made from the beginning of the design phase....

2. Scope. Nondestructive inspection methods can be applied over a wide variety of aeronautical systems. ... This Chapter will concentrate on describing the five classic methods, ... These classic methods are eddy current, fluorescent penetrant, magnetic particle, radiography, and ultrasonics. ...

3. Further information. ... MIL-STD-1472 ... is an excellent source for the principles and practices used to design systems to human engineering criteria for such applications as accessibility, use of equipment, and placement of hardware in systems.

SECTION 8B NDI METHODS explains how each of the five classic methods works. SUB-NOTE 1(1) of DN 8C3 is a table showing which materials each NDI method can be applied to. SECTION 8C gives detailed NDI design criteria for airframes. SECTION 8D gives detailed NDI design criteria for fluid systems (DN 8D1), mechanical systems (DN 8D2), electrical systems (DN 8D3), propulsion systems (DN 8D4), and ordnance systems (DN 8D5).

The highlights follow.

SECTION 8C AIRFRAME NDI DESIGN CRITERIA

DN 8C2 Defects

1. Dynamic environment

1.1 Tension, shear, and compression. ... Assure that all mechanically joined parts can be readily inpsected at faying surfaces and fastener elements using the best NDI technique, considering accessibility, material, surface treatment, and detection sensitivity requirements for a given part. ...

1.3 Torsion. ... Design parts that are subjected to torsion so that it is possible to inspect from as many different directions as possible. ... Bonded structures under torsion may exhibit failure either along the bond line, in the cell core, or a combination of both. ... Design parts so that maximum access permits radiographic inspection from sufficiently different angles to detect failures in a bond line or cell core. In laminated or composite materials, torsion can produce laminar failures. Neutron radiography and ultrasonics are used to inspect these parts. Design laminates and composites so that they can be inspected in planes sufficiently different to permit detection of any critical failure. When parts which are mechanically joined (welded, fastened, bonded) are subjected to torsion, deformation of faying surfaces often occurs. Design faying surfaces that are subject to torsional deformation so that the plane of the faying surface can be inspected from different angles to detect any critical deterioration of the joint.

SUB-NOTE 1 (1) Materials That NDI Can be Applied To

Penetrant	Magnetic Particle	Eddy Current	Ultrasonic	Radiography
Aluminum	Ferromagnetic materials	Aluminum	Aluminum	All ferrous metals
Magnesium	Note: Do not use on:	Brass	Titanium	All nonferrous metals
Brass		Copper	Brass	
Copper	Aluminum	Steel	Copper	Ceramics
Titanium	Magnesium	Iron	Magnesium	Plastics
Bronze	Brass	Steel alloys	Stainless steel Steel alloys	Composites
Cast Iron	Copper	Iron alloys	Nickel alloys (Inconel, Monel)	Note: Neutron radiography is better for hy- drogenous materials.
Stainless Steel	Bronze	Titanium	Composites	
	Lead	Magnesium		
Nonmagnetic alloys	Titanium		Note: Do not use on: Rubber, Foaming adhesives, or materials that greatly attenuate sound	
Ceramics	Most stainless steels			
Hard rubber				
Plastics				
Glass				

1.4 Chemical reactions. ... Areas in which corrosion can occur include skin seams, welds, lap joints, hinges, fastener holes, exhaust gas paths, landing gear, wheel wells, and enclosures such as avionics bays and wing boxes. ... When dissimilar metals ... are in contact at a faying surface, design the joint so that it can be sufficiently and easily inspected using visual, radiographic, or eddy current methods.

1.5 Thermal cycling. ... After an aircraft lands, ambient temperatures may have changed by as much as 150 degrees or more, which means the structure will undergo cold soak. This then is what creates thermal cycling on airframe and structural members. ... Faying surfaces may open, causing decreased strength at a mechanical joint. Design joints that are subject to thermal cycling so that all faying surfaces can be adequately inspected using visual or radiographic methods. This includes not only the ability to inspect the area with borescopes and/or fiber optics, but also the ability to orient an X-ray beam parallel to the plane of the faying surface(s) being inspected. ... Design parts subject to high internal stresses from thermal cycling so that they may be inspected for surface and shallow subsurface defects using penetrant, eddy current, and magnetic particle methods. ...

DN 8C3 Parts Configuration

1. Material. The choice of material for a structural member places certain inherent constraints on the type of NDI that can be performed. ... Refer to SUB-NOTE 1(1) for a summary of types of materials that can be used with each major NDI method.

2. Geometry. ... Airframe structural members fall into three different broad categories with respect to geometry. These include plane (linear) surfaces, nonlinear curved surfaces, and radii. ...

2.1 Plane linear surfaces. The inspection of plane linear surfaces is the least complicated geometry to deal with. Eddy current, magnetic particle, and ultrasonics are highly adaptable since relatively large areas can be scanned rapidly with little or no setup changes required. The constraint on these methods is that the surface must be sufficiently smooth to permit coupling with the probe or transducer. Design plane linear surfaces so that little or no surface preparation is required to accomplish NDI inspections.

2.2 Nonlinear curved surfaces. ... For parts to be inspected using penetrants, design curved surfaces so that smooth geometrical changes are made, not abrupt ones. The use of ultrasonics on non-linear surfaces also presents a more difficult problem from two aspects. First, it is more difficult to insure proper sound entry from an ultrasonic transducer.... This may require the use of a holding fixture or shoe. ... Second, the interpretation of reflected signals becomes very difficult in a part when the front and back surfaces are not parallel. ... If the material is ferromagnetic, then magnetic particle inspection may be possible. If not, radiography can be utilized for subsurface defects.

2.3 Radii. ... For large radii where the diameters equal or exceed the diameter of the smallest available eddy current probe, this technique can be successfully used to inspect circumferentially as well as longitudinally along the radii of a structural member.... Design small radii (less than approximately 0.125 inch) so that the primary inspection methods used are penetrant and eddy current, with radiography as the third choice. ... In confined or closed-out areas.... Adequate access must be designed into adjacent structure in such areas to permit proper placement of the fiber optics or borescope. ...

3. Surface treatment. Airframe surfaces are generally plated, painted, anodized, or galvanized to protect the part from the effects of corrosion. Plating may be either zinc, cadmium, silver, nickel, or chrome. Design parts to be inspected using magnetic particle so that plating thickness is less than 0.0004-inch thick. ... Eddy current and ultrasonics can be used on painted surfaces with little effect on sensitivity. ... The smoother the inspection surface, the greater the flaw detection capability. For critical inspection areas, design surfaces to be as smooth as possible for maximum detectability.

DN 8C4 Accessibility

1. Part orientation. The orientation of a structural part relative to the access provided for it directly affects the type of NDI that can be performed. Design access to parts to be inspected by penetrant ultrasonics, magnetic particle, and eddy current so that areas on the part to be inspected face in the direction of the access point. Areas of parts to be inspected by radiography must be oriented so that (a) the plane of the anticipated defect is in line with the X-ray beam and (b) the part is located between the X-ray source and the film. ... For fatigue cracks, orient parts to be inspected with eddy current so that scanning across the crack plane can be accomplished. For magnetic particle inspections, the part must be oriented so that a contour probe can be placed across suspected cracks. ... For parts to be inspected with radiography, the orientation of suspected cracks or other defects must be such that maximum contrast will be achieved on the X-ray film between the defect and the adjacent area. For corrosion detection, the area to be inspected must be oriented so that film placement can be readily accomplished. If borescopes or fiber optics are used to detect corrosion, provide direct paths through adjacent structure....

2. Access provisions. Design access provisions to meet anthopometric design requirements of MIL-STD-1472 for the most severe climatic conditions under which NDI inspections will be done. ... Design parts so that, for high-inspection-frequency items, quick-opening panels with captive devices are used. Hinge panels in a direction that permits maximum access for a minimum of two different NDI methods with a minimum hinge movement that will permit panel swing of 150 degrees from a closed point. Use SUB-NOTE 2(1) to to determine minimum access requirements.... To permit maximum visual and physical access, design panels to be used for NDI so that they can be completely removed. Panels must have sufficient length and width to account for parallax of the inspector while viewing and performing the inspection. Locate panels on the aircraft so that direct access to the part is possible through a single panel. ...

3. Local component density. ... Do not locate parts so close together that the area to be inspected is blocked from view when using penetrant or visual inspections. In areas where congestion is unavoidable, design clips, brackets, and attaching hardware to be out of the way of critical inspection surfaces. Space parts so that access around inspection areas is adequate to permit easy use of transducers or probes while wearing protective clothing. Design structure to take maximum advantage of simplest geometry possible for fastening and securing adjacent parts. Use common attach points for securing adjacent clips and brackets with the minimum number of fastener holes consistent with strength requirements. Parts to be inspected using radiography must have sufficient distance around them to allow adequate film and X-ray tube head placement. ...

4. Distance from mold line/contour. ... SUB-NOTE 2(1) illustrates that the deeper the part, the more difficult it is to inspect since the access opening must get larger. Design access to parts requiring NDI so that there is a minimum distance from the mold line to the area for inspection. ... Install high-inspection-frequency items closer to the mold line than low-inspection-frequency items in the same area. Use white paint or primer on closed-out areas and interior compartments of aircraft to allow maximum illumination when using borescopes or fiber optic inspection. If the use of ultrasonics or eddy current is required, design parts to be less than 20 inches from the mold line when access is limited to one arm only, since accurate placement of probe or transducer is not possible beyond this distance. ... Design structure so that adequate means are provided to get rid of excess inspection materials subsequent to NDI by providing sufficient access to allow complete cleanup by personnel through the access hole.

DN 8C5 Environmental Conditions

3. Sand and dust. When sand is blown against a part due to wind, pitting of aircraft surfaces may occur. In addition, this may cause deterioration of surface finish, which will ultimately lead to corrosion of the parent material. If dust is allowed to contact airframe parts in faying surface that move relative to each other, wear and possible part failure will occur. Design such faying surfaces so that inspection with fiber optics, borescopes, or radiography is easily accomplished.

SUB-NOTE 2(1) Arm and Hand Access Dimensions

MINIMAL ONE-HAND ACCESS OPENINGS WITHOUT VISUAL ACCESS

Empty hand, to wrist	Height		Width		
Bare hand, rolled	3.75 in. sq or dia				
Bare hand, flat	2.25 in.	x	4.0 in.	or	4.0 in. dia
Glove or mitten	4.0 in.	x	6.0 in.	or	6.0 in. dia
Arctic mitten	5.0 in.	x	6.5 in.	or	6.5 in. dia
Clenched hand, to wrist					
Bare hand	3.5 in.	x	5.0 in.	or	5.0 in. dia
Glove or mitten	4.5 in.	x	6.0 in.	or	6.0 in. dia
Arctic mitten	7.0 in.	x	8.5 in.	or	8.5 in. dia
Hand plus 1 in. dia object, to wrist					
Bare hand	3.75 in. sq or dia				
Gloved hand	6.0 in. sq or dia				
Arctic mitten	7.0 in. sq or dia				

Hand plus object over 1 in. in dia, to wrist	
Bare hand	1.75 in. clearance around object
Glove or mitten	2.5 in. clearance around object
Arctic mitten	3.5 in. clearance around object
Arm to elbow	
Light clothing	4.0 in. x 4.5 in. or 4.5 in. dia
Arctic clothing	7.0 in. sq or dia
With object	Clearances as above
Arm to shoulder	
Light clothing	4.0 in. sq or dia
Arctic clothing	8.5 in. sq or dia
With object	Clearances as above

MINIMAL TWO-HAND ACCESS OPENINGS WITHOUT VISUAL ACCESS

Reaching with both hands to depth of 6 to 19.25 inches

Light clothing	Width:	8 in. or depth of reach*
	Height:	5 in.
Arctic clothing	Width:	6 in. plus ¾ depth of reach
	Height:	7 in.

Reaching full arm's length (to shoulders) with both arms

Width: 19.5 in.
Height: 5 in.

*Whichever is larger

Note: Sufficient additional access beyond these minimums is required to permit simultaneous visual access for the inspector to see the inspection area.

4. Moisture. ... For airframe structural members whose faying surfaces consist of metals from different groups in SUB-NOTE 4(1), design members so that inspection for corrosion and visual (including borescope and fiber optics) and radiographic methods is possible. ... Design honeycomb assemblies subject to water entrapment so that they can easily be inspected using radiography.

SECTION 8D SYSTEM NDI DESIGN CRITERIA

DN 8D1 Fluid Systems

1. Introduction. ... Liquid levels in such components as reservoirs, pistons, and actuators can be quickly and accurately checked using techniques described in the following paragraphs. In addition, very sensitive ultrasonic techniques can be used to quickly inspect pneumatic systems for evidence of external leakage at fittings and components that are subject to small leaks in critical areas. ...

2. On-condition maintenance requirements. There are three aspects of fluid systems in which on-condition monitoring can be combined with the techniques of NDI to reduce maintenance costs and downtime. These are (1) monitoring fluid quantity in a closed system between maintenance activities, (2) periodic surveillance of total internal system leakage based on some percent of maximum allowable theoretical internal leakage, and (3) determining external leakage rates at prescribed intervals (primarily in pneumatic systems). ...

2.1 Fluid quantity measurement applications. Fluid quantity measurement for such items as hydraulic reservoirs, landing gear struts, fire bottles, and liquid nitrogen dewars can be made quickly and accurately using ultrasonic techniques. ... Design fluid containers that require periodic checks of liquid levels so that free access to the area on the part that is scanned is provided. ... Design landing gear struts so that outer cylinder walls are smooth and can accommodate good ultrasonic coupling in the region where the fluid level is located. ...

2.2 Leak detection

2.2.1 Internal leakage in fluid systems. Fluid systems normally exhibit internal leakage for two reasons: a. Seal deterioration between surfaces causes more fluid to bypass from the pressure side to the return side.... It is possible to use radiography to inspect internal seal cavities.... It must be emphasized, however, that radiography is an expensive method and ... the sensitivity of the technique is limited. ... b. Internal leakage can occur when faying surfaces begin to wear excessively, causing gaps. ... With the use of careful radiographic techniques, separation of faying surfaces can be detected. Again, the use of radiography must be examined from a cost-effective standpoint. ...

2.2.2 External leakage in pneumatic systems. When extremely small pinhole leaks or cracks develop in pressure bottles containing air, nitrogen, or other gases or liquids under pressure, gas begins to escape. This escaping gas creates sonic and ultrasonic energy. Ultrasound in the frequency range above audible sound is an extremely sensitive indicator of pinhole leaks and cracks in pressure vessels. ... Remote probes are available which do not require physical contact with the component. The probe must be pointed directly at the part being leak-checked, implying that direct access is required with no in-the-way items. Eddy current, penetrant, magnetic particle, or radiographic techniques can be used....

3. Component accessibility. Locate components such as bottles, reservoirs, and other fluid containers as close to the mold line or access point as possible, and orient container so that the area of interest is readily accessible with an ultrasonic transducer/wand.... Design access provisions for fluid systems to meet anthropometric design requirements presented in MIL-STD-1472.

SUB-NOTE 4(1) Grouping of Metals and Alloys

GROUP I	Magnesium and its alloys; aluminum alloys 5052, 5056, 5356, 6061, 6063; and tin
GROUP II	Aluminum (all), zinc, cadmium, tin, tin-lead (solder)
GROUP III	Zinc, cadmium, steel, lead, tin, nickel and nickel alloys, tin-lead (solder), and titanium
GROUP IV	Copper and copper alloys, nickel and nickel alloys, chromium, stainless steel, gold, silver, and titanium

1. Metals listed in the same group are considered similar to one another.
2. Metals listed in different groups are considered dissimilar to one another.
3. For additional information, refer to MIL-STD-889, Dissimilar Metals.

DN 8D2 Mechanical Systems

1. Introduction. ... These systems include mechanical flight controls, landing gear (non-fluid parts), wheels, tires, brakes, weapons launcher drive mechanisms, and other mechanical elements of aircraft systems.

2. On-condition maintenance requirements. ... on-condition maintenance requirements fall into three major areas ... (1) periodic checking to detect surface crack initiation, (2) periodically assessing any developed cracks for further growth, and (3) examining components for evidence of corrosion. Landing gear systems fall into the additional categories of fluid level checks, seal assessment, and tire condition.

2.1 Mechanical flight controls. Flight control systems such as flaps and slats, spoilers, elevator/stabilizer surfaces and their associated linkages, ... are highly susceptible to corrosion and stress corrosion cracking. Design mechanical elements of flight control systems so that areas requiring NDI inspection for corrosion (1) are provided with access sufficiently large to permit inspections using radiography, and (2) are geometrically arranged so that radiographic film placement can be readily accomplished. It must be emphasized that radiography should only be considered when visual, borescopic, fiber optic, and other NDI techniques are not practical. Design components of flight control systems subject to corrosion so that direct visual access is possible using the aforementioned techniques. When surface cracks are suspected in mechanical parts, the use of eddy current, penetrant, or magnetic particle inspection methods must be considered. ...

2.2 Landing gear systems. ... Design shock struts so that (1) the outer surface of the strut is sufficiently smooth such that it can be scanned with ultrasonics and (2) the fluid level on both sides of the cylinder and piston can is the same, permitting unambiguous ultrasonic indication of fluid/air interface. ... In order to exploit the use of ultrasonics to quickly assess the presence or absence of spare seals, design seal cavities to (1) carry spare seals in a wet configuration and (2) be geometrically simple to provide unambiguous ultrasonic coupling through the cylinder wall to provide positive identification of the seal.

2.3 Other mechanical systems. Design movable attach fittings so that (1) adequate access is provided to perform ultrasonic, eddy current, radiographic, or penetrant inspections and (2) critical or high stress areas are sufficiently smooth and geometrically simple to permit reliable application of these methods.

3. Component accessibility. To make effective use of NDI in mechanical systems, design parts so that they are readily accessible without the need for removal or disassembly of adjacent structure. Provide direct access pathways as close as possible to the component being inspected. ... The anthropometric design requirements of MIL-STD-1472 must be complied with....

DN 8D3 Electrical/Electronic Systems

2. On-condition maintenance requirements. ... a direct correlation can be established between the electrical power dissipation of an electronic component of a given design and the infrared radiation emitted by it. ... If a part fails or is not operating properly, one of the first indications is the change in heat transfer characteristics from the normal condition. ... With electrical connectors, wiring, and component parts, the assessment of cracked circuit boards, defective soldering, or pin alignment can be done using radiography. Design electronic assemblies so that inspection using thermal/infrared scanning techniques can be quickly and accurately accomplished. In addition to thermal techniques, radiography can be employed to inspect electrical and electronic single and multilayer circuit boards.

3. Component accessibility. Radiographic applications to electrical components require that connectors, wires, and circuit boards be designed to allow film placement behind the part being inspected relative to the X-ray beam. Orient the part so that the component is accessible with radiography to allow X-ray-beam-to-film angle to be within 5 degrees of perpendicular. ... Design access panels and doors so that their size meets anthropometric design requirements of MIL-STD-1472. ...

4. NDI equipment compatibility. ... In multilayer circuit board applications, it may become necessary to use multiple films with varying sensitivities in order to achieve visibility of each layer in a single shot. Design circuit boards so that adequate space is provided to allow X-ray film placement for radiographic inspections. ... Design electronic assmeblies that will be scanned with thermal techniques so that major heat sources are separated as much as possible. Locate heat sources that are not part of electronic assemblies sufficiently distant from the area to be scanned so that extraneous thermal noise is kept to a minimum.

DN 8D4 Propulsion/Powerplant Systems

2. On-condition maintenance requirements. ... Inspection of high- and low-pressure turbine blades, compressor fan assemblies, and other internal parts for cracks and excessive wear can be made through strategically placed borescope holes as well as with the proper use of X-ray techniques. ... Design fan/compressor, combustion section, low/high pressure turbine section so that access is easily obtained from the engine exterior with the engine installed in the aircraft to permit examination of blades/vanes, combustor, and other gas path rotating and static parts for foreign object damage and mechanical and thermal distress. Design the engine detail parts containing borescope provisions so they cannot be misassembled. Borescope plugs which span the fan discharge stream must be "Murphy-proofed" so that integrity of installation and removal is assured. Borescope holes must be sized and aligned so as to allow direct access to the area being inspected without the need to remove or disassemble parts. ... Design borescope ports to have larger diameters that the borescope to permit visual insertion into the engine. Provide guide tubes as required to assist in directonal orientation of the fiber optic bundle.

3. Component accessibility. ... Design borescope ports so that direct access to them is possible without the need for removal or disassembly of adjacent equipment or components.

4. NDI equipment compatibility. ... Design borescope ports so that the instrument can be inserted to maintain proper focal distance from the object being inspected. Design borescope ports and pathways to accommodate the shortest length borescope practicable. Due to light losses, brilliance of an image decreases as the length of the instrument increases. ... Also provide means to rotate the fan and/or the high pressure rotors of the engine in order to implement the NDI method. Consider eye fatigue in design and selection of NDI equipment.

DN 8D5 Ordnance Systems

1. Introduction. ... It is possible to assess the condition of ordnance devices by looking for cracks, grain continuity, integrity of case bond, and homogeneity of material (i.e., lack of porosity, voids, and foreign material).

2. On-condition maintenance requirements. Among ordnance devices, rocket motor systems require the most on-condition monitoring to assure integrity. Radiography, as well as ultrasonic techniques, can be used to examine motors for such defects as cracks, moisture, porosity, case bond integrity, and foreign materials in the propellant mixture. Design motors so that exterior casing surfaces are smooth and geometrically simple to permit good radiographic film placement as well as ultrasonic transducer coupling. Design rocket motors so that periodic assessment of motor material is possible during scheduled inspection periods without the need for removal or disassembly of the rocket motor assembly from the aircraft. In addition to rocket motors, NDI can be applied to other ordnance devices, including explosive bolts, detonating cord (rigid and flexible), ejection seat initiators, and linear-shaped charge devices. ... Design ordnance systems so that they can be inspected on aircraft without the need for in-the-way removal or disassembly of adjacent equipment.

3. Component accessibility. ... Design items such as rocket motors, explosive bolts, and energy transfer lines so that direct access is provided without the need for in-the-way removal of adjacent equipment or structure. Allow sufficient clearance around ordnance devices so that ultrasonic and/or radiographic inspection equipment can be easily inserted. Design attaching hardware so that it does not physically interfere with the designated inspection. ...

4. NDI equipment compatibility. ... Access to items requiring radiographic inspections must be such that if the X-ray tube head is to be placed inside the mold line, an 8-inch minimum diameter must be allowed for the access hole. Orient the access so that the angle of incidence of X-rays to film through the part is no greater than 5 degrees from the film perpendicular. Optimum image clarity on radiographic film is best achieved when the film is placed as close as possible to the object being inspected.

DN 2A1 Installation Requirements

8. Accessibility. Locate and mount all equipment in the engine installation to permit access for rapid equipment testing, servicing, removal, inspection, and replacement. Design to permit unobstructed adjustment over the entire range of component movement. To minimize repair time, avoid inaccessible and complex structure designs. Ensure that the effort required to provide accessibility is commensurate with the relative frequency and manhours of inspection, servicing, and repair required on the equipment. To expedite preflight and postflight inspections, provide maximum accessibility. Insofar as practicable, provide engine accessibility without the use of stands or ladders. Do not locate equipment requiring periodic inspection, service, or replacement behind or under stress members, components, or other items which are difficult to remove or are readily damaged, unless such practice is necessary. Arrange equipment and components so that: (1) maintenance personnel can accomplish their work without assuming awkward positions and (2) moving dirt is unlikely to drop on personnel and on other components during maintenance. Use removable fasteners such as bolts (not fixed fasteners such as rivets) to attach assemblies that are subject to frequent removal. Use quick-disconnects where practicable. Provide tool clearance for bolted connection. In remote areas and where the use of tools is restricted, mounting brackets with self-locking nut plates may be used provided the nut plates are compatible with the environment. Provide sufficient access to all lubrication fittings to permit the use of standard USAF lubrication equipment without the need for adapters. Arrange the installation to permit inspection, cleaning, adjustment, removal, and replacement of components and accessories with tools normally contained in a mechanic's tool kit. Ensure that the installaion design does not require the use of special tools. Mark access panels and doors in accordance with DH 1-2, Chapter 5, and MIL-M-25047 (Markings And Exterior Colors For Airplanes, Airplane Parts, And Missiles).

8.1 Equipment inspection, cleaning, and adjustment. Provide sufficient access to inspect, clean, and adjust all accessories and components of the engine installation while installed in the aircraft. Ensure that accessibility does not require the removal of the engine, accessory gearbox, propeller, propeller gearbox, transmission, fluid tanks, fluid lines, or important parts of the aircraft structure. Ensure that service items accessible on a bare uninstalled engine are also accessible on the installed engine. Ensure that the items in SUB-NOTE 8.1(1) and those listed in MIL-I-83294 (Installation Requirements For Aircraft Propulsion Systems, General Specifications For) are accessible for inspection, cleaning, and adjustment.

8.2 Equipment removal and replacement. Design the engine installation to provide adequate accessibility to permit removal and replacement of all accessories and components listed in SUB-NOTE 8.1(1). Accomplish removal and replacement of equipment without removing an engine accessory gearbox, propeller, propeller gearbox, transmission, fluid tank, fluid line, or important parts of the aircraft structure.

9. Maintainability. To lower the risk of equipment damage during maintenance activity, provide guards to protect vital components which could be seriously damaged due to minor maintenance irregularities. Consider maintenance personnel by minimizing sharp projections that may cause injury, providing instruction plates or decals adjacent to items equiring maintenance, and designing engine installations so that maintenance can be performed in cold weather by personnel wearing Arctic gloves and clothing.

SUB-NOTE 8.1(1) Examples of Accessible Items	
Actuators	Generators/Alternators
Actuator motor brushes	Hydraulic pumps
Afterburner fuel pump	Ice detector and controls
Bleed air ducting and valves	Inlet duct anti-icing components and controls
Constant speed drives	Inlet screen components and controls
Drain valves and sump plugs	Ignition excitors
Engine borescope inspection provisions	Ignitor plugs
Engine-mounted propeller governor	Oil coolers
Engine mounts	Oil filler plugs
Engine power takeoff (PTO) shaft and couplings	Oil filters
Engine thermocouples and harness	Oil sight gages
Variable exhaust nozzle and control assembly	Oil tanks
Fire detectors	Oil pressure relief valves
Fire detection control units	Power turbine governor
Fire extinguisher bottles	Propeller unfeathering accumulator
Fire extinguisher spray rings and nozzles	Propulsion control linkages
Fuel boost pumps	SOAP sample removal
Fuel control (engine and afterburner)	Starter
Fuel filters	Tachometer generator
Fuel flow divider	Tailpipe
Fuel flowmeter	Throttle boxes
Fuel heater	Thrust reverser components and controls
Fuel nozzles	Variable inlet geometry components, controls, and sensors
Fuel pressure relief valve	
Gearbox mounts	Water methanol tank or thrust augmentation fluid tank

11. Engine cowlings and access doors. Provide cowlings and service or access doors and panels for engine buildup to permit access for inspection, servicing, adjustment, removal, and replacement of the engine, the engine compartment, and engine compartment components (see Para 8.1). When practicable, use hinged cowlings and doors to permit rapid access to the engine. When appropriate, cowling sections may also serve as workstands for maintenance personnel. Ensure that the cowlings, doors, and panels have no sharp corners which may be hazardous to personnel. Design removable cowlings and doors to be of reasonable dimensions and weight for ease of handling by ground personnel. Design cowlings, doors, and panels to be interchangeable between engines in multiengine aircraft. Ensure that the basic airframe, cowlings, doors, and panels have the same design life. Design cowlings, doors, and panels so they do not separate from the nacelle in the event of a high-pressure bleed air line rupture or experience structural damage which would require a major repair or would result in a situation impairing safe operation of the aircraft. Design all engine cowlings, doors, and panels including those considered to be structural load carrying members or stress panels to be easily opened, removed, and replaced without requiring any aircraft, nacelle, or wing reconfiguring or jacking. Provide pylon and nacelle cowling with pressure blowout doors where high pressure bleed lines are located.

DN 2A2 Quick Engine Change Assemblies

2.3 Disconnects. Use quick-disconnect couplings for mechanical and electrical connections between the engine buildup and the airframe. ... Arrange the disconnects to preclude inadvertent reversal, mismatch, or improper connection of electrical and mechanical connectors, couplings, and fittings. Locate disconnects in convenient groupings on a wall of the engine compartment and arrange them so that several mechanics may simultaneously work in the area with a minimum of interference. ...

CHAPTER 2 DESIGN GUIDANCE

SECTION 2B GENERAL REQUIREMENTS

DN 2B3 Maintenance

5. Access doors and panels. As necessary, provide inspection doors or panels for servicing operations (inspection, testing, lubricant drainage, adjustment, and parts replacement). Consider these factors in the design:

a. Make the openings of sufficient size to (1) provide an adequate view of the parts to be serviced, (2) provide sufficient clearance for servicing the parts by personnel dressed in Arctic clothing, and (3) permit removing or connecting parts to be serviced without removing other parts unnecessarily.

b. To ascertain the particular needs, consider the ultimate application and specified operating environment for specific equipment.

c. To expedite replacement, identify the location of all removable doors and panels.

d. Provide quick-action fasteners where frequent inspection or maintenance may be required.

SECTION 2C DESIGN DETAILS

DN 2C3 Bearings And Gears

2. Sleeve bearings

2.3 Split bearings. If split bearings are used, consider the plane of the split to provide ease of disassembly. For example, split the crankshaft bearing on an engine connecting rod to permit bearing removal through ports without having to remove the crankcase cover.

3. Antifriction bearings

3.2 Accessibility. It is possible that it will be necessary to replace bearings and to change the lubricant to suit widely varying temperatures and conditions under which certain support equipment must operate. Therefore, provide the greatest possible accessibility to facilitate removing the bearing either for bench relubrication or for purging and relubricating in the installation.

3.3 Failure. Antifriction bearings usually fail through fatigue flaking of the raceways or of the surface of the rolling elements. All antifriction bearings will ultimately fail in this way unless premature failure is caused by improper design, poor mounting, or faulty maintenance. Some common causes of failures are (1) inadequate capacity, (2) insufficient or improper lubrication or contaminated lubricant, (3) inefficient seals, (4) out-of-round housing bores, (5) tapered housing bores, and (6) misalignment.

CHAPTER 3 DESIGN AREAS

DN 3A2 Radio Communication Equipment

9. Test provisions. ...

9.1 Built-in test provisions. To permit performance monitoring on a "go/no-go" basis incorporate test facilities into the equipment to the fullest extent possible. Include techniques which make it possible for unskilled personnel to assess the overall performance of the entire equipment. As far as possible also incoroporate marginal checking techniques to provide information on anticipated failure. Build such test devices into the equipment whenever any of the following conditions apply:

a. When it is necessary to observe characteristics having a frequency which makes it impractical to use portable, general purpose test equipment.

b. When it is necessary to make measurements while equipment is in normal operation without disturbing its operation.

c. When it is necessary to disassemble equipment or transmission line to measure a quantity required for equipment maintenance.

d. When use of portable test equipment will not give comparable or adequate results.

e. When a particularly high degree of reliability is required. Build into the equipment the kind of test instruments that maintain their specified accuracy under all electrical, mechanical, and other environmental conditions.

9.3 Sensitive components testing. When equipment contains such sensitive components as transistors, voltage tunable diodes, or other items that may be damaged by normal testing procedures, provide PROTECTION or a WARNING to indicate required test procedure.

9.4 Component failure. Design the equipment so that the failure of a component ordinarily used to improve performance will not completely disable the equipment. Instead, the equipment will continue operating but with a reduction in performance.

9.5 Adjustment and repair. In designing the equipment, consider construction which permits all parts, terminals, and wiring to be accessible for circuit checking, adjustment, maintenance, and repair (1) with a minimum of disturbance to other parts and (2) with a minimum use of special tools. Design for the least number of adjustments required to obtain satisfactory performance. Make adjustment controls accessible so that adjustments may be quickly returned to their original settings. Design them so that inexperienced personnel will not inadvertently get the equipment out of alignment. If sequential adjustments are required, design the equipment to minimize the possibility of their being made in the wrong sequence. Avoid harmonizing or mop-up adjustments unless such a procedure will permit considerable simplification of the equipment.

9.6 Parts mounting. Wherever practicable, mount parts so that they can be removed and replaced without interference from, injury to, or removal of other parts or wiring. If practicable, design the equipment to eliminate the necessity for designing it when a component is replaced.

9.7 Voltage and current monitoring. Wherever necessary, provide built-in meters for monitoring input voltages, input currents, and all separate power voltages generated within the equipment. Make the most efficient use of shunt and series resistors in conjunction with selector switches. This will insure employing a minimum number of meters for these measurements.

CHAPTER 4 SERVICE AREAS

SECTION 4F CONSTRUCTION AND MAINTENANCE EQUIPMENT

DN 4F2 Standardization

12. Maintainability. ...

12.1 Lubrication. Lubrication recommendations are as follows:

a. Eliminate as far as possible the requirement for periodic lubrication. This can be done by using sealed housings and constant oil bath lubrication sealed bearings or oil impregnated bushings.

b. Consider the application of a central mechanism for applying lubricant at all points where lubrication is required. This will also aid in reducing the amount of dirt that is often introduced through common grease fittings.

c. Where central lubrication is impractical, consider the addition of fittings which contain a small, spring-loaded grease reservoir.

d. Provide lubrication fittings in accessible locations with a lead tube to lubricate inaccessible points.

e. Avoid designs which produce high unit pressures and create a need for extreme pressure lubricants.

12.2 Adjustment and testing. For adjustments and testing:

a. Consider the required frequency of adjustment or servicing as a factor in accessibility and durability.

b. Where possible, design to permit external adjustment of internal components.

c. Consider the use of a locked-nut-and-thread-type adjustment instead of shims. Avoid shim-type adjustments which perform the dual functions of adjusting bearings and positioning units.

d. Where shim-type adjustments are required, design to provide shim removal rather than shim additions as parts wear.

e. Where corrosion of nuts and threads is a factor on the adjustment of large components, consider hydraulic-type adjustments.

f. Provide simple fittings at proper locations to permit easy attachment of any equipment required for test or service purposes.

g. Where applicable, use variable pitch V-belt drives for high-speed applications. Use spring-loaded idler sprockets on chain drives to avoid frequent adjustments.

h. Where possible, provide adjustment indicators and timing marks on the machine rather than on a separate unit.

i. Eliminate adjustment of hose fasteners used in low-pressure application by using spring-type fasteners which maintain a constant peripheral pressure.

j. Use dipsticks rather than pipe plugs as liquid level indicators.

12.3 Repairs. When considering repairs:

a. Design machines to permit disassembly and removal by groups of components. Avoid designs in which one part is common to two groups. Provide connections between groups which can be easily detached, such as universal joints, splined joints, or pinned joints.

b. For easy replacement, consider using individual piston-cylinder groups or engines.

c. Provide a common separation location for hydraulic lines and electrical lines which extend from one component group to another.

d. Consider suitably supported "O" rings for gaskets where ordinary gaskets are damaged during part replacement.

e. Provide taps in all shafts which must be removed with pullers.

f. Where possible, provide taps to permit the installation of fasteners to hold clutches or spring-loaded parts in assembly during removal.

g. Avoid selective fits to simplify parts replacement.

h. Avoid designs which require fabrication or machining on asssembly.

i. Consider that spur gear pinions usually wear faster than the mating gear. Develop a simple method of pinion replacement without disturbing other parts.

j. Avoid designs which allow worn parts to damage adjacent parts.

k. Use quick-type fasteners on covers, shields, and hoods to reduce maintenance dissassembly time. Retain fastener components in the cover to prevent loss.

l. When possible, use gravity flow to move liquids and avoid pump installation repair.

m. Avoid the use of jaw clutches to engage power trains having relative motion during engagement.

n. Place straight-threaded brass fittings near a pipe fitting to permit loosening the pipe fitting during assembly or disassembly. This helps avoid cross-threading.

o. Consider designs which permit simple reconditioning to extend service life instead of designs requiring frequent part replacement.

p. In using split bearings also consider the plane of the split to attain ease of disassembly. For example, the crankshaft bearing on an engine connecting rod may be split at an angle to permit connecting rod removal through the piston bore without removing the crankcase cover.

q. Provide means of rapidly replacing all parts subject to wear, damage, or rapid deterioration.

r. Allow adequate access for removing and installing parts which require periodic replacement.

s. Design lock rings so that they will stay in place under adverse conditions. Provide sufficient length of nib to assure good locking.

t. Design (1) so that normal installation and maintenance will not cause electrical insulation to become loose or misplaced, and (2) so that maintenance can be readily accomplished without damaging insulation.

u. Provide physical interference such as an indexing lug or a nonsymmetrical hole pattern to assure the correct installation of parts. Design parts so that they cannot be installed wrongly.

v. Supply adequate clearance or protection for vital parts or operating systems. Provide ample clearance between moving parts and nearby components.

w. Consider use of permanently installed fittings in place of washers.

x. Design for standard tools. Avoid designs that require special tools or equipment to perform routine maintenance.

DN 4F4 Snow And Ice Removal Equipment

7. Maintainability. Experience with past snowplow equipment indicates a number of mechanical, electrical, and structural deficiencies.

a. Design the equipment so as to reduce frequency of repair, servicing, maintenance, and repair operations.

b. Provide features which will facilitate maintenance and servicing operations at extremely low temperatures by personnel wearing heavy gloves or mittens and encumbered by bulky clothing and footgear.

c. Avoid intricate locking devices, controls and threaded fastenings which can be overtorqued by operators lacking feel through thick gloves or because of numbness.

d. Design major assemblies so they can be removed without removing control parts or draining liquids or coolants.

e. Provide lifting eyes (or approved equivalent) for readily attaching lifting devices.

f. Equip with substantial quick-disconnect fastenings, covers, or plates which must be removed for component adjustments or removal.

g. Where practical, provide disconnect plugs, protected receptacles, and multiple line connectors in the electrical system, and readily-detachable-and-attachable-type fittings in hydraulic and pneumatic systems to perform rapid component removal and replacement.

h. Clearly indicate all disconnect points.

i. The weight of the rotary engine and the plow weight affect spring deflection. Include this deflection when designing underbody blades to prevent interference when wheels are turned. Use a torque converter drive in this type of equipment to reduce shock loading and prevent breakdowns.

7.1 Field maintenance. To avoid field maintenance problems:

a. Furnish a heavy duty windshield wiper assembly to prevent blade failures due to heavy snow coating.

b. Provide a reinforced, steel core V-belt on engine fans to prevent fan belt failure.

c. Supply a sheet metal shield in front of horns to reduce horn malfunction due to moisture frozen in horn.

d. Use a vented fuel tank to improve tank filling time.

e. Place a shield around rotary snowplow engine air breathers to prevent clogging with snow.

f. Provide an adequate length and opening on discharge chutes to improve visibility when operating the rotary. CAUTION: Too wide an opening causes snow to flare.

g. Supply a shear pin on mounting brackets and plows to protect the equipment and yet reduce excessive pin breakage.

h. Provide a coarse thread on snowplow hydraulic hose connectors for easy engagement by personnel wearing gloves.

SECTION 4G TEST EQUIPMENT PROVISIONS

DN 4G2 Electrical And Electronic Test Equipment

4.7 Maintenance requirements. Comply with the following maintenance requirements:

a. Locate equipment and accessories for easy accessibility. Provide accessible mounting bolts so that equipment can be installed or removed without removing components and assemblies. Use easily aligned nut plates to facilitate installation in cramped spaces.

b. Mount tuning instructions and calibration charts on the equipment when such instructions and charts are required.

c. Minimize "nontamper" factory adjustments. When such adjustments are required, they should be marked as such and sealed.

d. Where possible, provide indicators of malfunctioning equipment.

e. Assure complete interchangeability of all functionally interchangeable removable units, maintenance parts, etc.

f. Use built-in test circuits where necessary to determine qualitatively if the quipment is operating normally.

g. Provide test points, according to MIL-STD-415, for checking essential wave forms and voltages where terminals are not otherwise accessible.

h. Supply voltage dividers with test points for measuring voltages in excess of 100 V.

i. Furnish a servicing power outlet with an independent fuse for each major unit.

j. Leave about 1/16 in. pigtail on leads beyond terminal. Do not mount more than three wires on one terminal.

k. Minimize the need for special tools. Where they are provided, mount them in a convenient place, preferably inside the equipment cabinet.

l. Mount controls and indicators, which are used infrequently, behind hinged doors.

m. Provide maintenance controls which can be adjusted by a screwdriver.

n. Use removeable side and back panels for terminal tube mountings.

CHAPTER 3 AIRCRAFT ENVIRONMENT, SECTION 3A OXYGEN SYSTEMS

DN 3A10 Installation

11. Maintenance and replacement. Install all parts of the oxygen system to permit ready removal and replacement without the use of special tools. Ensure that all tubing connections, fittings, regulators, converters, brackets for indicating instruments, and other items are readily accessible for leak testing with leak test compound and for tightening of fittings without removal of surrounding parts. Use flexible hoses to connect indicating instruments mounted on shock-mounted panels to permit easy maintenance.

CHAPTER 13 SAFETY, RELIABILITY, AND MAINTAINABILITY,

DN 13B2 Ground Maintenance

3. Design and mechanization considerations. In designing and mechanizing ground maintenance techniques (and in-flight maintenance techniques for manned spacecraft):

a. Every effort should be made to make maintenance and repair of the equipment as foolproof as possible.

b. Special attention should be given to making the proper operation of the equipment or the installation of a part the obvious and correct procedure. To do this, use such techniques as polarizing keys on connectors and replaceable modules, captive mounting hardware, and clearly legible identification numbers and instructions.

c. Spacecraft hardware, electronic components, circuits, and replaceable modules or elements should be standardized to minimize the different types of items stocked as spares.

d. Tools, job skill levels, and auxiliary equipment required to perform maintenance tasks should also be standardized.

e. Sufficient accessibility to hardware should be provided to facilitate safe and efficient servicing, testing, and repairing in the most timely and reliable manner.

f. The capability of removing and replacing any spared item should be provided without electrically or mechanically disturbing any other installed item.

g. Straight-out egress and straight-in ingress of spared items should be provided.

h. Taper pins or other indexing devices should be provided for spared items requiring precise mounting such as gyros.

SECTION 2G MAINTAINABILITY DESIGN