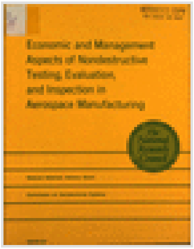

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This report reviews the roles of nondestructive testing, evaluation, and inspectio as they influence the manufacturing and operational costs of aerospace systems. It is based on a study of various aspects of quality assurance, program management, process control, implementation of advanced technology, and specifications to identify factors that might influence costs.

One major conclusion is that nondestructive testing (NDT) represents a small percentage of the overall costs of an aerospace system and that improvements in

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20. ABSTRACT Contd.

NDT evaluation procedures, through use of available technology, could lower costs of manufacture and reduce operational and maintenance costs. Several steps are recommended for reducing costs of NDT and increasing the overall effectiveness of the money that is spent to guarantee the reliability of aerospace systems. These recommendations include the establishment of a Department of Defense (DoD) Executive Committee on NDT to act as a steering body to guide and direct activities that will make more effective use of available technology and procedures. Other recommendations and suggestions relate to program management, the potential use of current technology, and procurement specifications.

ECONOMIC AND MANAGEMENT ASPECTS OF NONDESTRUCTIVE TESTING, EVALUATION, AND INSPECTION IN AEROSPACE MANUFACTURING

Report of

COMMITTEE ON NONDESTRUCTIVE TESTING
OF AEROSPACE SYSTEMS

NATIONAL MATERIALS ADVISORY BOARD
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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine.

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In developing the conclusions and recommendations contained in this report, R. A. Eddy, D. J. Hagemaier, J. M. Knadler, and E. O. Lomerson provided information on specifications; C. Hastings, P. F. Packman, J. R. Roquemore, and W. J. Whelan provided information on nondestructive evaluation in process control; J. D. Marble and R. R. Rowand provided information on implementation of current technology; and E. L. Caustin, G. Darcy, C. Hastings, and G. F. Hazelton provided information on the relationship of nondestructive testing to program management. G. J. Posakony, Chairman of the Committee, managed and coordinated the preparation of the final drafts.

PREFACE

DEFINITION OF NONDESTRUCTIVE TESTING TERMINOLOGY

The terms "nondestructive testing" (NDT), "nondestructive evaluation" (NDE), and "nondestructive inspection" (NDI) are used to describe the means for establishing the quality or integrity of materials and structures without impairing or affecting their end use. Nondestructive testing is an emerging technology that uses some methods dating back 50 years and others that are only a few years old. As in many emerging disciplines, the requirements for qualified people and improved instrumentation, procedures, and techniques continue to evolve.

The term "nondestructive testing" has been accepted internationally for more than 30 years and is incorporated into many specifications, standards, codes, and recommended practices and procedures. The terms "nondestructive evaluation" and "nondestructive inspection" are of more recent origin and have been generated to provide more accurate descriptions of functions performed. The principal nondestructive test methods in current use are X-ray, ultrasonic, eddy current, magnetic particle, and liquid penetrant; additional test methods include acoustic emission, thermography, microwave, optic and acoustic holography, optic-laser surface examinations and metrology, and many others. These test methods are used to examine both the surface and volume of materials, welds, structures, components, and assemblies to detect and characterize anomalies that might result in premature service failures. NDT, NDI, and NDE have enabled the integrity and quality of materials and structures to be improved and have provided the basis for quality assurance and maintenance inspection criteria.

In this report, the terms are used to describe specific functions:

> <u>Nondestructive testing</u> is used in a basic or generic sense to describe testing methodology or to define the general application of nondestructive testing principles.*

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* Visual techniques traditionally associated with metrology and surface examinations generally are not included with the other NDT methods. In this report, they are considered in the discussion of advanced or automated stations used for high-speed visual or surface inspections.

Nondestructive inspection refers to the performance of an inspection to meet an established specification or procedure whether during fabrication or during service.

Nondestructive evaluation refers to the examination of materials, components, and assemblies conducted to define and to classify material anomalies in terms of size, shape, type, and position.

Thus, NDT methods are used to nondestructively inspect materials, components, and assemblies and to nondestructively evaluate the nature of material anomalies. NDE provides a means for classifying material anomalies in terms of flaws or defects that may be significant to structural design or service performance.

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Chapter 1

EXECUTIVE SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. Introduction

The Committee on Nondestructive Testing of Aerospace Systems of the National Materials Advisory Board (NMAB) was established to provide the Department of Defense (DoD) with advice and guidance concerning research, development, and manufacturing technology programs to increase the reliability of future aerospace systems through the use of more efficient and more cost-effective nondestructive evaluation (NDE). In analyzing the problem and developing its recommendations, the Committee conducted a series of workshops and solicited information from technical experts throughout the country. A major goal was identification of those factors relating to nondestructive testing (NDT) that can cause the cost of aerospace systems to increase (or decrease). A second goal was to assess the effectiveness and timeliness of the use of nondestructive tests.

While the Committee was charged primarily to analyze NDE costs in research, development, and manufacturing technology, it found this charge too restrictive to permit it to identify and assess the influence and impact of NDE on the total system and therefore expanded its analysis to include life-cycle costs (i.e., the impact of NDT technology on initial quality, service operation, and maintainability). Specifically, the Committee was to identify major problems and opportunities and recommend actions that can be taken during the next three to five years either to reduce the costs associated with NDT functions or to provide for more effective utilization of the available technology. Those of the Committee's recommendations that relate to these objectives are presented below while other Committee recommendations that could result in more effective use of NDT technology to reduce the manufacturing and life-cycle costs of aerospace systems are presented in subsequent chapters.

As a result of its study, the Committee has concluded that the cost of NDT is insignificant when measured against the initial cost or the life-cycle cost of a system. It does believe, however, that substantial cost reductions can be effected in both manufacturing and operational phases through the timely and effective and, in some cases, expanded utilization of available technology. These cost reductions can lower total life-cycle costs without reducing the reliability of the aerospace systems.

Suffice it to say that the success of efforts to increase the reliability and decrease the life-cycle costs of future aerospace systems is highly dependent on the initial quality and the design inspectability of the critical components and structures.

The technical language imposed by the procurement document also as a substantial influence on the cost of the specified nondestructive inspections (NDI) and evaluations (NDE). Improperly prepared documents result in counterproductive and unnecessary inspection requirements while properly prepared specifications, which may increase initial NDT costs, can result in enhanced system reliability and an overall reduction in life-cycle costs. New approaches taken in the procurement specifications, such as those used in MIL-I-6870 [1], can be effective in integrating NDT and NDI into the design criteria and, thus, provide for the inspection of critical parts or assemblies both during and after manufacture.

Procurement documents, however, represent only one aspect of the overall problem, and the Committee has identified three other problem areas: Tri-Service NDT organization, program management, and implementation of current technology. The Committee's conclusions and recommendations regarding each are presented below.

B. Conclusions

1. Tri-Service NDT Organization

NDT can have a significant impact on the reliability, effectiveness, and cost of miltary vehicles and materiel, and the Army, Navy, and Air Force presently have ad hoc and standing committees or working groups designed to provide a medium for the exchange of technical information on NDT research, development, and applications. While these groups are effective as working committees, they have no authority to recommend, plan, or implement budgets or technical levels of effort on major DoD programs. The DoD lacks a central body responsible for coordinating efforts and developing planned and meaningful ways to promote and to utilize NDT technology to enhance the reliability of its military system. Even though the three services each have unique problems, it is important that positive and dynamic overall control be provided to obtain the most effective NDT programs, to ensure timely transition of technology between the services and industry, to develop national awareness and recognition, and to prevent unnecessary duplication of effort.

2. Program Management

The management of a program encompasses all aspects of planning, specifying, procuring, engineering, manufacturing, evaluating, and accepting the completed system. The role and costs of NDT are interwoven into the program at nearly every phase. Over-specifying or under-qualifying components and subsystems can substantially influence both initial and life-cycle costs. Those managing a program must recognize that there are risks and must identify the costs associated with these risks. Government program management as well as contractor management, engineering, manufacturing, quality assurance, and procurement can all increase the costs of NDT. During the development of a given aerospace system, NDT costs are increased when each of these disciplines has not been interrelated to properly define the total role of or need for NDT. Qualified NDT personnel must be involved in the development of the scope and role of NDT. Urgently needed is a basic handbook that describes the requirements and interfaces for NDT management applicable to procurement of original and replacement material.

3. Implementation of Current Technology

Given the results obtained with present NDT systems, the Committee believes that the currently used accept/reject decision process is highly subjective and relies almost exclusively on qualitative information and human judgment. The optimum accept/reject decision involves many diverse factors such as structural design, manufacturing procedure, and nondestructive inspectability. Less than optimum NDI decisions can result in appreciably increased life-cycle costs.

Current technology makes it practical (a) to implement quantitative economic and engineering decision modeling to describe the true economic effects of selecting specific NDT systems and NDI levels and (b) to utilize electronic and/or computer aids in selecting and grading anomalies in terms of accept/reject criteria and in establishing a base for identifying the effects of NDI criteria. Applying available technology can appreciably increase the accuracy and reliability of the decision process or reduce the total manufacturing, inspection, and failure costs.

4. Specifications

The influence of military, government, technical society, and industrial specifications on NDT costs has been studied by various groups, including earlier NMAB committees [2-4]. Problems concerning specification proliferation, maintenance control, interpretation, and application have evolved nationally in an uncontrolled and undirected fashion. The net result has been an increase in costs but not necessarily an increase in reliability. The specification problem is further complicated by the predominant role of aerospace manufacturers' company specifications that are imposed by prime contractors on vendors and subcontractors in lieu of military or Society documents. Vendors often must comply with multiple documents to fulfill a contract or to provide like services for different prime contractors. This Committee has not developed a solution; still, the need for a unified national solution remains, and if no action is forthcoming, specifications will continue to become less effective. Actions to ameliorate this situation proposed by the Committee members included:

a. Development of a series of new military NDT method specifications;

b. Tailoring of existing specifications;

c. Deletion of tutorial statements from existing military NDT method specifications;

d. Replacement of NDT methods specifications with two documents, one on personnel qualifications (e.g., MIL-Q-410) and one on NDT program control (e.g., MIL-I-6870), supplemented by handbooks on how to apply these specifications to achieve and maintain control of NDT programs.

The problem of specifications is treated in Chapter VI and again, with more detail, in Appendices A and B.

C. Recommendations

The Committee has chosen four specific recommendations that it believes will be most effective to control and direct the future plans for NDT within the DoD. Many other recommendations and suggestions are presented in the body of the report, but the Committee's major objective was to describe specific opportunities that, when implemented, could provide solutions during the near term (three to five years). The Committee recommends that the DoD take action on all recommendations included in this report. The NMAB Committee that drafted this report is a potential resource for assisting DoD in developing the implementation plan.

1. Tri-Service NDT Organization

The DoD should establish an Executive Committee, consisting of not more than four persons representing the Army, Navy, Air Force, and DoD, plus a chairman, to act as the coordinating committee for consolidating, integrating, and recommending budgets for all NDT research, development, and application activities. Figure 1 shows the conceptual organization charge for the NDT activities within the DoD. Further, the Committee recommends that each Service establish an Operating Manager's Group to coordinate and identify the requirements of each respective Service. The Operating Managers Group would report to the Executive Committee, which in turn would present its recommendations to the DoD for approval and implementation. The output of the Executive Committee and Operating Managers Groups could take the form of DoD Technical Coordinating Papers and other appropriate documents.

The development of the Executive Committee has the highest priority and should be undertaken immediately to effect continuity, planning, and control of DoD programs. This Committee also could serve as a national information resource for NDE as it relates to national issues and problems and, thus, provide a central body for focusing NDE technology on problems such as energy conservation and system reliability.

2. Program Management

The DoD should direct the Executive Committee to establish and implement a plan to develop an NDT Program Management Handbook as the guideline for NDT program management for use by government and industry. The Committee suggests that the Army Materials and

TRI-SERVICE NDT ORGANIZATION CHART
(CONCEPTUAL)

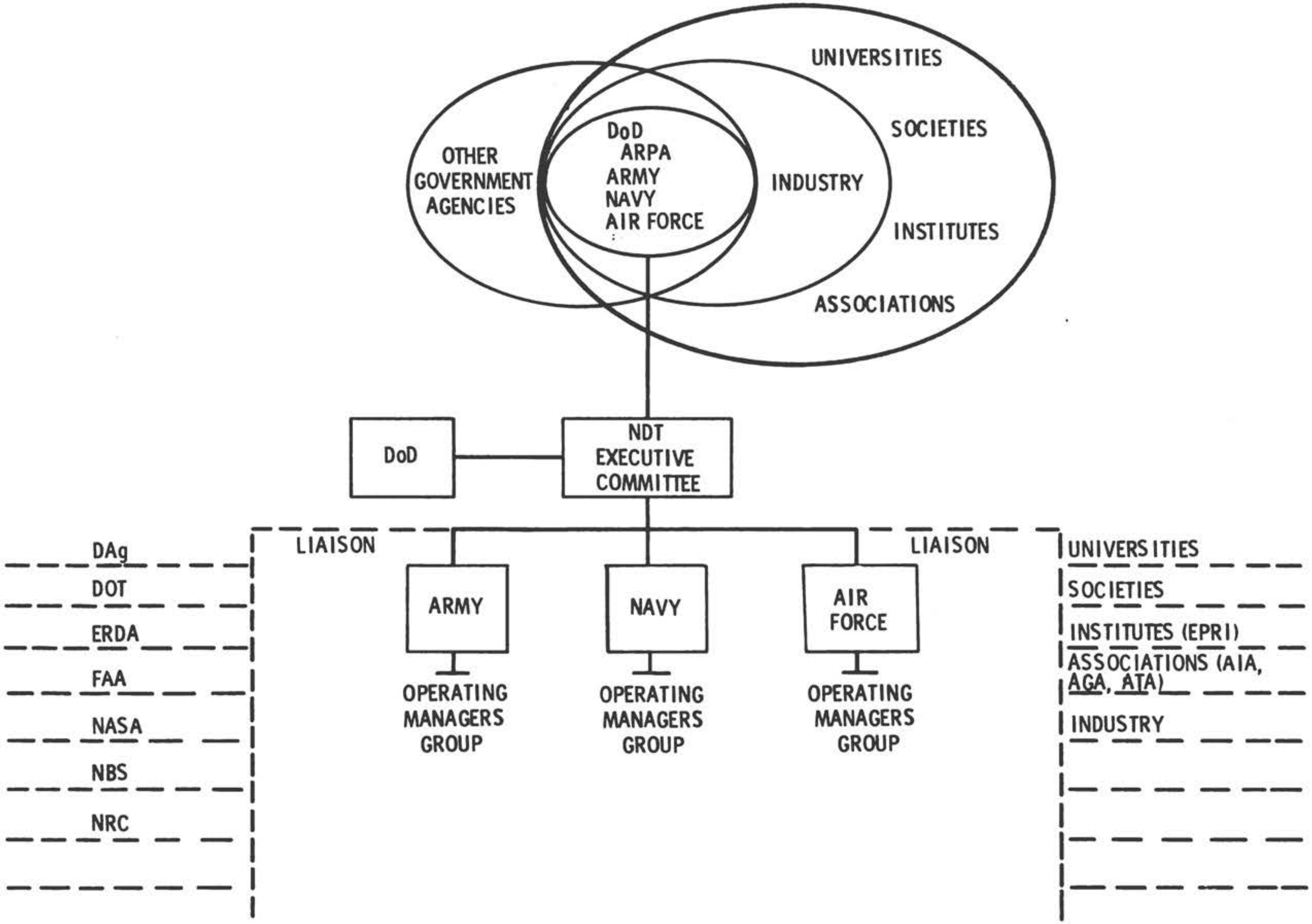


FIGURE 1 Concept for Tri-Service NDT organization and its relationship to other activities.

and Mechanics Research Center (AMMRC) be assigned the responsibility for effecting the development of the handbook. This could be accomplished by revising, updating, and consolidating AMCT-702-10, Guidance to Nondestructive Testing Techniques, and AMCP-702-11, Guide to Specifying NDT in Materiel Life Cycle Applications, as the coordinated handbook for NDT program management. Work on this handbook should be initiated immediately and the publication date should be no later than the end of FY 1978.

3. Implementation of Current Technology

The Executive Committee should establish a coordinated plan for adapting and implementing current technology to aid in the NDT "decision processes." The specific plan developed should (a) apply electronic and computer enhancement, and (b) implement quantitative engineering and economic decision modeling to define the accept/reject criteria and to establish the base for identifying the effect of the NDI criteria. The Committee suggests two specific areas that offer immediate potential for cost-effective utilization of current technology, namely, nonfilm radiography and computerized economic and engineering analyses. Savings result not merely from the avoidance of film use, but rather largely from automatic and timely decision-making. The Committee feels that substantial "cost of inspection" savings for both manufacture and maintenance can be realized by further development and use of nonfilm and electronic radiographic imaging and suggests that the development program outlined in Figure 2 be implemented.

NONFILM RADIOGRAPHIC SYSTEMS (PROGRAM OUTLINE)

● SYSTEM ENGINEERING		
∘ Light Amplification/Detection		
· Isocon Production Improvement		
· Light Amplification Refinement		
· Establish Magnification Control	(12 mo)	
∘ Operator Interpretation - Decision/Comparison		
· Location Difference		
· Intensity Difference		
· Automatic Alert	(12 mo)	
∘ Automatic Decision		
· Dimensional Difference		
· Intensity Difference		
· High-Speed Automatic Interpretation	(24 mo)	
		1,000 K
● SYSTEM APPLICATION		
∘ Tire Inspection Systems		
· New Production		
· Recapping Operations	(24 mo)	750 K
∘ Aircraft Production/Air Frame and Engine Analysis		
· Process Control		
· Defect Screening	(33 mo)	1,000 K

● PAYOFF

- National Capability/Availability for Industrial and Maintenance Operations
- Improved Decision/Manpower Savings
- Zero Film and Processing Costs
- Simplified Records
- More Effective Feedback to Process Control

FIGURE 2 Implementation flow for nonfilm radiography.

Computer engineering and economic analysis technology has developed sufficiently to be useful in predicting the cost effectiveness of NDT decisions. This analytical technique may be used to weigh maintenance, failure, and liability costs against the costs of manufacturing and inspection and to describe the impact of increasing these costs to achieve increased reliability and lower life-cycle costs. The total life-cycle costs associated with the various NDT systems and NDI examination levels can be assessed. (An example of a computerized engineering and economic analysis of a specific roller bearing in a jet engine is presented in Appendix C. This analysis describes the decision-making process in terms of costs per hour of engine life attributable to bearings.)

4. Specifications

The Committee believes that the problem of development, implementation, use, and maintenance of specifications appropriate for use by the DoD can be resolved. While a specific plan is not outlined, the Committee believes that the solution to the problem can be developed by an ad hoc group consisting of professional NDT specification writers from aerospace manufacturers and cognizant Tri-Service representatives. This group should be assigned the responsibility for developing alternate approaches that could provide guidelines for reducing, eliminating, updating, and tailoring specifications while still retaining those primary controls essential to the DoD. The Committee also believes that all military NDT specifications retained by the DoD must be updated and maintained if they are to become practical, enforceable documents. It recommends that the Tri-Services NDT Executive Committee be directed to give high priority to the development of a plan for influencing the generation and application of present and future military specifications.

The Executive Committee should initiate priority action to ensure that the Army Materials and Mechanics Research Center (AMMRC) develops and implements a plan to:

a. Identify NDT/E/I specifications that should be retained or revised within the DoD system;

b. Identify NDT/E/I specifications that should be eliminated;

c. Develop a mechanism for preparation of new specifications;

d. Develop guideline documents to define the procedure for "tailoring" specifications.

The Tri-Services NDT Executive Committee should overview these efforts and solicit industrial professional comments and technical assistance as needed.

D. Committee Overview Comments

1. Support for Nondestructive Testing

The DoD has identified NDT/E/I as key areas of technology important in enhancing the serviceability of military vehicles and materiel. During the Committee's deliberations, however, it became evident that national awareness and recognition of the potential impact of NDT technology on quality and reliability are lacking. While the technology is of growing interest to the DoD and other government agencies, commitments made to date for support of this technology have been relatively insignificant and ineffective. Substantial increases in manpower and funding are required to develop the "critical mass" needed to successfully implement the technology.

2. The Cost of Nondestructive Testing

Few measures have been applied to relate the costs of NDT technology to the benefits that accrue from it in terms of greater safety, reliability, and serviceability of aerospace structures--i.e., while the dollars associated with the loss of an aircraft or the particular costs of a nondestructive test often are identified, the specific relationship between nondestructive tests performed on a system and the greater reliability and reduced life-cycle costs that accrue from these tests seldom are identified. Nevertheless, these relationships must be recognized if specific justification for improved nondestructive tests is to be developed and if national awareness and recognition of the impact of NDT technology are to be increased.

In generating this report, the Committee concentrated on the NDT associated with the manufacture of future aerospace systems. While this is only one segment of the NDT applied during a system's life cycle, the techniques applied during manufacturing determine the baseline reference to which service evaluations are compared.

Separating the NDT costs directly associated with the manufacture of an aircraft is difficult. Organizationally, the NDT function generally falls under the quality and inspection department and the tendency is for management to include all costs associated with quality engineering, product inspection, vendor quality control, quality assurance, and product quality control under one costing code representing the total "quality function."

To place NDT costs in perspective with other elements of the total quality assurance program, data developed by the Aerospace Industries Association (AIA) [5] were combined with an industrial sampling to illustrate the relationship of NDT costs to the quality assurance function and to selling costs. NDT costs for three elements (forgings, engines, and airframes) were considered and the comparisons are shown in Figure 3. In no instance did the actual NDT costs approach 1.5 percent of the selling cost of the item. Thus, NDT costs represent a small percentage of the final selling price and a relatively small percentage of the total quality function. A typical industrial quality assurance organization is shown in

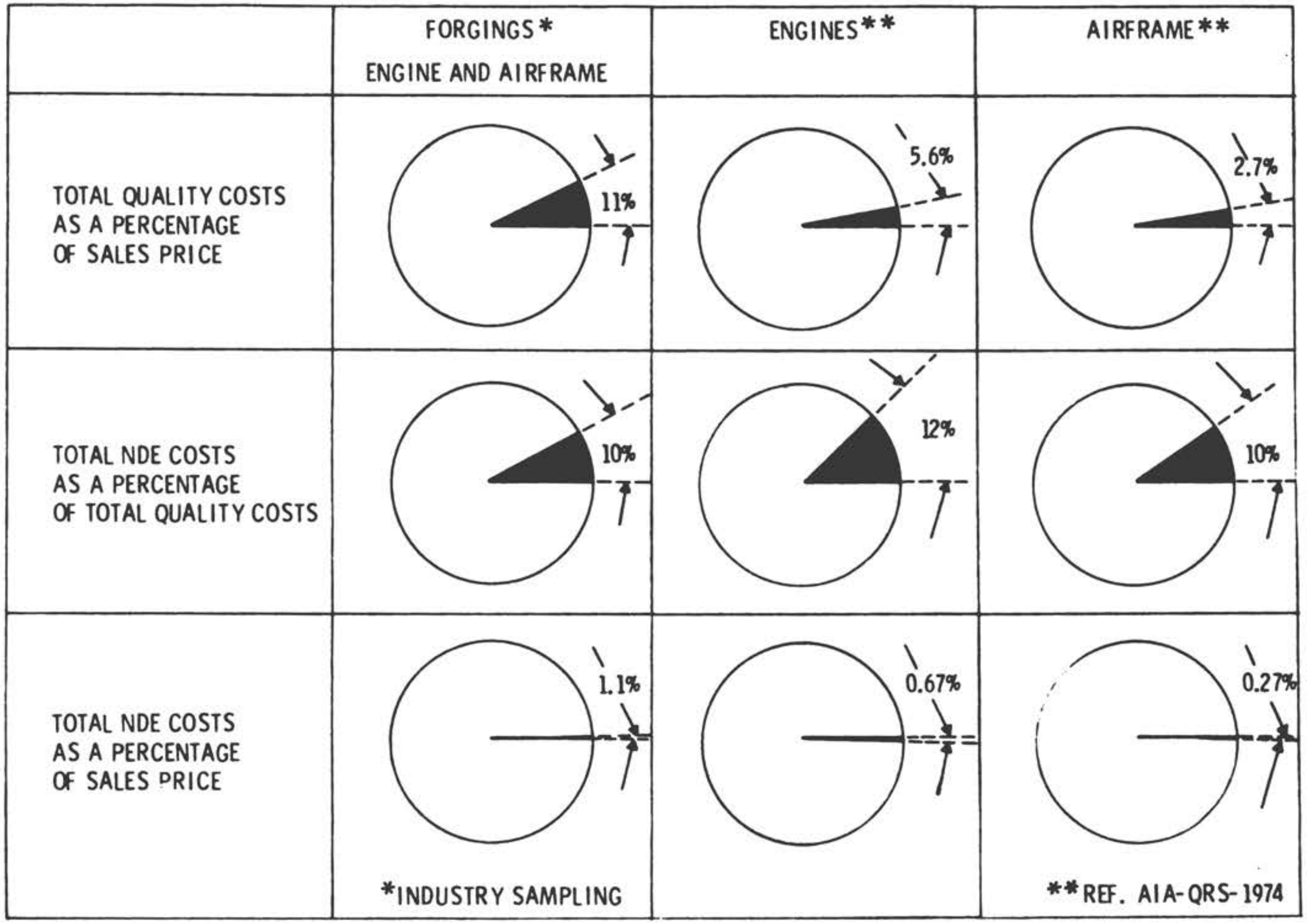


FIGURE 3 Relationship between quality and NDT costs.

Figure 4 and the elements that involve NDT technology are highlighted. When viewed in this context, the cost of the NDT function does not appear to be excessive.

From the Committee's findings, there appears little rationale for attempting to reduce the dollars expended on NDT in lieu of reducing costs in other "quality function" cost elements; however, if life-cycle performance is considered, there appears to be justification for increasing the amount and level of NDE in order to obtain higher overall quality, which may lead to higher reliability, greater serviceability, and lower life-cycle costs. In addition, modeling techniques such as engineering and economic analysis may provide major life-cycle cost savings through the identification of the effectiveness of nondestructive tests performed on critical components of the aerospace system.

Efforts aimed <u>specifically</u> and <u>exclusively</u> at reducing the costs of NDT and NDI associated with the manufacturing sequence will have little overall impact on reducing the total cost of a system. To improve the cost effectiveness of the NDT function, the Committee has made recommendations aimed at the development of a more effective NDT program through the reduction of ineffective or unnecessary tests and the enhancement of technology. In addition, it suggests that a practical and comprehensive NDT program covering all aspects of manufacture, service inspection, and maintenance can greatly reduce total life-cycle costs.

QUALITY ASSURANCE

PRODUCT INSPECTION

- Tooling Inspection
- ➡ Detail Parts Inspection and NDT
- ➡ Assembly Inspection and NDT
- Checkout Inspection
- Material Review

PROCUREMENT QUALITY CONTROL

- Purchase Order Review
- ⇨ Source Inspection
- ⇨ Receiving Inspection
- Subcontractor Control
- Supplier Quality History
- Shipping Inspection

QUALITY ADMINISTRATION AND AUDIT

- Budgets
- Audits
- Corrective Action
- ⇨ Manuals and Procedures
- ⇨ Quality Planning
- Administrative
- Cut Complaints Investigation

QUALITY ENGINEERING

- Technical Services
- Materials Control Lab
- ⇨ Process Control
- ➡ NDT Research and Development
- ➡ NDT Procedures and Certification
- ⇨ Failure Analysis
- System Equipment Acceptance Test Procedures

METROLOGY

- Maintain Company Measurement Standards
- Calibrate Inspection Instrument
- Calibrate Test Equipment

➡ = Specific NDT Responsibilities
⇨ = Related NDT Responsibilities

FIGURE 4 Typical manufacturing inspection quality organization.

3. Special Considerations

a. NDT Research

While the Committee does not recommend major advanced research activities as a solution to near-term or current NDT problems, it does not wish to imply that advanced research is not needed but rather that presently available technology (e.g., nonfilm radiographic imaging, economic engineering analysis, and electronic decision processes) can be implemented now to make more effective use of the dollars available for NDT. The charge to the Committee specifically directed it to restrict the scope to activities which could be brought to fruition within the next three to four years; it takes much longer than this to convert research findings into application. While specific recommendations are not made in this report, efforts in advanced research must continue to be funded to provide better solutions to existing problems or to find means for evaluating new material and structures. In fact, development of NDT procedures should be an integral part of any materials development program.

b. Life-Cycle Costs

The Committee focused much of its attention on aerospace manufacturing costs, but since the life-cycle costs (including maintenance NDI) of aerospace systems are of equal or greater importance, the Committee has included the limited overview of life-cycle analysis in the report. The Committee believes that life-cycle cost analysis should be given priority by the DoD and the Services and that studies should be conducted to identify the relationships between original manufacturing cost and life-cycle costs and, thus, to determine the overall cost impact of NDT.

Chapter 2

NONDESTRUCTIVE TESTING, EVALUATION, AND INSPECTION AS RELATED TO PROGRAM MANAGEMENT

A. Introduction

A major cost associated with NDT can result from a failure to develop a coordinated management plan for integrating the design engineering, quality assurance, manufacturing, and procurement disciplines with the requirements of NDT. Experience has shown that unless the NDT program is considered collectively by each of the functional disciplines, a cost-effective program cannot be developed. For years, NDT has been sought only "after the fact" to locate defects in suspect parts. The net effect has been that the value of NDT in the manufacturing and life-cycle of the aerospace systems often is diminished because the assembly is uninspectable or because the applied test is inadequate since access is insufficient or the material history is lacking.

Program managers recognize the decision and design compromises that must be reached by engineering and manufacturing personnel in the development of aerospace systems. However, both in government and industry, program managers seldom recognize the impact that material and design compromises have on the cost effectiveness of NDT and, more importantly, the risks incurred by not performing an adequate NDT.

The lack of NDT is reflected in the research and development, manufacturing, and service life costs of the system, and it is important that program management recognize what, when, and where risks are taken when testing is not performed. To keep cost down, known risks may have to be taken, but such a decision should be accomplished by coordinating the technical knowledge of government program management and contractor engineering, manufacturing, quality assurance, and procurement disciplines. Some of the risks and costs may not be readily apparent (e.g., machining time that can be lost when defective raw materials have not been inspected). Early failure of parts also can be costly in terms of design changes, production schedule delays, replacement cost penalties, and personnel injuries.

Personal injury, in particular, is one major risk associated with product liability, and product liability lawsuits are gaining in popularity and cost. For a single incident involving a faulty artillery shell, the involved Army contractors were held liable in a judgment of several million dollars. (The ability to prove 100 percent testing could be used as one defense in such a suit, but that also could be a reason for high cost.) Even should the company be adjudged free of product liability, liability suits put management in a "no-win" position; regardless of the outcome, the public image of the company suffers. In addition, considerable time and money are spent on the investigation to gather enough data to make a credible case and to indoctrinate the legal counsel.

Within a program, management must recognize the existence of the factors just described and must be aware of their role in influencing the cost of NDT. Government program management as well as contractor management, engineering, manufacturing, quality assurance, and procurement all can increase NDT costs and total life-cycle costs by their decisions or indecisions. It is important that the actions of each discipline be closely coordinated with the others during all phases of the program.

B. Design, Development, and Manufacture

1. Program Management in Government Procurement

The program management team for major DoD procurement must consider the requirements for the timely use of appropriate NDT during the design, fabrication, and operation of a given system. These NDT requirements must be developed by personnel qualified in NDT disciplines who also have experience in NDE and NDI. The requirements for specifications such as MIL-I-6870 and MIL-STD-410D, as well as the requirements for fracture mechanics, should be specifically included in the contract statement of work when applicable. To avoid blanket application of specifications and prevent over-specifying, which is yet another major cost driver, these requirements must be tailored for the particular product being procured.

Government program management must consider that the product design and the identification of the various available NDT methods must take into account the need for inspections during the service life of the system, the capabilities of service inspection personnel (training and equipment), and the environment under which NDI must be performed. The prime contractor should not design and build a unit that cannot be inspected unless inspection will not be required during the life of the article. A basic ground rule for program mangement in making decisions related to NDT or NDI is to consider the life-cycle costs. Lower total life-cycle costs may be achieved by doing more NDT/I at the time of fabrication and thereby improving safety and reliability and reducing downtime of the operating system.

During contract performance, government program managers must follow-up to ensure that the contractor is responsive to the comprehensive NDT/I requirements established by the contract and that the functional disciplines--engineering, manufacturing, quality assurance, and procurement--have established means for determining that the requirements of the contract are being implemented.

2. Program Management in Design and Manufacture

The program management requirements during design, development, and manufacture can be divided into several disciplines including: system management, engineering design, manufacturing, quality assurance, and procurement as indicated in the following discussion.

a. System Management

System management personnel have the overall responsibility for integrating the disciplines in the manufacturing cycle. Engineering design, quality assurance, NDT, manufacturing, and service organizations must all have an interface. If NDT is to be effective, these interfaces must be identified and coordinated. Requirements for fracture mechanics and safe life/fail safe design technology have a direct impact on the cost of NDT; therefore, they must be tailored to suit production and performance needs. The factors increasing cost should be identified for a given product and eliminated or modified to provide manufacturing with realistic product requirements. The quality assurance, manufacturing, and engineering operations must interface to develop the proper interrelationship between the design, the NDE, and the processes. The process capabilities must be known and the types of flaw that are to be expected with the process must be identified. Engineering personnel should design to allow acceptable flaws and quality assurance should identify the method and level of NDE/I to be employed. Zoning of critical areas is another effective means for reducing NDT costs and increasing system reliability. Process controls should be identified, and quality assurance personnel, working with manufacturing personnel, must identify the most strategic timing sequence for performing NDE/I. If properly coordinated, the NDT process can be applied effectively during the manufacture and service operation of the system.

b. Engineering Design

Engineering has a major impact on the cost of NDT/I. Areas of responsibility include identifying the critical areas (zoning) and the accept/reject criteria, and designing inspectability into the system. Requirements such as "no defects allowed" are meaningless. Meeting such requirements is impossible and attempts to do so are extremely costly.

Advanced aerospace designs pushing the state of the art are costly and can substantially increase the cost of NDT. Engineering personnel must be knowledgeable of NDT capability and must coordinate their efforts closely with quality assurance personnel during the design phase to ensure that any decisions made provide for adequate inspectability of the part or assembly. Engineering personnel also must identify the type, shape, and zoned location of "acceptable" flaws and must modify the design of critical assemblies to accommodate the capabilities of the NDT process. They also play an important role in helping to identify the risks that can be taken. Certain areas require little or no NDT; therefore, engineering can concentrate on the areas where NDT minimizes the risks. Specific items that must be considered are the application of fracture mechanics principles and damage tolerance requirements.

c. Manufacturing

The selection of manufacturing methods and the fabrication sequence can increase the number of NDT techniques required and the costs. Some processes may require that several techniques be used to determine whether or not the part is satisfactory. Manufacturing personnel should interface with the NDT personnel to learn which NDT methods are to be employed and what impact the manufacturing process will have on the total cost of the NDT program. It is usually cost effective to inspect a part when it is in its simplest form; as it is built up and becomes more complex, accessibility to the critical area and applicability of the NDT technique may be limited and a more costly NDT technique will have to be employed or developed. Thus, the manufacturing and NDE/I sequences must be coordinated.

d. Quality Assurance

Quality assurance personnel are responsible for identifying the method of NDT to be used. It is essential for them to interface closely with manufacturing and engineering personnel to identify the most practical method. To prevent ascalation of costs, MIL-I-6870 or any other documents requiring NDT must be tailored to ensure that only the needed elements are required. Unrealistic desires or impractical inspection requirements must be eliminated. To utilize the proper NDT with the design, quality assurance personnel must review production processes and be part of the team making the decision that outlines the fabrication sequence. Manufacturing personnel usually identify the fabrication sequence and the processes to be used.

To select the most effective method, NDT personnel must know the manufacturing sequence and the various critical areas of the design. Quality assurance can increase cost if improper or redundant methods are selected (e.g., methods to be used after the part is completely fabricated or specified for application at an improper sequence usually are the most costly). Instructions for performing NDT should be sufficiently detailed to prevent variance from standard practices and procedures that have satisfactorily met engineering and customer requirements.

e. Procurement

The procurement function is seldom perceived as one that can increase the costs of NDT. Procurement personnel must recognize and appreciate how total product costs are affected if an NDT is or is not performed at the supplier's facility. In addition, they must coordinate decisions for supplier fabrication and supplier NDT with internal manufacturing and quality assurance personnel and must insist on procurement specifications that specify the level and type of NDE/I to be applied to the product.

The procurement process should include NDT specifications that have been tailored to the specific parts being inspected. This tailoring should be done by the supplier, based on his experience and equipment, and negotiated with the prime contractor. The prime contractor's quality assurance NDT staff should coordinate and monitor all procurement efforts to ensure that an adequate level of inspection is performed and that the supplier maintains a qualified capability to perform the service.

Once an acceptable sequence has been established and a supplier has been qualified, breaking that sequence costs additional money. It wastes money to test at a source and then retest at the prime contractor's facility.

Audits also can have an impact on the supplier's NDT cost. Numerous redundant audits are conducted by both government program managers and the prime contractors, and supplier control personnel must develop means to accept audits and specifications of other major auditors. To eliminate redundant audits and their associated costs, NDT suppliers should work out a system with their customers to permit reviews of the various audit results and should consider a cooperative approach to control.

Differences between various specifications and various companies' requirements for personnel qualifications and requalification now imposed are not relevant to the practical applications of the NDT process or technique being used. Some examples of possible irrelevant requirements are in the areas of visual acuity, theoretical derivations of NDT principles, and frequency of requalification to a specific test method. Many inequities could be overcome if a common procedure acceptable to industry and government were developed for qualification or requalification of individuals.

C. Impact On In-Service Maintainability

The role of NDT program management during the procurement, design, and manufacturing phases has been emphasized. While it is essential to deliver a product that will meet the performance requirements, it is equally important to be able to maintain the product during the service life of the system and this fact is often overlooked or ignored. The NDT program management imposed by the prime contractor has an important economic impact on the maintainability of the aerospace system.

The NDT method used during maintenance may be considerably different from the test and evaluation performed during manufacture and these differences often cause problems. The design may not reflect the needs or requirements for maintenance inspection in which service-induced defects such as cracks or corrosion are the major concern. Such defects may occur at the surface, below the surface, or at a weld, joint, or fastener and may or may not be accessible. Location, type of defect, intervening structure, and accessibility may not permit the use of the optimum test method. Thus, electronic, radiographic, or ultrasonic access ports must be provided to facilitate the use of appropriate NDT methods.

In-service inspections are accomplished at many different locations under many different environmental and testing conditions. Service maintenance is dependent on the inspection manuals prepared by the prime contractor. These manuals often lack the detail needed to perform an effective test, have been prepared based on manufacturing conditions, and do not accommodate the field or service testing requirements. Further, the staff that prepares the NDI manual seldom has the field experience required to define the test procedures needed to make an adequate inspection. Inadequate manuals for service inspection represent another cost factor, but one that is reflected in operating costs rather than in the cost of NDT involved in manufacturing.

Chapter 3

TRI-SERVICE NDT PLANNING AND COORDINATION

A. Introduction

The Army, Navy and Air Force each have NDT, NDE, and NDI programs that are designed to respond to the specific needs of each agency. While the basic NDE technologies are based on the same fundamental principles, the application and the range of problems may be substantially different from Service to Service. Still, the Committee believes that none of the NDT programs of the three Services has reached the level of acceptance and recognition required either to obtain and to sustain the continued financial support needed to promote, or to utilize effectively, the available technology and engineering capability. Some of the problems faced are common to each of the Services, but the level of effort that can be applied by any one organization is often insufficient to resolve the problems faced by the DoD.

While considerable national resources (dollars and manpower) are being spent by the DoD each year for NDT in areas such as quality control, quality assurance, safety inspection during manufacture, NDT testing systems, instruments, research, development, supplies, training, and in-service maintenance inspection, the Committee believes that a substantial expansion of NDT activity is needed and warranted to achieve the full cost effectiveness obtainable through utilization of NDT technology. A coordinated plan is required to ensure effective utilization of existing and expanded funds to be spent by the DoD, and the Committee has identified several areas in which the spending of additional funds could substantially decrease the initial and life-cycle costs of aerospace systems.

Several government groups have mounted efforts to promote technical exchange of information or to maintain an awareness of what is going on in industry or in other government agencies. While reasonably effective in achieving specific objectives, the authority and responsibility of the committees or task forces conducting these efforts are limited, and little or no planning is provided for longer range programs or for commonality in program efforts. As presently utilized, the Service NDE committees tend to look at reactive programs such as the prevention of duplication rather than at the proactive programs such as pooling resources to meet a common problem. A broader base must be developed to gain the necessary recognition and support within the DoD if the real potential of NDT is to be utilized.

B. Plan for Unifying Efforts

The Committee observed that each Service and, for that matter, each government agency has separate and at times "guarded" programs addressing problems unique to its activities. To a great extent these programs are justified and necessary; however, there are problems (e.g., specifications, standards, personnel qualifications, and technology implementation) that could benefit from a joint and unified effort. A coordinated plan for dealing with immediate problems (which are often unique to each Service), intermediate problems, and generic problems, and with long-range planning in NDT is needed. Simply recommending that the DoD provide additional budget support will not result in a solution.

The solution proposed by the Committee is that a Tri-Service NDT Executive Committee be established by the DoD to develop, plan, formulate, and implement all NDT activities. This Executive Committee would consist of not more than five technically qualified members, including the chairman appointed by the DoD, representing the Army, Navy, Air Force, and DoD. In addition to the Executive Committee, it is recommended that separate NDT operating Manager Groups be established by each Service to represent that Service in planning, budgeting, information exchange, and problem solving. (See Figure 2 for conceptual organization chart.) Examples of the responsibilities of each group are presented below.

1. The Executive Committee would:

a. Recommend to the DoD courses of action to be pursued to resolve major NDT problems;

b. Identify specific opportunities and problems common to the Services;

c. Recommend courses of action to be pursued by each of the Services;

d. Request and obtain budgetary funding for the operational groups;

e. Serve as a national advisory team to stimulate national technical societies, universities, institutions, etc., and to influence and focus technical efforts on DoD problems;

f. Assist the DoD in establishing intermediate and long-range goals for NDT technology;

g. Interact with operating managers to assist in defining and achieving goals and in reviewing progress of the established programs;

h. Develop a matrix of critical problems to identify common areas that could be resolved effectively by pooling resources or by providing the critical mass (dollars and staff) to effect a solution;

i. Review activities on a national basis (e.g., those of the National Aeronautics and Space Administration, the Electric Power Research Institute, and the Nuclear Regulatory Commission) and set national DoD priorities, making maximum use of outside consultants and technical capabilities to enhance the DoD resource;

j. Coordinate Tri-Services NDT activities and ensure that adequate funds for staff, equipment, and travel are available to develop and maintain a strong NDE staff within the Services.

2. The Operating Managers Group would:

a. Assist with Tri-Service coordination of NDT programs;

b. Provide coordination of NDT programs with the Services;

c. Establish the management plan for NDT goals, levels of funding, and development;

d. Increase efficiency of DoD NDT efforts by integrating goals and programs;

e. Interact with other NDT operating managers in other government agencies (e.g., National Bureau of Standards, Department of Transportation, and National Aeronautics and Space Administration) through technical coordination conferences and direct interaction to provide more effective utilization of funds, strengthen the national posture of NDT, and focus efforts of all agencies on national problems;

f. Interact with NDT managers in industry to identify and exploit activities of importance to the DoD;

g. Ensure timely implementation of Executive Committee program plans;

h. Establish a realistic and logical sequence for industrial implementation of development programs to reduce the time loss between research and utilization;

i. Serve as the collecting body of NDT problems or needs as established within the Services (e.g., Manufacturing Technology Advisory Group, Air Force Managers Monitor Meetings, Army Quarterly Managers Meetings);

j. Interact with universities, societies, and associations to identify DoD problem areas so as to concentrate scientific efforts to effect a solution.

The Executive Committee could also be effective in providing the chain of communication required to implement NDT in all major weapons system development programs. To expedite implementation of the recommendations, the DoD may choose to call upon the technical community (e.g., an ad hoc Committee under the National Materials Advisory Board) to provide additional conceptual and programmatic input.

Chapter 4

IMPLEMENTATION OF CURRENT TECHNOLOGY

A. Introduction

Research on advanced instruments, principles, and concepts has been the accepted means for developing improved NDT capabilities. Such research remains a vital segment of future or long range developments, and substantial funding, direction, and management should be perpetuated. However, it generally takes years for concepts or ideas to be reduced to practical industrial applications. A review of existing technology, both NDE and related technology, indicates a substantial potential for providing more cost-effective solutions to existing problems without the delay and uncertainty associated with the development and implementation of new technology. In many instances, more careful selection of the accept/reject criteria or more careful engineering of the test method for a particular application can lead to major overall cost savings. In some cases, current research can be applied immediately to an industrial problem while in others existing technology in allied fields, principally in electronic, electro-optical, and computers, can be adapted to new configurations that will result in more cost-effective nondestructive tests.

NDT, as practiced in industry today, is labor intensive and requires highly skilled personnel not only for the test development phase but also for the inspection and evaluation phases. While the aerospace design analyst may have established the accept/reject level in terms of the size and nature of allowable imperfections, the actual decision often is based on an NDT signal response rather than on the severity of the imperfection. While the design or test engineer would like to establish the relevance of an NDI indication and how the defect may affect product life and performance, all the individual really knows is the size or pattern of the NDT signal response or a combination of responses. Substantial training and experience are required to set up and interpret these NDT signals in terms of imperfection severity.

The nature of NDT is that there usually exists a significant variation or uncertainty in the actual severity of the imperfection associated with an NDT indication. Because of this inspection uncertainty [6], an NDT decision on accepting or rejecting a part is subject to two types of errors:

1. defective parts may be accepted, or
2. sound parts may be rejected.

The costs associated with these errors often greatly exceed the specific test and test development costs.

It has become clear that consideration of the costs associated with NDE and the specific costs of nondestructive testing and test development should not be considered in isolation from consequential upstream manufacturing costs and consequential downstream life-cycle benefits or cost savings. The introduction of a nondestructive test involves not only the specific cost of the test and test development, but also additional manufacturing costs because some material units may be rejected by the test or the manufacturing process may have to be modified to pass the test. These increased costs are justified only by an increase in reliability and a corresponding reduction in the total expectant life-cycle cost of the material units. Often these consequential manufacturing and life-cycle costs greatly exceed the specific inspection cost.

B. NDT Improvements

Improvements in NDT capability can be enumerated in the following categories and subcategories:

1. Better Decisions

a. Emphasize measurements related to strength or life;

b. Process control rather than defect control (after processing);

c. Field experience feedback (especially by periodic diagnostics);

d. In situ examination for periodic or continuous feedback;

e. Assessing changes in environment (especially by in situ monitors);

f. Assessing need for replacement (especially by in situ monitors);

g. Quantitative economic decisions (including liability aspects);

h. More repeatable NDT processes;

i. Replacement for cause rather than by time;

j. Enhancement of measurements;

k. Pattern recognition rather than individual measurements;

l. Adaptive examination to achieve needed precision of measurement.

2. Better Process Control

a. Quicker feedback (especially of digital data);

b. Adaptive control of dimensions during processing;

c. Continuous or periodic control of chemical composition;

d. Temperature or time control by individual or batch measurement.

3. Less Costly Preparation for NDT

a. Combining dimensional measurement with defect control;

b. Combining preparation for NDT with dimensional measurement;

c. Adaptive contour-following so extra machining is not needed;

d. Computer determination of position to eliminate extra machining;

e. Chemical rather than mechanical surface preparation;

f. Automatic positioning for radiography.

4. <u>Fewer NDT Examinations</u>

a. Selective examination;

b. Digital data transfer to user from supplier to eliminate repetition;

c. Using process control to minimize need for defect control.

5. <u>Faster Examination</u>

a. Numerical-controlled positioning;

b. Computer-controlled contour-following;

c. Array scanning (multiple scans simultaneously);

d. Simultaneous examinations (rather than sequential);

e. Combining metrology with conventional NDT;

f. Instantaneous radiography (rather than film radiography).

6. <u>Faster Decisions</u>

a. Digital comparisons;

b. Position comparisons;

c. Pattern comparisons (physical or holographic);

d. Automatic decisions;

e. Computer decisions;

f. Defining decision criteria so fewer committee decisions are required.

7. Savings in Basic NDT Processes

   a. Film replacement by advanced isocon system with monitor (especially for in-process rather than permanent radiography);

   b. Film replacement by magnetic tape, hologram, or microfilm;

   c. Automation of scanning and recording of ultrasonics or eddy current;

   d. Combining scans (multiplexing).

Some of the technology discussed below fits into more than one category and specific examples will be cited where the item is not self-explanatory. The Committee believes that each of the items could be implemented within a three- to five-year time frame and all have potential for eventual life-cycle cost savings. Some items already are being used by certain companies to improve quality and reduce costs. Dissemination of information can provide more widespread usage.

1. Better Decisions

Generally the most important aspects of NDI that result in increased costs are inspection errors--either the acceptance of parts that fail in service or the rejection of parts that would not have failed in service. The key to reducing the frequency and impact of these errors is the development of inspections with better correlation between the NDT parameters used in making accept/reject decisions and the life of the part.

From an engineering point of view two things are needed to improve this decision process. First is better understanding of the effect of a given severity of imperfection on the life and failure probability of the part. This depends on good fracture mechanics or other failure mechanics modeling and better knowledge of the stress, loads, and environment to which the part will be subjected. Second is improved correlation between the NDT response used in making the accept/reject decision and the severity of imperfection. Reduction of the inspection uncertainty normally is considered within the realm of the NDT engineer, but increased interaction between the design analyst and the NDT engineer should improve the decision process. Recent technology allowing for integration of failure probability data (design, materials, and field service engineering information) and their associated costs with NDI costs, either in initial manufacture or in service, to show their overall effect on the cost of the aerospace system is discussed below.

a. Probabilistic Economic and Engineering Analysis

One barrier to more effective utilization of NDI is the lack of quantitative information relating higher product reliability with manufacturing costs and with downstream cost savings resulting from increased serviceability and lower maintenance. The cost effectiveness of a nondestructive test is dependent upon a number of diverse factors including: the details of the total cycle of manufacturing-testing-service; material quality; failure modes; failure consequences; inspection uncertainty; the accept/reject criteria; and the various costs associated with the NDI, manufacturing process modifications, part rejection, and failure. In order to assess the potential cost effectiveness of an NDE/I, these factors must be combined and a projection made of the costs and benefits that will accrue from the application of the inspection. In the NDT industry, these cost and benefit assessments typically are made subjectively, often without full understanding of the impact of all the diverse influencing factors.

The computer hardware, inspection uncertainty analysis techniques [7,8], Monte-Carlo simulation techniques [9,10], fracture mechanics, reliability theory [9], and risk assessment techniques [11,12] necessary to make a quantitative assessment of the cost and benefit relationships are available and recently have been integrated into practical methodology. This methodology, described in detail in References 10, 11, 13, and 14, can predict accurately the effects on total manufacturing and life-cycle costs of modifications in NDT procedures.

The methodology has been applied successfully to components with complex manufacturing and life cycles such as steam and gas turbines, bearings, nuclear reactors, pressure vessels, and railroad track. Some of the specific techniques have been applied to supertankers, bridges, tower complexes, and automobile components.

Utilization of this engineering and economic analysis methodology to assess the cost effectiveness of present or potential test modifications represents a major technique for reducing the NDI and failure costs in aerospace systems. Its application can lead to more cost-effective utilization of present NDI technology, guide future research and development efforts, and eliminate many ineffective nondestructive tests.

Appendix C illustrates a preliminary application of the methodology to the generic problem of premature replacement and failure of rolling element bearings. The quantitative economic and engineering analysis of this specific bearing shows that present magnetic particle inspection and certain types of in-service monitoring are highly cost-effective. Despite this, there are high failure costs per hour of bearing use (i.e., costs associated with all bearing-related failures divided by total service hours). Initial manufacturing costs prorated in the same manner (i.e., per hour of bearing use) are approximately 1 percent of the failure costs per hour. The analysis also indicates that improved in-service monitoring using available technology shows tremendous potential for greatly reducing the failure cost per hour of bearing use. With such improved in-service monitors, bearing life limits might be extended without the need for bearing reconditioning.

b. Other Aids to Better Decisions

Direct correlation analysis of field failures and life data or laboratory failure data with NDT measurements can bypass some of the usual intermediate steps of trying to relate life to size (which may be only a minor factor in determining life) with consequent improvements in the decision process. Adaptive learning and associated signal analysis techniques, such as those developed by Adaptronics [15] can achieve better correlation between the accept/reject decision and the life of the part.

More repeatable NDT measurements and more commonality of measurements between supplier and user would lead to better decision making and major cost savings. Removing the operator (automation and digital measurements) from the decision-making process should be the primary means of achieving more repeatable measurements. Optic-laser surface scanning systems (nonholographic) with digital output would offer some decision-making possibilities, but this technique presently appears best suited for dimensional and surface condition measurements.

2. Better Process Control

A key to a cost-effective product is process control. Improved process control reduces the costs associated with scrapping or reworking of parts, reduces the need for defect screening and other defect control inspections later in the manufacturing or life cycle, and increases the overall product reliability. Greater utilization of NDI immediately after manufacture or during manufacture, with deviant information quickly fed back to process control, is an excellent means for achieving improved reliability and reduced overall costs using present technology. Even on individual or batch manufacture operations, quick feedback is necessary for good process control. Use of data-link systems for transmission of data from remote locations or even from the customer's incoming inspection could speed up process control corrections at the manufacturing site.

There are many examples of measurements of specific properties providing information to control the process and maintain quality, but in other cases, less effective measurements are made because they historically have been made or no measurements of any kind are made. In many instances, the correctness of a heat treatment or a casting process for metal parts could be ensured by an NDT measurement that would replace the historically used, time-consuming, and generally unrepresentative metallographic sectioning.

Dimensional control measurements generally are made at a location remote from the fabrication. However, a process control using NDT measurements, such as ultrasonics, readily can be incorporated into an adaptive control system to make precision measurements almost simultaneously with the metal removal. This information can be used to correct for tool wear other changes in the process.

In the manufacture of composite parts when polymeric compounds are involved, the results of NDT measurements of the chemical composition, temperature, and environment during manufacture readily can be used to improve the strength of the resulting component.

Instrumentation can be adapted either to batch process or to continuous on-line measurements to furnish quick process control adjustments.

Optimizing properties, particularly those related to strength, by such in-process controls would be cost effective in reducing the unknown design factors and the amount of material used. Much of the scatter in material properties could be removed so that the average properties are increased and the low-side deviations eliminated. Similar technology is available for using NDT techniques to achieve more ideal heat treatment on some of the high-temperature alloys, thereby eliminating much of the variation that now exists.

Feedback information on failures and on any aspects of the manufacturing process that may be related to failure should be reintroduced into the process as early as possible; often this has not been done in the past. One example of process feedback control is to provide the casting vendor with the deviation information on casting discrepancies of turbine blades on a near real-time basis. The real-time nonfilm radiographic system using digital pattern recognition techniques for immediate feedback on the process offers one approach that could be implemented with current technology.

3. Less Costly Preparation for NDT

By using current technology, many of the separate handling or machining operations that are performed to accommodate NDT could be eliminated. For example, if nonfilm radiography is used, the parts could be positioned and handled automatically as is being done with the tire inspection equipment already in existence [16]. This apparatus conveys, positions, and adjusts the examination parameters for various size tires.

In adaptive control machining, when the thickness is being measured ultrasonically to control the metal removal, the same or additional ultrasonic apparatus could simultaneously examine that volume of material for anomalies (defect control) and eliminate the need for a separate ultrasonic examination for defects. Dimensional measurement might be combined with the positioning and handling equipment used for NDT. An example of such a possible system is the combination of electromagnetic examination of bearing components with optical holography [17, 18] or other optical dimensional measurements on either new bearing components or those being examined for possible regrinding.

Time and money are saved when adaptive contour-following is used for either ultrasonic or electromagnetic examination since the need for special machining to achieve uniform, repeatable contours is reduced or eliminated. Even where nonadaptive numerically controlled NDT scanning is being performed, extra machining in preparation for the NDT is not required if the control has the location of each scan matched to the contour being produced by commercially controlled machining.

Specifying chemical or electrochemical machining that can produce a finish compatible with NDT requirements for penetrant or ultrasonic examination can eliminate the need for additional machining or etching to prepare the surface for examination. These examples are indicative of what can be done to reduce the time and cost of preparation for NDI by combining or specifying processes with the requirements for NDI.

4. Fewer NDT Examinations

Developing procedures for digital data acquisition and storage offer the potential for major cost savings. Present practices for NDI data collection, transfer, and storage are labor intensive. Many of the data stored are never again used but are necessary to the quality assurance programs that maintain traceable information to be used in case of failures. Retrieval of the relevant data from the total stored is difficult and time consuming. Since many of the data used in such failure reviews are compared to other data in "go" "no go" decision processes, it also is practical to store analog and video information by using references that describe the deviation from a "norm." Digital data collection, transfer, storage, and retrieval are compatible with automation of the decision processes. Since the data can be made available to remote locations on a near real-time basis via telephone line, the time required to compare and interpret information (e.g., two radiographs taken at different locations) would be minimal.

When the decision process circuitry is incorporated into in situ instrumentation, it is possible and practical to keep components and assemblies in service until cause is shown for replacement or reprocessing rather than replacement based on maintenance scheduling. Such a procedure could save the cost of periodic teardown and inspection and still maintain the reliability and serviceability of the system.

5. Faster Examination

Current technology offers many opportunities for decreasing examination time by permitting simultaneous examinations and eliminating time-consuming manual operations (especially ultrasonic and electromagnetic examinations). Some companies have made sufficient studies to justify the needed capital expenditures on the basis of cost effectiveness. Others will require partial subsidy by government agencies to expedite and introduce the test instrumentation.

In one case involving the introduction of numerical control for the positioning of ultrasonic transducers on a relatively simple part, a 50% cost reduction resulted. Not only was the positioning faster but greater dependence was placed on the electronic gating and recording systems, thus allowing faster scan speeds. Manual contour-following of even relatively simple curves is very time consuming, and even partial computer control of contour-following results in tremendous manpower savings. The near net shape inspection program being pursued by the Air Force has reduced the complexity of transducer positioning and provided the potential for more rapid inspections that can employ numerical control.

Simultaneous examinations should be considered when separate nondestructive inspections require specialized equipment or special fixturing. When only a small portion of the component is examined on each scan, multiple signal generation and processing (e.g., multiplexing of arrays of transducers) becomes cost effective.

The development of nonfilm radiographic systems that incorporate high-resolution isocons with TV monitoring screens offer prospects for faster, less expensive radiography. Real-time nonfilm radiographic systems eliminate the cost of the film and the time required to expose and process the film. These X-ray systems can be furnished with automatic enlargement, electronic micrometers, and electronic superposition of desired or reference contours and patterns providing a means for rapid comparison of displayed image with the reference part (pattern recognition). When archival storage is required, dramatic cost savings can result if magnetic video tape storage or microfilm storage is used. This type of instrumentation seems ideally suited to tire examination for belt misplacements, broken fibers, and other anomalies, or to other inspections that involve a high volume of like parts.

Recent developments in the automation of metrology make it feasible to combine this operation with other NDT examinations. One example is the combination of laser contour measurements on bonded or sandwich structures with holographic examination used to establish the integrity of the bond after the contours are established. Pressurization or a thermal transient causes local dimensional changes that can be detected by holography to indicate improper bonding. Automated metrology has been developed for dimensional measurement of bearings. This measurement might be combined with a near-surface examination for inclusions using laser excitation or ultrasonic or eddy current excitation for the near-surface examination. The highest bearing stresses occur a few thousandths of an inch below the surface. Since bearing costs and especially bearing replacement costs are high for many pieces of aerospace and ground-based military equipment, fostering developments in combined NDT and metrology should contribute to the production of cost-effective systems.

Another example of combining metrology and NDT is ultrasonic thickness measurements combined with defect control examinations. This could be applied when ultrasonic thickness measurement is being used in an adaptive control of machining of complex shapes to specified thicknesses. If any rejectable indications are found or if the thickness measurement is out of tolerance during the adaptive machining process, the process could be stopped with potential major cost savings on machining.

6. Faster Decisions

Given the proliferation of devices for converting nearly any physical measurements to digital form, a change to digital rather than analog or visual comparisons will result in faster, more reliable decisions even when the decisions are man-made rather than automatic. Dimensions measured in more than one place on a component can be combined into a position comparison. When the radiographic image is presented on an electronic TV monitor, a multitude of measurements can be position-compared by superimposing the desired pattern on the displayed image. Holographic images may be compared in this superposition manner by combining the desired image with that of the component being examined.

Even with fairly simple NDT equipment that permits analog or digital measurements, automatic decision making can be built into the apparatus often with a manyfold increase in reliability and speed of inspection. Optical holographic comparisons could have automatic decision making incorporated, and automatic decision making usually is offered as a featured option on ultrasonic equipment. Automatic decision making readily could be incorporated in nonfilm radiography.

The rapid expansion of digital microelectronic integrated circuits (IC) has exploded the potential for developing digital logic electronics for use in high-speed or automatic decision and comparison processes. While earlier attempts to adapt full-scale computer systems to the decision processes were effective, the cost of both hardware and software systems limited their use to inspections involving multiple like parts [19] or elaborate and complex assemblies.

Low-cost integrated circuits with digital logic capabilities have been reduced to both simple and complex forms. It is now practical and economical to design logic and comparison electronics to perform routine decision functions or to establish reference values for a test instrument. Instruments have been developed [20] that use erasable program read only memories (EPROMs) for digitally recording acoustic emission signals from in-situ continuous monitors of structural components. These low-cost, nonvolatile EPROMs replaced expensive and bulky multichannel magnetic tape recorders and made it practical to reduce the size and cost of the instrument without compromising the basic data. Being in digital form, the data can be retrieved in a few seconds for visual analysis and plotting or can be fed directly into a computer. Savings accrue in instrument costs and, more importantly, in the time required to recover the data for analysis. (Note that the time required for data analysis from magnetic tape can equal the recording time.)

In a new development, EPROMs are being used to calibrate eddy current instrumentation [21,22]. Calibration signal and flaw signal signatures are stored digitally in the memories, and more than

12 different waveforms have been stored in a single device. These waveforms can be used as reference signals for set up and calibration or to compare unknown signals against the references to make decisions. The approach lends itself to automatic signature correlation and can be expanded to cover many waveforms of both actual and artificial signals.

The future for digital logic IC electronics is bright. While the complex process will continue to be developed for microprocessor or computer analysis, the logic ICs can and will be incorporated into instrumentation to effectively select or compare routine signal information and reduce the reliance on the computer.

7. Savings in Basic NDT Processes

Nonfilm radiography is one implementable current technology that would result in substantial savings in the NDT process. For in-process radiography when dimensions are to be measured or the success of a weld repair is to be evaluated, and whenever archival film storage is not required, the cost of exposing and processing the film and the cost of disposing of exposed film can be eliminated. When storage is required, the cost of magnetic tape or microfilm of the video image is much lower than that of X-ray film storage.

Efforts to automate many of the NDT processes by incorporating scanning and limited decision systems to determine acceptability of parts are under way. These systems can function at a rate many times that of an operator, and the increased repeatibility offered by such equipment generally represents a considerable cost savings because it eliminates the need to reprocess parts because of a questionable operator decision. Combining scans done separately into a single scan by multiplexing arrays of transducers and receivers is now possible because of recent technology and should be a high priority item for continued application sponsorship.

8. Additional Suggested Recommendations

Other specific applications of similar computerized economic and engineering analysis recommended by the Committee, in order of priority, are:

a. Other bearings;

b. Jet engine turbine blades;

c. Jet engine discs;

d. Welds;

e. Composite structure (a specific aerodynamic component).

In addition, electronic aids to defect screening are available (e.g., solid state programmable memories for making specific decisions) and the Committee recommends that the DoD expedite the application of electronic subsystems to enhance inspection capability. Adaptive learning computational techniques are available and should be applied not only to defect screening but also to process control.

Chapter 5

NONDESTRUCTIVE TESTING SPECIFICATIONS

A. Introduction

NDT specifications, as they currently are used during the manufacture of original or replacement assemblies for aerospace systems, can readily be recognized as increasing. Many of these costs are hidden in the procurement and manufacturing cycle and become apparent only when one considers that the price for a military product or service may be significantly higher than that for an item of the same quality purchased for a nonmilitary application. Specifications imposed on many products are selected by individuals who lack the training to correctly identify what is needed to obtain the quality level required. The tendency is to impose more and more specifications in an attempt to improve the integrity of the product obtained; however, merely writing and imposing specifications will not contribute to the achievement of this goal in an economical way.

Many NDT specifications are obsolete, inadequate, or inappropriate; some are too general to be control documents, and still others are ineffective because they are not maintained properly. Nearly every branch of the Service has its particular specification. In addition, specifications are generated by a variety of groups. Many professional societies develop "consensus" specifications or standards while most large industrial organizations have internal specifications that are used during the manufacture of their product. The result is near chaos with multitudes of new specifications being generated, many of which conflict with other documents.

The subject of specifications is almost universally controversial. Even within this Committee opposing viewpoints were expressed. One segment of the Committee emphasized that the existing pattern of NDT military specifications should be maintained, that the specifications should be modified and updated, and that a maintenance team should be established to guarantee the continuity and accuracy of the documents. A second segment of the Committee favored a plan for the organized withdrawal of all NDT military specifications except a minimum few that would impose the responsibility for quality and inspection requirements on the major suppliers of aerospace systems. Specific example documents cited for retention included MIL-I-6870 and MIL-STD-410D.

Full recognition must be given to the fact that aerospace manufacturers must develop company specifications and procedures that are associated directly with the performance guarantees of their products. Specifications of this type generally are product-oriented and, hence, more exacting, modern, and enforceable than a counterpart society or military specification. The experience gained at Rockwell International and other organizations on the favorable economic and management impact of MIL-I-6870(C) illustrates the effectiveness of this type of document. Expanding the philosophy extended by MIL-I-6870 which requires the manufacturer to take the initiative and the responsibility for establishing the specifications associated with the system supplied, is one means for developing more efficient product-oriented specifications.

B. The Nature of the Problem

NDT specifications fall into two categories--i.e., developmental or standard--based on their application or limitation to a specific product. For example, a standard specification such as MIL-STD-00453 adequately covers the X-ray and gamma-ray inspection of most metal products; however, it is not applicable when the subject to be radiographed is an electronic component, adhesive-bonded assembly, solid-propellant rocket motor, ceramic rocket nozzle, fiber-reinforced epoxy composite, etc. As a consequence, prime contractors must prepare developmental (product-oriented) specifications to control the quality of their products. When a product is continually manufactured by various prime contractors, it is economical for them to pool their technical knowledge and prepare a standard specification. (A more detailed discussion on the nature of the problem is presented in Appendix A.)

C. The Influence of Specifications on Cost

The Committee studied many aspects of specifications and identified many factors influencing costs. Factors that cause the price of a product to be higher or lower (generally higher) as a result of the enforcement procedure used in implementation are called "cost drivers." To illustrate the factors that have caused specifications to evolve as cost drivers, the Committee has chosen the following four examples: the proliferation of NDT specifications, the lack of NDT specification control, facility certification, and fracture control--NDI demonstration plan.

1. Proliferation of NDT Specifications

A specification is a document used in manufacture and procurement that describes the technical requirements for material, parts, or services. NDT specifications may include procedural, tutorial, and/or quality requirements. There are five general types of specifications--military, federal, Society, company, and commercial. Company specifications usually include method requirements and accept/reject criteria. Such specifications may develop into Society or government specifications after they have been used for some time and accepted by industry. Government or Society specifications tend to be general in content and widely accepted within industry; however, many agencies produce similar specifications, and this duplication often results in conflicting or redundant requirements.

For NDT test results to be meaningful, the method of test must be defined. For the test to be uniform or reproducible, a reference standard must be employed. For determining product quality, accept/reject criteria must be specified. Therefore, to adequately specify an NDT inspection, these items must be defined. Normally, these items are not specified in a single document but are incorporated by reference to other documents.

Before a new product can be manufactured, the material and process specifications must be defined by engineering. During the research and development phase, the NDT method, accept/reject criteria, quality of materials, and fabrication methods must be established. With the increasing complexity of the aerospace products, method specifications will be more effective if they are oriented to aerospace products. Being product-oriented, the individual method requirements can be tailored to the product and this should permit better process control and should minimize the need for repeating general requirements. Combining the tailoring developed in company specifications with a reduction in number and nature of additional specifications will reduce overall costs.

Military NDT specifications and standards tend to be general rather than specific to a given product and such generalization is unsuccessful because NDT test methods and techniques are sensitive to such things as the material, processing, shape, size, surface roughness, rate of inspection, acceptance limits, and type of flaw. Few military NDT documents contain acceptance criteria for specific test procedures and, therefore, they must be supplemented with detailed specifications and test procedures for any given product. Since designs, production, and responsibility for quality are now vested in the industrial contractor [MIL-I-6870(C)], the general military NDT specifications and standards cannot be adequately related to the required detailed specifications and procedures.

Since the product or structural accept/reject criteria is established in specifications developed by the company manufacturing the product and since the procurement agencies do not have staff qualified to tailor specifications to meet a performance requirement, the principal responsibility for the NDT specifications must be undertaken by the contractor. Acceptance of the specifications proposed by the contractor is the responsibility of the contractee. *A competent technical staff specifically qualified in nondestructive testing must be employed to perform this activity*.

Some Committee members recommended that use of NDT military method specifications immediately be discontinued and that military NDT program planning control documents similar to MIL-STD-410 and MIL-I-6870(C) be substituted in their place. Other members, however, thought that this would create administrative contractual problems concerning the definition of general requirements such as X-ray penetrameters, ultrasonic test blocks, X-ray film classification, and penetrant material classification. While some of the required documentation could be provided by referencing ASTM E-7 specifications and recommended practices, this would not resolve some basic problems because most Society documents are written for very general industrial applications and must be tailored to aerospace applications if they are to be effective.

2. Lack of NDT Specification Control

Recognizing that certain types of military specifications and NDT methods documents will be required for use in procuring items, parts, assemblies, and structures, action should be initiated to provide and maintain these documents. For procurements that fall outside the pattern available under a MIL-I-6870 style document, a plan for controlling and updating specifications must be developed.

Two items are of particular concern regarding existing NDT military specifications:

a. the lack of periodic review to update, and

b. the inclusion of detailed tutorial or "how to" statements.

Military NDT documents are not periodically reviewed and revised and, as a result, can become technically obsolete which demands that Societies or companies prepare documents with updated requirements. In addition, many military NDT specifications are procedural documents and do not contain acceptance criteria although they do contain test performance requirements and, in some cases, reference standards. If the test results are to be meaningful, the test conditions must be known and if they are to be reproducible, the method of test must be uniform. To obtain uniformity at reasonable cost requires that only those requirements determined by knowledge and not supposition be specified. The needed requirements should not be ambiguous but clearly stated in measurable terms. Further, NDT specifications should be clear and concise and tutorial statements should not be included. (An example of undesirable tutorial statements is shown in Appendix B.)

3. Facility Certification

Materials or product producers frequently have their products nondestructively inspected in their own or at an independent NDT facility prior to their being shipped to the prime contractor. MIL-STD-410 presently specifies the procedure by which an NDT facility can qualify its own personnel; however, to qualify independent or vendor NDT facilities, the prime contractor must survey and certify each one separately. Each prime contractor therefore must establish procedures for performing this task. The NDT facilities, on the other hand, must comply with all the different requirements specified in order to remain certified. Unfortunately, meeting these requirements and handling the inordinate number of resulting audits increases the costs of a vendor producer or independent NDT facility [23].

An additional problem associated with laboratory qualification is related to the fact that much of the NDT equipment requires periodic calibration. In many cases, independent subcontractors maintain and calibrate the equipment, and there are no existing requirements to qualify subcontractor personnel or calibration equipment.

The vendors and laboratories also are confronted with hundreds of conflicting requirements regarding the same material or test method. For example, one laboratory may have to maintain five or six different penetrant oils from different manufacturers to qualify for different prime contract approval despite the fact that these oils often are comparable and the end results are the same. Further, MIL-I-6866 (penetrant) states that ". . . you shall etch all soft alloys previously machined prior to penetrant inspection," but prime contractors differ on the definition of soft alloys. Thus, the laboratory must comply with the prime contractors' interpretations of "soft alloys" and prepare different test procedures.

4. <u>Fracture Control--NDI Demonstration Plan</u>

Detailed damage tolerance requirements are specified in various categories as a function of design concept and degree of inspectability. The contractor is required to perform all analytical and experimental work necessary to demonstrate compliance with the damage tolerance analyses and tests as specified in MIL-A-83444, MIL-STD-1530, MIL-A-8867, and the procurement contract.

MIL-STD-1530 states:

> Damage tolerance design approaches shall be used to insure structural safety since undetected flaws or damage can exist in critical structural components despite the design, fabrication, and inspection efforts expended to eliminate their occurrence...Design concept shall assume the presence of undetected flaws or damage... The damage tolerance control plan shall include any special <u>nondestructive demonstration programs</u> conducted in accordance with the requirements of MIL-A-83444.

MIL-A-83444 states:

> Initial flaws shall be assumed to exist as a result of material and structure manufacturing and processing operations...Each element of the structure shall be surveyed to determine the most critical location for the assumed initial flaws...Specified initial flaws sizes presume the components...Where special nondestructive inspection procedures have demonstrated a detection capability better than indicated by the flaw sizes specified, and the resulting smaller assumed flaw sizes are used in the design of the structure, these special inspection procedures shall be used in the aircraft manufacturing quality control.

MIL-A-83444 also states:

> Where designs are based on initial flaw size assumptions less than those specified, a non-destructive testing demonstration program shall be performed by the contractor and approved by the procuring activity to verify that all flaws equal to or greater than the design flaw size will be detected to the specified reliability and confidence levels. The demonstration shall be conducted on each selected inspection procedure using production conditions, equipment and personnel. The defective hardware used in the demonstration shall contain cracks which simulate the case of tight fabrication flaws. Subsequent to successful completion of the demonstration program, specifications on these inspection techniques shall become the manufacturing inspection requirements.

Defining the damage tolerance design, developing appropriate test models and demonstrating the capability of NDT for fracture-critical parts is costly and time consuming. Techniques and methods must be refined to develop potential damage tolerance requirements which can economically meet the specified requirements. Further research is required to enhance the fracture control approaches for in-service inspection.

D. Summary of Committee Recommendations on Specifications

The Committee recommends that the DoD:

1. Require all Services to impose on their contractors the NDT inspection program requirements specified in MIL-I-6870.

2. Require contractors to implement MIL-STD-410D for qualification and certification of NDT personnel.

3. Establish a policy that requires all procurement agencies engaged in the purchase of aerospace systems to have technical staff qualified to review contractor NDT specifications and that this staff be part of the team that generates the procurement specifications and part of the review team reviewing contractor proposals.

4. Develop an NDT specification, patterned after MIL-I-6870, that can be added to Section XIV of the Armed Services Procurement Regulations (ASPR). The objective is to establish recognition at management levels for the requirements for nondestructive testing.

5. Authorize the Tri-Service Executive Committee to establish a planning committee to set national direction and policy in the area of NDT specifications and standards for the DoD.

6. Prepare guidelines and requirements that specify minimum requirements for NDT laboratory qualification.

7. Prepare guidelines that specify requirements for an NDI demonstration plan for fracture-critical parts.

As an additional suggested recommendation, the Defense Contract Administrative Services (DCAS), responsible for subcontractor surveillance, having initiated an experimental program to voluntarily certify industry laboratories [23], should form an ad hoc committee, chaired by a DCAS representative, of well-qualified NDT personnel representing all Services and industry to develop a system for qualifying and certifying subcontractors to minimize the number of audits and surveillance necessary to assure compliance with NDT requirements. This program would reduce suppliers' costs and prevent delays caused by the unavailability of government witnesses. Use of certified subcontractors would eliminate the need for separate and redundant audits by each of the Services and by individual prime contractors.

Chapter 6

NONDESTRUCTIVE EVALUATION AND INSPECTION IN PROCESS CONTROL

A. Introduction

NDT technology plays an important role in enhancing the reliability of future aerospace systems. The application of proper nondestructive evaluation techniques at appropriate sequences during the production of raw material, fabrication of structural parts, or assembly of components can significantly reduce the manufacturing and life-cycle costs of a system. To effect improvements:

1. NDE/I procedures must be introduced at the earliest possible time in the process;

2. NDE/I information must be used as the control for the process;

3. Material anomalies detected during the fabrication and assembly phases must be evaluated to determine their significance to quality and life-cycle serviceability.

Engineers base designs on material that meets specific performance criteria. The "zero defects" philosophy is no longer accepted and design groups have replaced it with design criteria that permit acceptance of material anomalies falling below established accept/reject values. Establishing realistic accept/reject criteria is a vital but most difficult job; however, fracture mechanics analysis provides a good basis for defining allowable values. NDT has developed better means for defining the nature of anomalies and describing the type, size, and location of material flaws.

It is evident that many inspection procedures involve detecting and identifying "rejectable" material anomalies. Implementing procedures that will produce higher quality raw material is of greater significance than employing a procedure for detecting "rejectable" material after fabrication or assembly. It is impractical, however, to place emphasis only on the raw materials as many subsequent steps in the manufacturing process may result in material anomalies that are cause for rejection of the part of assembly (e.g., machining, welding, heat treatment). What is necessary, however, is that NDE be introduced at the earliest possible stage in the manufacturing process so that it can prevent detrimental changes in the life-related properties of the assembly or structure. This section of the report addresses the role of NDE in defining design requirements for raw materials, fabrication and assembly techniques, and associated process operations.

B. Rationale for NDE in Process Control

The need for NDE in process control is based on the following rationale:

1. The goal of in-process NDE is to increase the yield of acceptable product through timely correction of the process as opposed

to the costly accept/reject limit, final inspection operations, performed after all processing errors have been committed.

2. Pre-production monitoring of processes during their development and qualification is clearly an interdisciplinary operation. At the start of production, management must force the coordination of the design team, the materials and processes engineers, destructive test personnel, and the nondestructive test engineers to obtain the best possible design. Government and industrial quality assurance management must jointly assist on NDE/I for in-process control. NDE/I should be employed as a tool during the development of new or modified processes to qualify the process before specifications are drawn up. Those critical steps in the process when quality can be degraded, must be identified during this pre-production or process development phase and nondestructive tests adapted, developed, and calibrated for monitoring each critical step as early as practical.

3. Specifying the steps in a fabrication process is a necessary, but rarely sufficient, means for assuring the quality of fabricated materials or parts. It is the function of NDE/I to detect variations in processing due to inadvertant or deliberately introduced process changes (e.g., process change to reduce costs). NDE is required to measure the output of fabrication operations. Measuring what is being achieved and analyzing deviations from a "norm" result in better quality assurance than prescribing what should be done in processing.

4. NDE process control that prevents the occurrence of anomalies can eliminate the need for post-fabrication screening. For example, NDE measurement (not NDI) limits for the nature and degree of polymerization and bonding in composite material can be established at a level that results in properties that are well above the limit required for adequate service; therefore, no defect screening (NDI) would be required.

C. The Role of NDE in Defining Design Requirements

1. Raw Materials

Most industries depend on some other industry to supply the basic raw materials for their products; thus, they are vulnerable to the level of quality control established by the vendor for these materials. Government and industry specifications have been published to aid in establishing material requirements and these certainly are essential to industry. However, raw material producers often unwittingly generate materials that do not meet the specifications of the contract. Destructive tests conducted on random samples may indicate adequate process control although the material may be deficient in one or more vital areas. The user then must decide whether he will accept industry standards and vendor-designed process controls or develop controls and his own specifications. With rare exception, the latter results either in an undesirable increase in cost or in potential suppliers being unable to meet the new specifications. The real cost of the decision <u>not to control</u> this stage of production is often never known; it is a judgment that must be rendered on the basis of little or no historical data.

Powder metallurgy is becoming an increasingly important process for making metal products. NDE process control of the basic raw materials and subsequent processing is important in maintaining the properties of the final product. Control of metal particle size is normally accomplished by standard screening techniques; however, specific attention should be given to parameters such as subsieve particle size, size distribution, shape, porosity, and composition of the raw material. By developing and specifying specialized NDE/I process controls to monitor and control these parameters, improved powder metallurgy products can be produced.

In the wrought metals industry, self-imposed NDE/I process controls have considerably improved the quality of the metal during the last decade. With the advent of ultrasonic inspection of ingots to determine the presence of piping, nonmetallic inclusions, porosity, and cracks, the incidence of contaminated metal has been greatly reduced. This type of process control not only has improved the quality of the metal supplied to users, but also has been a cost-effective investment for the producers. NDE/I gives producers a tool to pinpoint where and how the defects in the raw material occurred and enables them to avoid attempts to process defective materials. Early feedback information can prevent the problem of producing additional defective materials.

Often a meaningful NDE/I process control for composite structures is in the control of the raw materials of the composites. Filament size, strength, and uniformity can be vital to the quality of the final composite structure, and the necessary NDE/I process controls must be applied to consistently achieve these attributes.

2. Design

To effectively apply NDE to a product, the capabilities of NDT must be recognized early in the design phase. Design engineers and structural analysts are beginning to seriously consider process engineering and NDE during product design rather than simply specifying vague, after-the-fact inspection requirements. This trend has acted somewhat as a two-edged sword. On the one hand, the importance of early application of NDE requirements in the design has been recognized, but on the other, some designers and analysts generally have a low regard for NDE because they do not understand NDT and its limitations and lack confidence in its ability to locate unacceptable conditions. Designers may consider NDT to have an adverse effect on their designs (design compromises may have to be made because the NDE/I process cannot reliably detect defects located at orientations adverse to the NDT methods). This is often misunderstood by the designer so an NDT credibility gap is created within the engineering community. NDE/I is a desirable process control tool, but if its application is to be expanded, its positive aspects must be reinforced and the ignorance and prejudice acting as a deterrent to its use eliminated.

As a first step in designing for process control by NDE, realistic accept/reject criteria must be established by engineering. What constitutes realistic criteria is not always obvious. Analytical determination of the effects of porosity or nonmetallic inclusions in structural metallic components is difficult, and an empirical determination of these effects might prove to be prohibitively expensive. What distribution of voids in nonstructural composite honeycomb can be tolerated for satisfactory service life? What quality of surface finish must be achieved to make the product acceptable? What level of material anomalies can be reliably detected by NDT? How must the design be changed to accommodate the NDE/I procedures? If the correct NDE/I process controls are to be established, these and similar questions must be appraised realistically and answers agreed upon as early as possible.

One of the most complex problems involves determining when during the overall fabrication and assembly process the NDE/I controls will be most effective and least expensive. It is obvious that if a product is to perform its intended function, the basic raw materials from which it is made must meet the standards presumed by the design. However, it is not always obvious just what NDE/I process controls must be used to ensure economical application of these criteria.

NDE/I requirements must be considered at every stage of the design phase. If design is considered as involving four phases--conceptual, preliminary design, layout, and detail--one can justify the level of NDE influence developing from the conceptual to the design stages. For example, in the conceptual phase, one must determine whether the design concept is compatible with NDE. If it is not and if the design requires a quality measure, then the concept must be revised. In the preliminary design phase, one must determine whether performance criteria and material selection are adaptable to NDE. During the layout phase, one must determine the inspectability of the product. It is most important that the design consider the following:

a. Fracture mechanics/NDE relationships;

b. Safe life/fail safe criteria;

c. Tailoring requirements for production "needs" rather than "desires";

d. Shop and field NDT capabilities;

e. Accessibility for inspection;

f. Cost/trade-off studies;

g. Testing and verifying procedures;

h. Characteristic process anomalies.

Even in the design stage, it is important that the efforts of qualified materials engineering (including processing), stress engineering (including fracture and fatigue), planning (manufacturing), and quality control (NDE) personnel be closely coordinated. Producibility and quality should receive the greatest attention in the detail design phase, but all disciplines must be considered. Areas of complex structure not inspectable because of geometrical constraints either must be redesigned or must be designed with full knowledge of uninspectability. NDE is obviously a cost element at this point; but, when properly applied, it could substantially reduce the total life-cycle cost.

The NDE/I specialist must participate in the design process to assist the designer in understanding the function of NDE. This can best be accomplished by:

a. Providing qualified NDI specialist support during design;

b. Revising design handbook data to appropriately cover the NDE function;

c. Establishing an NDT guide.

The inaccessibility and, hence, the uninspectability of the critical or high stress zones of structural members on a completed assembly can increase costs significantly.

3. Fabrication

The costs involved with NDE/I during fabrication are relatively high compared to those involved with phases of the overall operation such as design assembly. The work of the NDT specialist must include studies to minimize the impact of NDE on production rates.

One of the factors contributing to the high cost of aircraft is the expense for inspection and reinspection of virtually every part that goes into the airframe and equipment. Since safety and reliability dictate this degree of inspection, it is a challenge to the NDT specialist to apply faster, more reliable methods to satisfy these requirements.

During the fabrication of a structurally significant part of an airframe, as many as 200 separate inspections may be required. Many of these inspections are very slow and completely disrupt the fabrication and assembly process. It is the job of the NDT specialist either to eliminate the need for as many of these operations as practical or to improve the inspection time.

Automation, when its initial costs can be tolerated, is often an aid in fabrication inspection. Elimination of the human error factor, uniform application of the NDE/I, significant speed-up of the operation, and reduction in manpower costs are all normal fallouts of the introduction of automated NDE/I. There are, however, those inspection operations in which the number of units to be evaluated is too few to warrant full automation, then partial automation should be considered.

Current technology, properly applied, will optimize the use of automated NDE/I in producing quality parts on a competitive basis. Modification and adaptation of existing equipment and knowledge can provide this desired end result. If inspection operations can be eliminated in production areas and moved to inspection areas, better and certainly cheaper inspections often can be accomplished, and the NDT specialists must consider whether the desired end result can be accomplished outside the normal production flow. When it cannot, every effort must be made to design the NDE/I procedure to have a minimum effect on production operations. The most significant payoff for any NDE operation is its feedback to in-line process control. The materials and process engineers working in conjunction with the NDT specialists must establish the necessary in-process controls to provide quality products since quality cannot be inspected into a product.

4. Assembly

In theory, the assembly process should not introduce material anomalies or conditions that will cause a part or assembly to be rejected. The quality of parts being assembled is dependent on prior inspection and the accept/reject criteria establish the acceptance levels. While NDE quality overchecks are an essential component of quality assurance, the assembly NDE/I should be minimal.

In practice, many assembly procedures can and do introduce conditions that can result in subsequent failure and that must be evaluated nondestructively during assembly. Processes such as materials joining through welding, bonding, or mechanical fittings can introduce material flaws or apply stresses that result in structural failure. Inadvertent deletion or substitution of components (e.g., when a component is no longer available) or tool scratches or gouges at critical locations may result in failures. Design deficiencies that result in changes to accommodate the assembly process are another potential problem source.

Appropriate NDE/I procedures must be developed and applied during the assembly phase to:

a. Ensure that the assembly process has not introduced defects or conditions that may be detrimental;

b. Verify the integrity of the completed assembly;

c. Develop the base for subsequent in-service inspections that will be performed during the life cycle of the system;

d. Provide engineering feedback to design on structural changes desired for assembly or life-cycle inspection access to critical components.

D. Interactions Between NDE/I and Fracture Mechanics

There is a growing acceptance within both industry and government of linear elastic fracture mechanics as a technique for minimizing the potential for premature material failure. The initial use of fracture mechanics was limited to high strength-to-weight components in the missile field. Now, however, the technique has become an accepted procedure for the selection of materials in low- to intermediate-strength design. Linear elastic fracture mechanics procedures have become accepted for a wide range of applications from nuclear reactors and highway bridges to railroad rails and pipelines.

It is felt that in some cases the use of fracture mechanics theory in the life prediction process has been overused, and in limited instances, the assumptions used in fracture theory are not justified. The validity of many of the predictions may therefore be open to question.

Acceptance of the fracture mechanics concepts places a major burden on NDT process for the following reasons:

1. Fracture theory using fracture mechanics assumes the presence of small crack-like defects. This is a direct departure from the previous concept of "zero defects." The knowledge that defects can be present places importance on the ability of NDT to locate, identify, and measure material defects prior to initial service.

2. The NDI requirements become quantitative rather than qualitative and the NDI process must ensure the absence of defects greater than a specific size as established by fracture mechanics.

3. The fracture mechanics design procedure uses the flaw size as a <u>design material parameter</u> to ensure reliability and therefore

must have the associated statistical parameter of confidence, conformance, and variations identical to those previously determined for mechanical properties such as tensile and yield strength.

4. Fracture theory makes no distinction between different types of defects and assumes that all crack-like defects considered in the design are significant and, hence, must be detectable. This is contrary to the known ability of NDI to detect different types of defects to greater or lesser degrees. Experience has shown that NDI results can sometimes predict actual crack behavior more accurately than would be calculable from general fracture mechanics theory.

5. The most critical defects in the fracture theory are those associated with the stress fields within geometric changes in cross section. These are often the most difficult to detect by NDI because of the possibility of geometric interactions.

Interactions between nondestructive testing technology and fracture mechanics establish a means for enhancing the reliability while reducing the costs of NDT. To realize this potential, many factors must be considered including the following:

1. Cooperative interaction between design, engineering, manufacturing, and quality control (both incoming and in-house) should be made mandatory. Each contractor should establish lines of communication between management and technical staff to permit them to discuss the problems associated with NDE technology, inspection capability, and material defects. Designs seldom make a

distinction between defects that are readily detectable (e.g., porosity) and those that are difficult to detect (e.g., thin lamella inclusions). The accept/reject criteria for various defects should be realistically established to ensure high probability of detection of the detrimental anomalies.

2. Realistic measures must be used to describe the quantitative ability of NDT techniques, regardless of the type employed, to detect defects. Guidelines are needed to define specific levels of reliable detection as a minimum for quantitative demonstration of the ability of the NDE/I techniques [24]. The guideline criteria should include a comprehensive demonstration program to establish the confidence limits for detecting flaws in specific zones of aerospace structures.

3. The number of specifications and procedures needed to validate the ability of inspection techniques and method of operation to detect specified defects to the required confidence levels must be reduced. One aspect of this problem relates to the qualification of the operator and a second applies to the procedure itself, which, even though followed, does not ensure that the significant defects will be detected and described. Developing or tailoring specifications and procedures to specific parts and, further, to key sections of those parts can provide a cost-effective program. In addition, a program is needed to validate or guarantee the confidence with which significant defects

can be detected. Further, a study is needed to examine the cost impact resulting from a design philosophy based on "the probability that a critical defect will be missed by the inspection procedure."

In summary, many of the users of NDT are unaware of the limitations, shortcomings, and difficulties of advanced NDT equipment. Too much emphasis has been placed on the comparison between calibration references (e.g., flat bottom holes, voids and easily produced defects) and actual service or production flaws. Too much reliance is placed on the response from a reference defect and too little on the realities of the application. Fracture mechanics has been accepted over a broad range of technical areas, and the users are in many cases placing too much reliance on theoretical analytical processes with insufficient knowledge of synergisms and interactions that must be understood to provide a reliable life prediction.

E. Additional Committee Recommendations

Application of NDE procedures to individual operations of the processing sequence as a means for controlling the process as well as detecting process defects can significantly reduce rejection and scrappage costs and system downtimes. Example recommendations are described below.

1. Chemical Processing NDE

High rejection rates occur in the chemical processing of metal components for aircraft structures due principally to the fact that such processing generally follows in continuous operations and inspection is not possible until the process is complete. Parts are batch processed from chemical tank to chemical tank, to cleaning and surface treatments, and to metal components before an inspection operation can be effected. Out-of-specification conditions of these chemical tanks (e.g., chemical imbalance, temperature variations, and tank contaminants) lead to the impairment of product quality through scrappage and rework and, ultimately, to higher manufacturing and total systems costs. NDE control systems that sense chemical tank concentrations, temperatures, acidity and alkalinity (pH), conductivity, and solution contaminants currently are available to monitor the production process for out-of-specification conditions of chemical solutions.

2. Ultrasonic Measurement of Machining Operations

Maintaining uniform metal thickness on machined components fabricated from long, slender aluminum extrusions currently is a problem that stems from the fact that the machine cutter is designed to maintain a designated distance from a datum plan against which the metal surface opposite that being cut is assumed to be nested. Theoretically, this approach should result in uniform thickness cutting, but because of transverse and longitudinal bow and the inability of the vacuum chuck to hold the metal uniformly in intimate contact with the tool surface, variations in metal thickness outside acceptable tolerances result. By adapting an ultrasonic transducer coupled to the cutter controls a method of controlling metal thickness could be achieved. In addition, another transducer independently could confirm the metal thickness after cutting if it were mounted to trail the cutter. Coordination of these sensing systems with automated chemical mixing and feeding systems can provide a total system concept capable of maintaining extremely close limits of process control, sensing deviations from the norm, and adjusting for these deviations to provide high-quality metal processing at lower cost.

Other examples could be provided; however, the main point is that the cost for implementing many available techniques is nominal and the savings in terms of reduced costs for manufacture and fewer scrapped parts is significant. NDE technology should be introduced at the earliest practical process stage to provide a product with higher quality and increased reliability.

REFERENCES

1. MIL-I-6870C, "Inspection Program Requirements, Nondestructive: For Aircraft and Missile Materials and Parts."

2. "Summary of Air Force Industry Manufacturing Cost Reduction Study," August 28 - September 1, 1972, AFML-TM-LT-73-1.

3. National Research Council, National Materials Advisory Board, Nondestructive Evaluation, NMAB-252 (Washington, D.C.: National Academy of Sciences, 1969).

4. National Research Council, National Materials Advisory Board, Materials and Processes Specifications and Standards, NMAB-330 (Washington, D.C.: National Academy of Sciences, 1977).

5. Aerospace Industries Association, Quality Resources Study (Aerospace Industries Association of America, Washington, D.C., 1974).

6. D. P. Johnson, "Inspection Uncertainty: The Key Element in Nondestructive Inspection," Materials Evaluation, 34 (Columbus Ohio, American Society for Nondestructive Testing, Inc., 1976).

7. D. P. Johnson, Determination of Nondestructive Inspection Reliability Using Field or Production Data, Electric Power Research Institute Technical Report NP-315 (Palo Alto, California: EPRI, 1976).

8. D. P. Johnson and T. L. Tommay, In-Service Inspection Detection Probability for Thick Section Steels (in press).

9. P. M. Besuner and A. S. Tetelman, Probabilistic Fracture Mechanics, Electric Power Research Institute RP 217-1, Technical Report 4 (Palo Alto, California: EPRI, 1975).

10. D. P. Johnson and P. M. Besuner, Engineering Cost-Risk Analysis of Defective Rail, prepared by Failure Analysis Associates for the Association of American Railroads (Palo Alto, California: Failure Analysis Associates, 1976).

11. D. P. Johnson, Cost Risk Optimization of Nondestructive Inspection Levels, Electric Power Research Institute RP 217-1, Technical Report 5 (Palo Alto, California, EPRI, 1975).

12. P. M. Besuner, A. S. Tetelman, G. R. Egan, and C. A. Rau, "The Combined Use of Engineering and Reliability Analysis in Risk Assessment of Technical and Structural Systems," in Proceedings of Risk Benefit Methodology and Application, UCLA-ENG-7598, edited by David Okrent; paper presented at the Engineering Foundation Workshop, September 1975 (University of California, Department of Engineering, Reports Group, 1975).

13. P. M. Besuner, K. G. Sorenson, and D. P. Johnson, "A Workable Approach to Extending the Life of Turbine Rotors," paper presented at the ASME Gas Turbine Division Annual Meeting, Philadelphia, Pennsylvania, March 1977.

14. D. P. Johnson, "Nondestructive Uncertainty and Inspection Optimization," in Proceedings of ARPA/AFML Review of Progress in Quantitative NDE, edited by D. Thompson (in press).

15. A. N. Mucciardi, R. Shanker, and M. J. Buckley, "Applications of Adaptive Learning Networks to Nondestructive Evaluation Technology," in NAECON 75: Proceedings of the National Aerospace and Electronics Conference, pp. 460-9 (Dayton, Ohio: IEEE Aerospace & Electronics Systems Society, 1975).

16. R. L. Belin, "X-Ray Inspection," NDT Tire Testing Symposium, Atlanta, Georgia, November 19, 1976 (Imaginex, Inc., Mentor, Ohio).

17. J. R. Bohn, "Holographic Characterization--Part 3, Measurement of Surface Roughness," TRW, Inc., Contract No. N0001973-C-0298 (Redondo Beach, California: TRW, Inc., 1973).

18. T. B. Roszhart, D. J. Pearson, and J. R. Bohn, "Pulsed Ruby Holographic Instrumentation for Materials Testing and Research," ASTM Materials Research and Standards (Philadelphia, Pennsylvania, 1974).

19. W. J. Coleman, F. R. Reich, M. D. Erickson, and W. S. Kelly, "On-Line Automatic High Speed Inspection of Cartridge Cases," Standardization News (1975).

20. P. H. Hutton and J. R. Skorpik, "A Simplified Approach to Continuous AE Monitoring Using Digital Memory Storage," BN-SA-574 (Richland, Washington: Battelle-Northwest, 1976).

21. J. C. Crowe, Evaluation of Computer Simulated Signals or Metallic Tabs for Standardizing Eddy Current Inspection Systems, prepared for the Naval Ship Engineering Center by Battelle Pacific Northwest Laboratories (Richland, Washington: Battelle Pacific Northwest Laboratories, 1976).

22. J. C. Crowe, "Calibration of Eddy Current Systems with Simulated Signals," paper presented at the 36th National Fall Conference, American Society for Nondestructive Testing, September 1976 (Houston, Texas).

23. U.S. Department of Commerce, "Procedures for a National Voluntary Laboratory Accreditation Program," ASTM Standardization News, (January 1976).

24. F. Chang, J. Bell, P. Walker, J. Norton, P. Packman, and L. Gilstrap, Methods for Determination or Sensitivity of NDE Techniques, Report AFML F33615-76-C-5066 (Wright-Patterson Air Force Base, Ohio: Air Force Materials Laboratory, in press).

Appendix A

AN OVERVIEW OF NDT SPECIFICATION PROBLEMS

1. Specification Development

A specification is a contractual document used by the contractor to tell the producer what he wants. Obviously, the skill and accuracy with which NDT can be specified depends on the state of knowledge concerning it and on the precision with which its qualities can be determined. As the art and science of NDT are advanced, the basis for preparation of adequate specifications is improved; however, the effectiveness with which NDT is specified also depends on how well the specification is written and how enforceable the provisions are.

In the past, it was customary to specify merely a given brand or "equal" and past performance and the integrity of the producer were the only guarantee of potential quality. Early specifications were often necessarily crude because the contractor knew little about the test he tried to specify; many present specifications are just as crude and for the same reason. With the increasing complexity of the industrial system, more adequate specifications have become necessary, and with the advance in scientific knowledge of NDT, more adequate specifications have become possible.

A specification is intended to be a statement of a standard of quality. The ideal NDT specification would uniquely define the qualities of a test necessary to serve most efficiently for a given use. Calibration of tests can be made to determine the presence of the required qualities. An NDT specification often falls short of the ideal because:

a. It may be so loose that it admits material of inferior quality;

b. It may be overly restrictive and exclude an equally or more efficient material;

c. It may be based on inadequate or improper criteria, or

d. It may make no provision for proper enforcement.

These and other defects lead not only to the procurement of unsatisfactory materials but often to disproportionate costs and endless disputes. It also is important to note that a specification may admittedly and necessarily be imperfect because it would be impracticable to produce an ideal test to obtain the ideal material. All things considered, it may be just as inefficient to require too high a quality as to accept too low a quality. Practically, specifications are drawn up not to achieve an ideal test, material, or product but rather to achieve a test, material, or product that is possible to obtain at reasonable cost under existing conditions of manufacture and that performs adequately in service.

Several considerations are involved in fixing the limits within which a specified quality value may be allowed to vary. The maximum and minimum to be set may be based upon experiment but should recognize the limitations of the manufacturing or inspection process. These limits correspond to the size limits allowed in making machine parts, where tolerances are allowed for economic manufacturing without unduly impairing the efficiency of the assembly. In fixing these limits of tolerance for tests or material, care must be exercised to avoid ranges that are too narrow or too wide or that will result in poor quality. These limits often involve safety and generally involve durability and efficiency.

2. Standard Specifications

A notable development of the past decade has been the preparation and use of standard specifications. A standard specification is usually the result of agreement between those concerned in a particular field and involves acceptance for use by participating agencies. It does not necessarily have, however, the same degree of permanence as a dimensional standard because technical advance in NDT usually calls for periodic revision of the criteria or requirements. Some of the various types of standardizing agencies are independent companies, trade associations, technical and professional societies, and bureaus and departments of municipal, state, and national governments. The breadth of acceptance depends to an extent on the scope of influence and authority of the standardizing agency. Under the standardizing procedure followed by important agencies in this country, a period of negotiation, formulation, and trial usually precedes the use of a specification as a standard so that it has assurance of being workable.

A standard specification implies standard methods of testing and sometimes also standard definitions. In some instances, the methods of testing are incorporated within a materials specification, but some standardizing agencies set up standard methods of test separately from the materials specifications and make mandatory reference to the test methods.

Properly devised and enforceable standard specifications can be of immense value to industry because:

a. They usually represent the combined knowledge of the producer and contractor and reduce the possibility of misunderstanding to a minimum;

b. They lower unit costs by making possible the uniform inspection of standardized commodities;

c. They permit the contractor to use a specification that has been tried and is enforceable;

d. They simplify the preparation of special-use specifications because published standard specifications can be incorporated by reference;

e. They aid the purchasing agent in securing truly competitive bids and in comparing bids;

f. They set standards of testing procedure in commercial testing and hence permit comparison of test results obtained from different laboratories.

In the initial development of a standard test procedure, considerable research often is conducted by cooperating organizations to develop a procedure that will yield reproducible and meaningful test results. The disadvantage of standard specifications is that they tend to "freeze" practices that may be only in the developmental stage and, thus, hinder progress where most needed. For this reason, standard specifications should be under the jurisdiction of a well informed and thoroughly open-minded agency, and specifications for both materials and methods of testing should be subject to continuous review to determine their suitability under changing conditions. The various codes based on these standards also should be reviewed frequently.

One problem with standard NDT method specifications is that they are by nature product or process oriented. Unfortunately, current aerospace technology covers a vast array of materials or products and manufacturing processes and standard NDT specifications for products other than metals do not exist. To produce them would be costly and time consuming; however, if present developmental materials or processes become a standard for fabrication, preparation of standard NDT specifications may be beneficial.

Appendix B

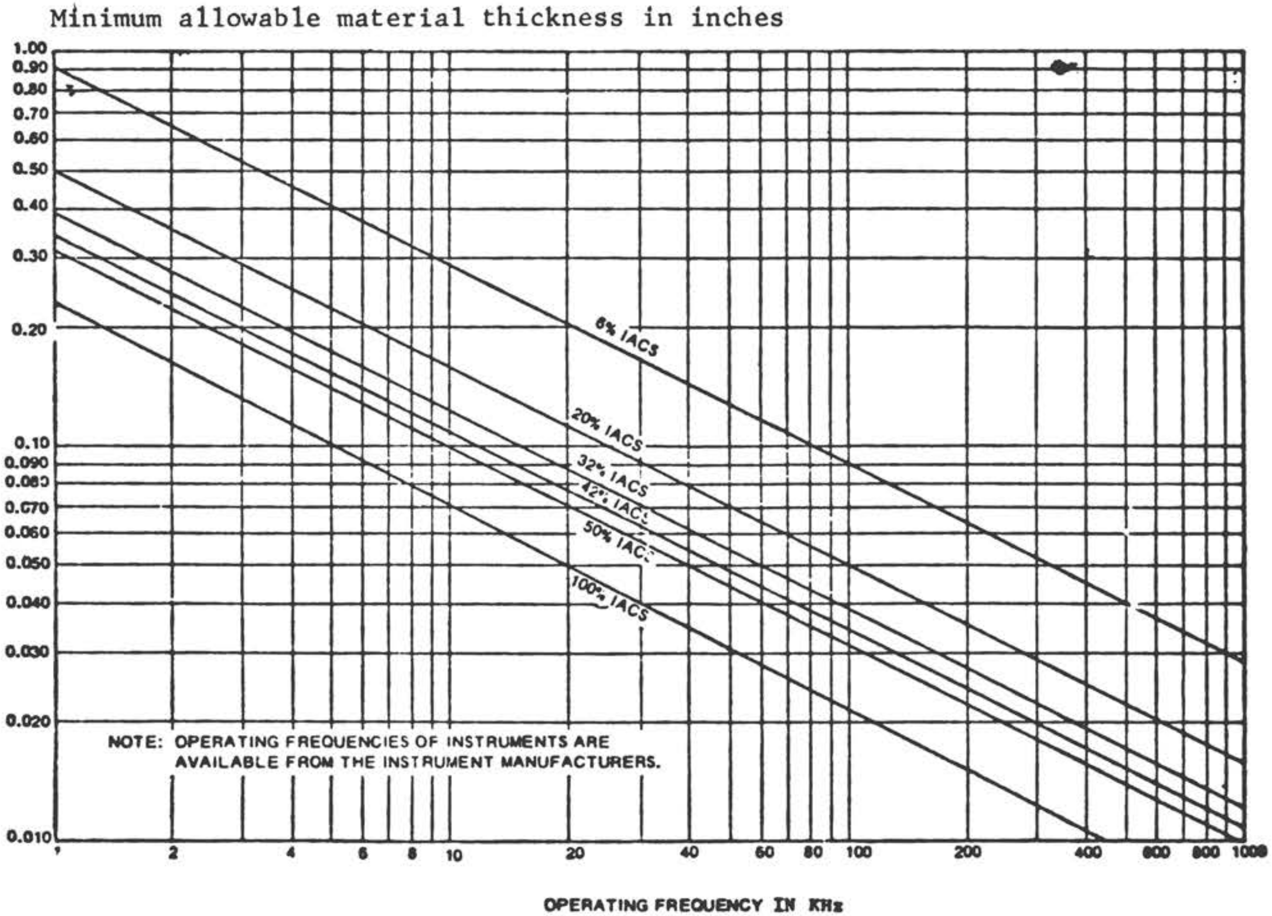
EXAMPLE OF TUTORIAL STATEMENTS

The Committee has chosen one specification--MIL-STD-1537 (7 February 1973)--as an example of "how to" or tutorial statements that should not be included in specification requirements. Statements such as these should be deleted from specifications or placed under a section entitled "Instructions or Procedures." The tutorial statements are underlined.

4.2.3.1

e. An example: Suppose a lot of bare .040 in. 7075-T6 material is to be tested with a 60 kHz instrument and the acceptance range for this material is 30.0 to 34.5 percent IACS. In accordance with Figure B-1 at 60 kHz and 32 percent IACS, the minimum thickness is .050 in. The thinnest 7075-T6 material that may be tested without stacking is .6 by .050 = .030 in. The .040 in. thick material shall therefore be tested in accordance with the 4.2.3.1 exception.

4.2.3.2 Suppose three samples taken from the lot and tested while stacked give readings of 34.0, 34.5, and 34.0 percent IACS. All readings are in the acceptable 30.0 - 34.5 percent IACS range. "Unstacked," the specimens read 36.0, 36.5 and 36.0 percent IACS. The average change in conductivity between the "unstacked" and "stacked" readings is +2 percent IACS. This is within the acceptable 0 to +2.5 percent IACS range acceptable as specified in 4.2.3.1. The new acceptance range for this lot of .040 in. thick 7075-T6 material is then equal to 30.0 +2 to 34.5 +2 percent IACS or 32.0 to 36.5 percent IACS. The remaining specimens in the lot are then tested. Any specimens with "unstacked" conductivity outside the 32.0 to 36.5 percent IACS range are rejected.



NOTE: OPERATING FREQUENCIES OF INSTRUMENTS ARE AVAILABLE FROM THE INSTRUMENT MANUFACTURERS.

FIGURE B-1 **DEPTH OF PENETRATION AS A FUNCTION OF CONDUCTIVITY AND OPERATING FREQUENCY**

4.2.4 Cladding has a pronounced effect on conductivity readings as compared to the base metal values. The effect of cladding becomes more pronounced as instrument operating frequency is increased. Eddy current conductivity tests for acceptance of clad material shall be restricted to material below .080 in. thick. Instruments used for testing clad material shall not have operating frequencies exceeding 62 kHz. The above restrictions do not apply if the cladding is removed in the area to which the probe is to be applied. For all tests the minimum operating frequency shall be such that the minimum thickness requirements of 4.2.3 and Figure B-1 are met.

"How To"

5.1.2 A suggested procedure for establishing a correction factor for round stock is specified in 4.2 is using flat stock of the same material and temper as the round stock to be tested. Measure the conductivity of the flat stock with eddy currents (reading "a"). Then form or machine the flat stock to a radius within the tolerance of the radius on the round stock to be tested. Again measure the conductivity (reading "b") using a fixture to hold the probe in the same position as is to be used on the round stock to be tested. The correction factor to be added to the readings on the round stock is reading "a" minus reading "b".

Requirement

5.1.3 Establish lift-off corrector factors for material or parts having a non-conductive coating as follows:

Tutorial

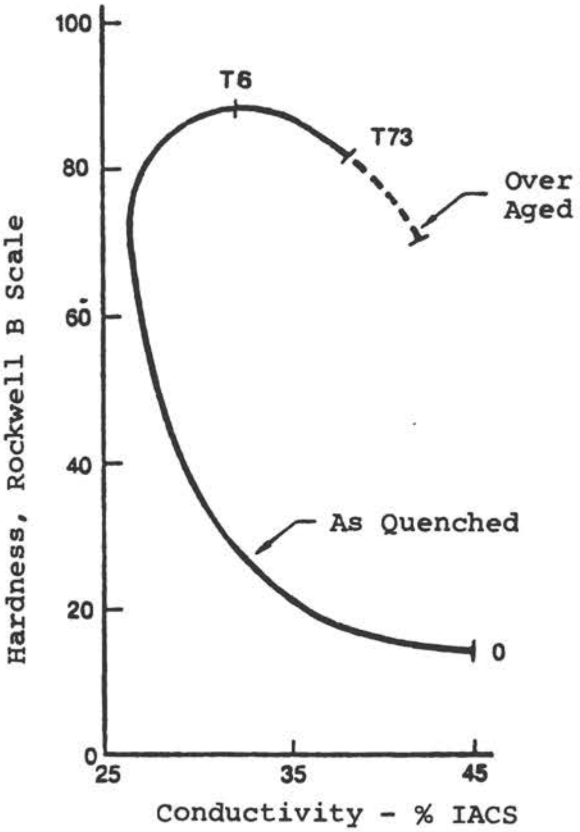
5.1.3.1 Obtain plastic shim stock or paper of the same nominal thickness as the non-conductive layer on the parts to be tested.

5.1.3.2 Place the shim or paper on a bare specimen of the same nominal composition and heat treated condition as the parts to be tested.

5.1.3.3 Note the deviation in readings of conductivity between tests run when the probe is placed directly on the surface of the bare specimen and when the probe is placed on the paper or plastic shim stock on top of the specimen. Use this deviation as the correction factor for reading on the parts to be tested.

6. Notes

6.1 **Hardness tests shall be used to supplement electrical conductivity tests on aluminum alloys. Figure B-2 shows a typical variation of hardness and conductivity with heat treat condition. Note that both hardness and conductivity values are required to define a given heat treat condition.**



Note: Two different hardness conditions will provide the same conductivity reading. Use hardness to verify condition.

FIGURE B-2 Hardness vs. conductivity for 7075 aluminum alloy.

(Note: Figure B-2 is for information purposes only and shall not be used for accept or reject criteria.)

Appendix C

COST EFFECTIVENESS OF VARIOUS NDT APPROACHES FOR CONTROLLING BEARING FAILURES*

1. Summary

An engineering and economic analysis was conducted to determine the potential cost effectiveness of various NDT methods for controlling aircraft gas turbine engine main shaft bearing failures. The failure control methods that were considered are:

a. Improved process control;
b. Improved raw material defect screening;
c. Conventional defect screening during bearing manufacturing;
d. Advanced in-flight monitors;
e. Additional in-service inspection and/or rework.

A summary of results provided by the engineering and economic analysis of the specific aircraft engine bearing studied is given below:

a. Bearing production costs (raw material, inspection and manufacture) are less than 2 percent of the total experienced bearing failure costs. Hence, modification in production that, for example, would double the bearing production costs would be justified if these

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* Prepared for the NMAB by D. P. Johnson and T. L. Tommay of Failure Analysis Associates, Palo Alto, California.

modifications led to as little as a 2 percent reduction in the frequency of bearing failures.

b. The conventional defect screening during bearing manufacture makes up approximately 0.04 percent of the total bearing costs (production and failure costs); yet, the calculated effect of removing these inspections would be a 50 percent increase in the total bearing costs because of the resulting increase in the frequencies of bearing failures.

c. A factor of six improvement in the raw material process control would lead to an 85 percent reduction in the total bearing costs, mainly due to a reduction in the frequency of bearing failures.

d. The insertion of an improved inspection to screen raw materials would cost an estimated 0.04 percent of the total bearing costs and result in an overall reduction in the bearing cost of 75 percent.

e. An ideal in-flight monitor would reduce the experienced failure cost by approximately 25 percent.

f. Introduction of in-service bearing inspection or rework, which involves removal of bearings from the engine, would greatly increase the total bearing cost due to the additional engine removal and tear down costs. Rework of bearings by grinding would not produce significant cost savings over simple reinstallation of the bearings because of the more-or-less constant bearing failure rate experienced in the exemplar bearings.

It is evident that major life-cycle cost savings can accrue from better control of bearing raw material either through direct process control or defect screening of the raw material. It also is evident that in-service monitoring has potential for appreciable cost savings. For the specific engine bearings considered in the analysis, a 25 percent reduction in failure costs means a savings of 13 million dollars per year.

2. Introduction

In examining the general questions surrounding NDT costs, it became clear to the Committee that the specific costs associated with a given nondestructive test or inspection should not be considered in isolation from consequential upstream manufacturing costs associated with the nondestructive evaluation (e.g., the reduced yield because of the parts that fail the test) or from the consequential downstream cost savings (e.g., decreased premature removal rate, reduced failure rate, and reduced liability costs). In most situations these indirect costs are much larger than the direct costs associated with the NDT. It is evident that a major barrier to optimum utilization of NDT and full recognition of its impact is the lack of quantitative understanding of this interchange between downstream cost savings and inspection and manufacturing costs. Failure Analysis Associates, under contract to the Electric Power Research Institute, has developed the engineering and economic methodology required to describe and predict this interchange and the Committee believes that the application of this technology represents a major technique for reducing NDT and failure costs in aerospace systems.

It also is evident that premature replacement and failures of roller bearings represent a significant generic problem throughout the military Services and that a number of NDT procedures or potential procedures can be used to control these failures. Which procedure or combination of procedures is optimum for controlling the failures is the type of question that can be answered by engineering and economic analysis of the bearing manufacturing, life, and failure cycle.

The preliminary analysis of roller bearings described in this appendix was conducted because:

a. it would be a clear illustration of the interchange between the inspection, manufacturing, maintenance, and failure costs;

b. it would illustrate the application of the engineering and economic analysis technology;

c. it would identify the most effective approaches for controlling the defective rolling-element bearing problem.

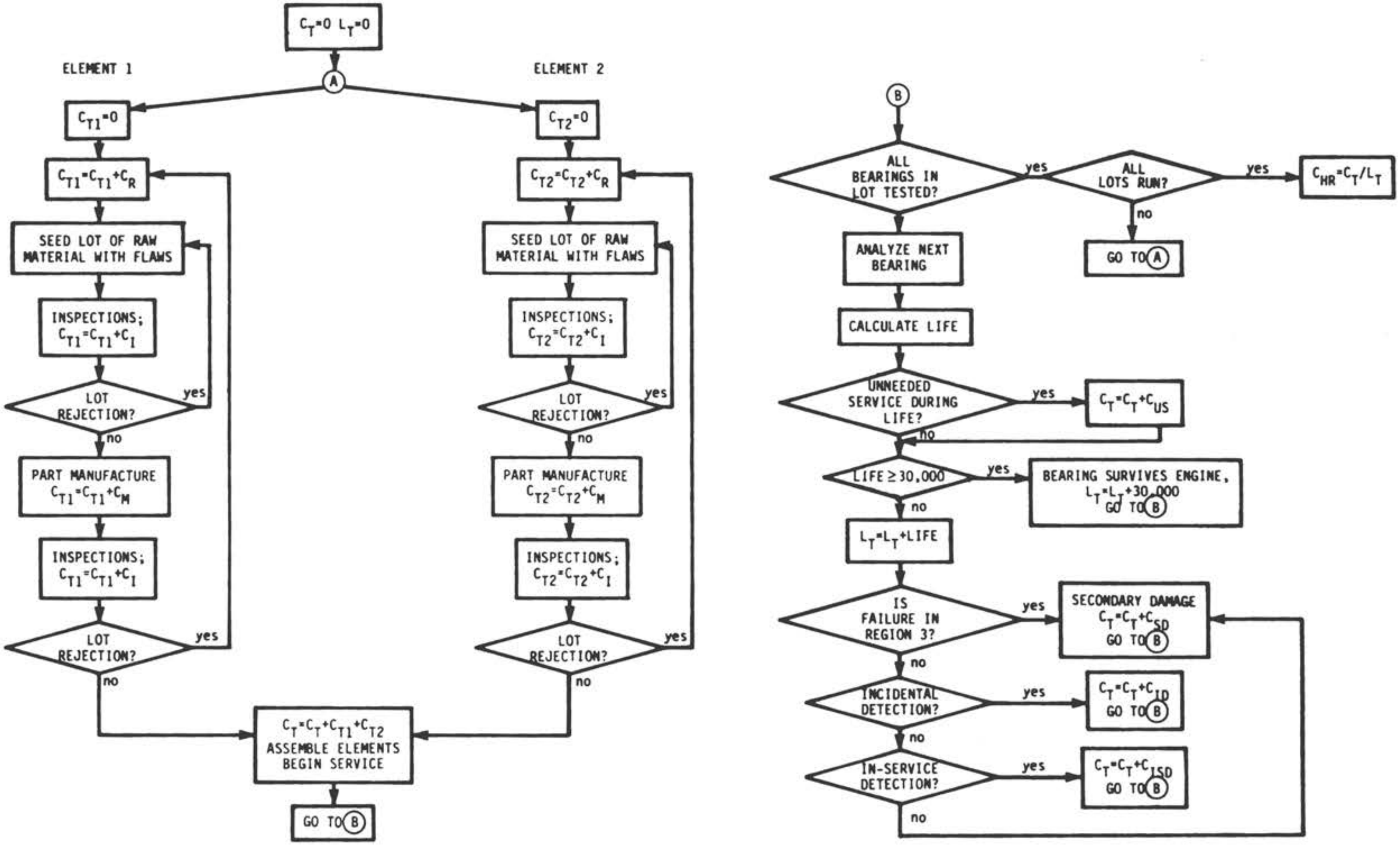
The analysis of the bearing failure problem uses representative data supplied by bearing manufacturers and users to select the most effective trade-offs between process control, defect screening, in-service monitoring, retirement-for-cause, and reconditioning.

3. Process Description

The analysis employs a Monte Carlo technique [1] in conjunction with an algorithm modeling the bearing production and life cycle of an aircraft gas turbine main shaft bearing. Figure C-1 is a flow chart of the algorithm.

The model treats the individual bearing as the sum of two elements. The first consists of the races and the second of the balls. The bearing production and life sequence is divided into three phases: Phase 1 is raw material production and inspection; Phase 2 is bearing manufacture and inspection; Phase 3 is the service life and maintenance of the ball bearing. All inspection processes are treated probabilistically with each being characterized by the probability of rejecting defects as a function of flaw size.

Each bearing element is divided into four regions. At the raw material level, one lot of each type element is randomly seeded with flaws, one flaw per region. The first three regions--surface, critical, and deep--represent the material of the bearing that is subject to fatigue (that related to the contact zone). The fourth region is the region of insignificant stress and is included because an inspection device may reject a flaw in this region even though the flaw is not dangerous to bearing life. The distribution used to establish the flaws in each region varies from one lot to the next, simulating lot-to-lot variation in raw material quality.



Legend:

C_T = Total Bearing Cost

L_T = Total Bearing Life in Hours

C_{HR} = Bearing Cost Per Hour

C_{T1} = Total Cost of Element One

C_{T2} = Total Cost of Element Two

C_1 = Cost of Inspection

C_M = Cost of Manufacture

C_{SD} = Cost of Secondary Damage

C_{ID} = Cost of Incidental Detection

C_{ISD} = Cost of In-Service Detection

FIGURE C-1 Algorithm flow chart.

Each of the two lots is sent through the appropriate raw material inspection. If the number of rejections occurring exceeds the lot rejection threshold, that lot of raw material is rejected. A new lot is seeded with flaws and inspected. The process is repeated until one lot of each type element has passed all inspections. The inspection cost is cumulative in that if a lot is rejected, the cost of inspection is added to the cost of the new raw material. In Figure C-1, C_{T1} is the cost of inspecting a bearing element. For this example, the raw material and raw material inspection costs are small when compared to the expectant production and failure costs.

Once a lot of raw material for each element has passed the raw material inspections, the elements enter the manufacturing phase. The cost of manufacture (C_M) is added to the total cost and the manufactured parts are sent through the appropriate inspections. If lot rejection occurs at this point, the rejected lot is returned to the raw material level and the entire process is repeated for that element until one lot of each element has completed manufacture and is ready for assembly. If the event of lot rejection occurs at the manufacturing level, the total cost including manufacturing cost and inspection cost is carried to the new lot of raw material. As each lot enters the in-service phase, the cost figure reflects the total cost to produce that lot of bearings.

After the two lots (one for races and one for balls) have passed the post-manufacture inspections, the elements in the two lots are combined and each bearing is put into service. The life of the bearing is calculated based on the size of the flaws in the three contact regions. If the life of the bearing exceeds engine life, only the costs related to in-flight shutdowns or engine removals due to false indications from the in-flight monitors are assessed. The occurrence of unneeded servicing is treated probabilistically as a function of time-in-service--i.e., the longer the service life the more likely unneeded service will occur.

If the life of the bearing is less than the engine life, the costs associated with replacement and with secondary damage are assigned to the bearing. In most instances, bearing problems are detected before they become severe enough to cause secondary damage, but even in those cases, major costs are still accrued because of the high cost of engine removal. The cost of the new bearing is an insignificant part of the bearing replacement cost. If the bearing problems are not detected in time, secondary damage will occur before bearing removal. In this case, the cost of the secondary damage is also assessed to the bearing.

In this manner the algorithm computes the total costs and the number of bearing hours accumulated. By changing certain constants and distributions, the program is modified to simulate various potential failure control methods. With each failure control method, several thousand bearings were run by simulation and the cost per bearing hour determined. It should be reiterated here that actual data on failure mechanisms and failure rates are used; only the effects of possible changes in inspection techniques on the detection of anomalies and changes in monitoring detecting spalling at an earlier time are simulated.

4. Determination of Algorithm Parameters and Distributions

There are basically four types of quantities that must be determined to complete the engineering and economic analysis of the bearing performance. These are:

a. Detection probabilities;
b. Raw material defect distributions;
c. Bearing life given defect size;
d. Cost factors.

The detection probabilities are based on expert opinion and factory experience and the detection rates observed in the exemplar engine. The raw material defect distributions are based on the frequency and flaw sizes observed in rejected bearing lots and the rejection rate obtained when an improved raw material inspection was introduced. The bearing life model is based upon the actual frequencies of bearing service failures for the exemplar engine and laboratory tests on similar bearings. The cost factors are based upon the exemplar engine experience. Hence, the model with conventional defect controls gives cost, failure rates, and detection rates characteristics of the actual engine example used. A more detailed description of how the four types of quantities are determined is given below.

a. Bearing Defect and Failure Detection

In general, the inspection processes used have been treated probabilistically. Each inspection process is characterized by its probability to detect flaws of different sizes so that, given a particular flaw, there is some probability of detection uniquely defined for that process. This detection capability is assumed to be a lognormal function of flaw size; the probability of detection is related to the log of the flaw size by the standard normal distribution. Thus, two numbers, a mean and a standard deviation, completely define an inspection system. When an inspection occurs, the large flaw in the inspected volume is used to determine the probability of detection. A random number between zero and one then is selected and compared to the probability of detection. If the random number is less than the probability of detection, the defect is detected. If not, it is not detected.

For the improved raw material inspection, the two numbers required to describe the inspection performance are determined from actual experience and experts' estimates. Figure C-2 shows the distribution used for the improved raw material inspection. It is assumed that when an 0.004 in. defect is present, it will be detected 90 percent of the time, and that when an 0.002 in. defect is present, it will detected 10 percent of the time. The improved inspection is assumed to be a volumetric inspection equally effective in all four regions.

For the conventional defect inspections used during manufacture and the conventional raw material inspections, the mean and standard deviation of the distributions are determined from expert estimates of the size of flaw that would be detected 90 percent of the time and the observed rejection rate. In these cases the inspection is only sensitive to near surface defects. Figure C-2 shows the distribution used to describe the conventional defect inspection used during manufacture.

The conventional in-service systems for flaw detection were modeled somewhat differently. There are four ways flaws in the bearing can be discovered: incidental detection during overhaul, in-flight detection, maintenance detection, and detection due to secondary damage. If an engine is overhauled for reasons other than indicated bearing problems and if during that overhaul a bearing problem is found, an incidental detection has occurred. The bearing

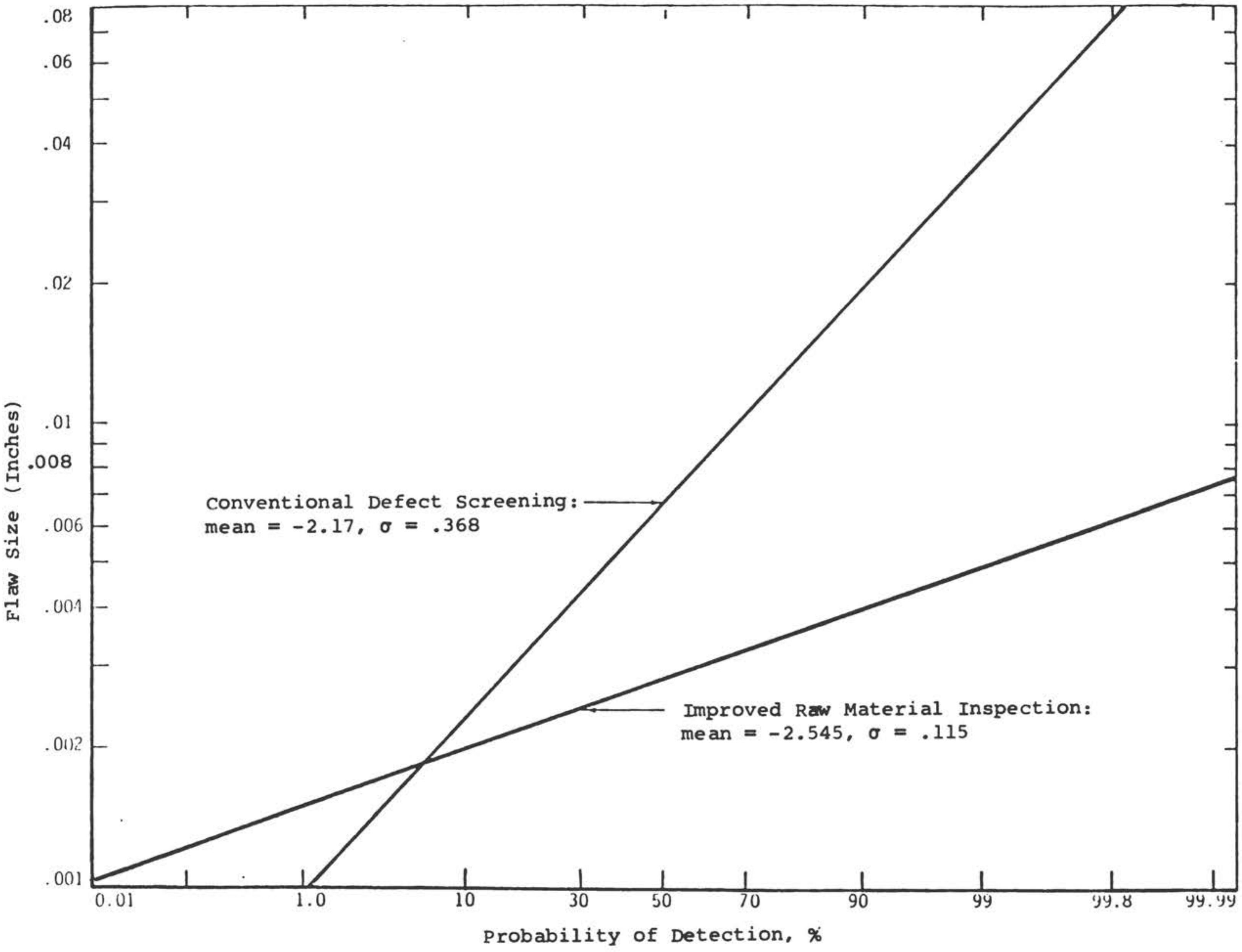


FIGURE C-2 Inspection effectiveness.

may show signs of fatigue such as pitting which indicates that spalling is imminent although no spalling is present or the bearing may be spalled. Either event is grounds for removal. Field data for the exemplar engine show that about 55 percent of all bearings removed from service before completion of their design life were removed during incidental inspections, a quarter of these being spalled bearings. Coincidentally, the spalled bearings removed in this manner constitute 25 percent of all spalled bearings prematurely removed from service. Given the rate of incidental inspection, the total spalling rate and the rate of incidental detection of spalls, a surprisingly large value is indicated for the life of a bearing after it has spalled. On the average, a spalled bearing spends nearly 500 hours in-service before it is removed. Two percent of the spalled bearings escape in-service detection and lead to secondary damage.

The observed incidental overhaul rate is used to determine how many spalled or nearly spalled bearings are removed incidentally. The definition of nearly spalled is adjusted such that when conventional defect and failure control is modeled, the actual incidental removal rate for unspalled bearings is obtained.

The rest of the bearings removed from service prior to the end of their design life were removed by various in-service monitoring systems (e.g., vibration monitors, oil particulate monitors, oil leakage monitors). About 43 percent of all bearings removed from the exemplar engine were taken out of service as a result of these in-service monitors. One third of these bearings (14 percent) caused in-flight shutdowns to occur and the remaining 30 percent were detected on the ground. It is estimated that one in ten engine removals for suspected bearing problems is unnecessary, the same for one in ten in-flight shutdowns.

In the model, these in-service monitoring systems are lumped together according to the observed ratio of in-flight to ground detections. The lumped system spall detection and false detection probabilities are determined from the performance of these systems on the actual engine example.

As part of the study, the effects of ideal in-service monitors are considered. These ideal vibration monitors mounted directly on the bearing housing are assumed to detect all spalled bearings before they lead to secondary damage. Two ideal monitors are considered. Ideal Monitor 1 is considered to integrate the vibration signal over a period of one minute with a detection threshold that is six standard deviations above the noise level. This system is checked by the pilot in-flight and when a deviant bearing is detected the engine is shutdown immediately. Ideal Monitor 2 is considered to integrate the vibration signal over a period of one hour with a detection threshold that is also six standard deviations above the noise level. This system is checked only on the ground and does not lead to in-flight shutdowns. Given the length of spall life and cost of in-flight shutdowns, this latter approach is a far more cost-effective solution.

b. Raw Material

In the analytical model, each bearing element is divided into four regions. The first three regions--surface, critical, and deep--represent the material of the bearing that is subject to fatigue and the fourth region is the region of insignificant stress. Each region in each element has a characteristic volume that is seeded at the raw material level with a flaw from the parent distribution. When the seeding is complete, the races and balls each are characterized by the largest flaw present in each region. Life calculations then are performed based on the flaw and stress in each region and are made to match actual fatigue failure data.

The parent flaw distribution is assumed to be lognormal and is defined by three parameters--a mean, a standard deviation, and a scaling factor. The scaling factor is taken to be a random variable lognormally distributed about 1. The scaling factor is included to simulate lot-wise fluctuations in the quality of the raw material. Prior to the seeding of each lot, the scaling factor is selected at random according to its distribution. It then is used to scale by multiplication of each flaw seeded in the new lot.

The standard deviation for the scaling factor and the mean value for the parent flaw distribution were determined from raw material rejection rates and rejected population flaw sizes observed when an inspection of known effectiveness was applied to bearing raw material. The standard deviation of the parent distribution is based on an estimate by an expert in the field. Based on these observations, 90 percent of the time the largest flaw found in 0.01 cubic inches of parent material is less than 0.00012 inches in diameter. The standard deviation for the log of the scaling factor was found to be 0.6, indicating a very large lot-to-lot variation in material quality. Again, these are related to actual bearing manufacturer experience. As part of the study, the effect of improved process control was examined by reducing the standard deviation on the log of the scaling factor from 0.6 to 0.1 (i.e., better raw material process control was simulated).

c. Life Model

The life model was developed based on the assumption that a high percentage of bearing failures is due to material defects, such as nonmetallic inclusions and seams, that provide for initiation of cracks which eventually lead to spalling or fracture. Failures resulting from dimensional problems, surface damage in-service, oil contamination and so on, were considered beyond the scope of the study.

The field of rolling contact fatigue is not yet fully quantified and agreement has not been reached as to the exact nature of the processes involved. However, it is generally conceded [2,3,4], at least for inclusions greater than 0.001 inch in diameter, that there is a good correlation between inclusion size and fatigue life (i.e., the larger the inclusion under a given stress, the shorter the life). The relationship between life and stress also is fairly well defined with one study [3] showing the total life to be inversely proportional to the eighth power of stress.* To cover these two broad relationships, a typical fatigue model was used:

$$\frac{da}{dN} = A \Delta K^{B}, \qquad \text{(C-1)}$$

where $\Delta K = \Delta\sigma \sqrt{\pi a}$,

a = crack size,

N = number of cycles,

$\frac{da}{dN}$ = crack growth rate,

ΔK = range of stress intensity factor,

$\Delta\sigma$ = range of stress driving the crack, and

A, B = constants.

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* It is interesting to note that power relationships of this order occur frequently in crack initiation data for steels. Also, as shown in plots of ΔK vs. da/dN for low crack growth [5], B, the slope of the log-log plot, is large, and $B = 8$ is a reasonable value.

Since life is inversely proportional to the eighth power of stress, B is chosen to be 8. By solving Equation C-1 for dN and integrating, the total life is found. If the final defect size is large compared to the initial defect size, the final defect size will not significantly affect total cyclic life and the total cyclic life may be simplified to:

$$N = \frac{1}{3A(\Delta\sigma\sqrt{\pi})^8} \; \frac{1}{a_i^3} \qquad \text{(C-2)}$$

where a_i is the size of the largest local material defect. The value of A was selected so that the model would predict the results observed for the actual engine bearings in the example.

Each element is divided into four regions-- (1) critical, (2) surface, (3) deep, and (4) unstressed--to simplify the life calculation. Fatigue cracks in bearings are considered to be driven by the shear stress, which varies with depth reaching a maximum in this example 0.010 to 0.018 inch below the surface. The critical region is defined as the region between 0.008 and 0.032 inch in depth and a maximum shear stress of 50 ksi characteristic of the exemplar bearings is assigned to any flaws falling in this region. The surface region extends from the surface to 0.008 inch deep and the stress for this region is 25 ksi. The deep region extends from 0.032 inch to 0.5 inch with a stress of 10 ksi. All of these regions exist beneath the wear track only, calculated to be 0.066 inch wide, with the remaining volume of the races considered to be insignificantly stressed. The balls contain no volume that is unstressed. Table C-1 summarizes the volume in each of the four regions for each type element.

Each flaw in each region of the race is cycled each time a ball rolls by. There are 20 balls in the bearing and assuming no slip, approximately half of the balls cross a given point on the race per revolution. Assuming a speed of 8,000 rpm, the number of stress cycles per hour is $4.8 \cdot 10^6$ for a flaw in the wear track of the race. For the balls, again assuming no slip, the number of cycles in a revolution is about seven, where ball diameter is 1.125 inches and wear track diameter at the center line is 7.8 inches. It is assumed that the ball does not always rotate about the same axis, but that it may drift or precess. Consequently, the wear track on the ball is estimated to be about 20 percent wider than that of the race, each flaw receiving about five stress cycles per revolution.

By using the fatigue Equation C-2, the flaw size present, and the number of stress cycles per hour, a life is calculated for each region of the two elements in the bearing. In Regions 1 and 2, the failure mode is considered to be spalling and the life calculated is the life to spall. In Region 3 (deep), the failure mode is considered to be fracture; with conventional in-service monitors, failure in this region leads directly to secondary damage. The shortest of the three calculated lives is taken as the life of the bearing. The general trends shown by the study are believed to be insensitive to the details of the life model since the A parameter was selected to predict the actual bearing failure rate of the example.

TABLE C-1 Region Volumes

Region	Element 1	Element 2
1	0.026	0.045
2	0.077	0.130
3	1.5	12.1
4	25.0	0.0

d. Cost Factors

The bearing production costs are broken down into five areas in Figure C-3. Based on the production experience on the exemplar engine, 2 percent of the production cost goes to NDI, 10 percent for raw material, 25 percent for manufacture of the bearing elements, 23 percent for etch and metrology inspections, and 40 percent for handling and assembly.

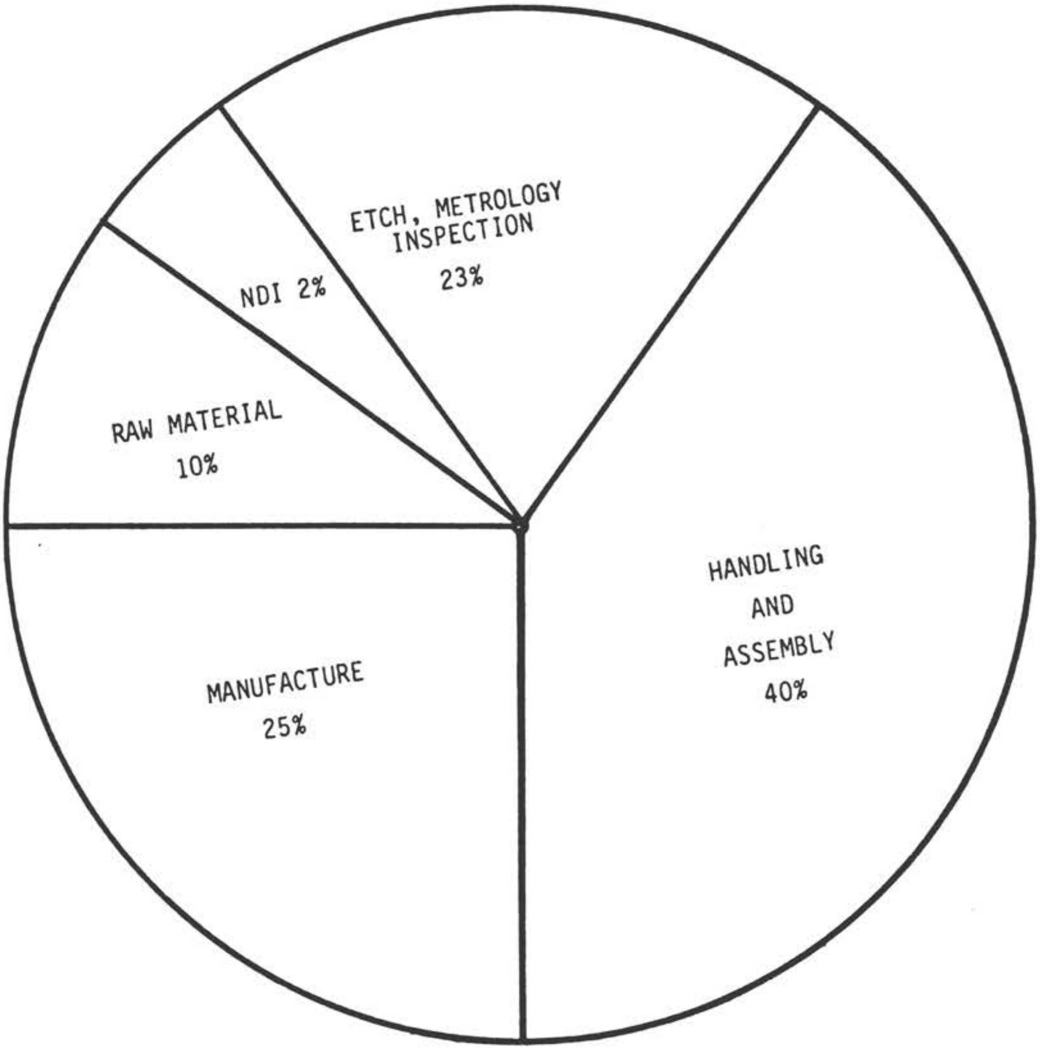

FIGURE C-3 Production cost breakdown.

The in-service bearing failure costs when they occur are much larger than the production costs. In the exemplar engine, the cost to tear down an engine and replace the bearing is 57 times the cost of a new bearing. The cost to shut down an engine in flight because of a bearing problem or a suspected bearing problem is 43 times the cost of a new bearing. Hence, an in-flight detection of a bearing failure and subsequent replacement of the failed bearing cost is approximately 100 times the cost of a new bearing.

Approximately 2 percent of failed bearings lead to secondary damage. When secondary damage occurs, the average cost is 710 times the cost of a new bearing. These cost factors characteristic of the exemplar engine are used in the model calculations.

5. Results and Conclusions

This engineering and economic study was conducted to establish the cost effectiveness of various NDT methods for controlling aircraft gas turbine engine main shaft bearing failures. The failure control methods that were considered are:

a. Improved process control;

b. Improved raw material defect screening;

c. Conventional defect screening during bearing manufacturing;

d. Advanced in-flight monitors;

f. Additional in-service inspection or rework.

The model is based on the actual performance of main shaft bearings in a specific engine. The calculated cost performances of the bearings with various failure control methods are given in Figure C-4. In the figure, the bearing cost if no failures occurred (the bearing production cost) is taken to be unity with the other accumulated costs being expressed in units of the bearing production cost.

For the engine bearing considered in detail, the production costs under conventional failure control made up less than 2 percent of accumulated bearing failure costs. Over 90 percent of total bearing cost was due to the high frequency and related cost of removing failed bearings from service. The cost of replacing a bearing after a ground inspection is about 57 times the cost to produce a new bearing. The cost of shutting down an engine during flight because of a bearing problem combined with subsequent bearing replacement is 100 times the cost to produce a new bearing. If the engine is damaged (a rare occurrence from failed bearings) before the problem is discovered, the cost is 710 times the production cost. The failure rate of the main shaft bearings in the engine studied was such that over half of all bearings put into service had to be removed prior to engine retirement. The cost impact of the bearing failures is the product of the frequency and specific cost of a bearing failure. Clearly, the high frequency and cost of removing the bearing from

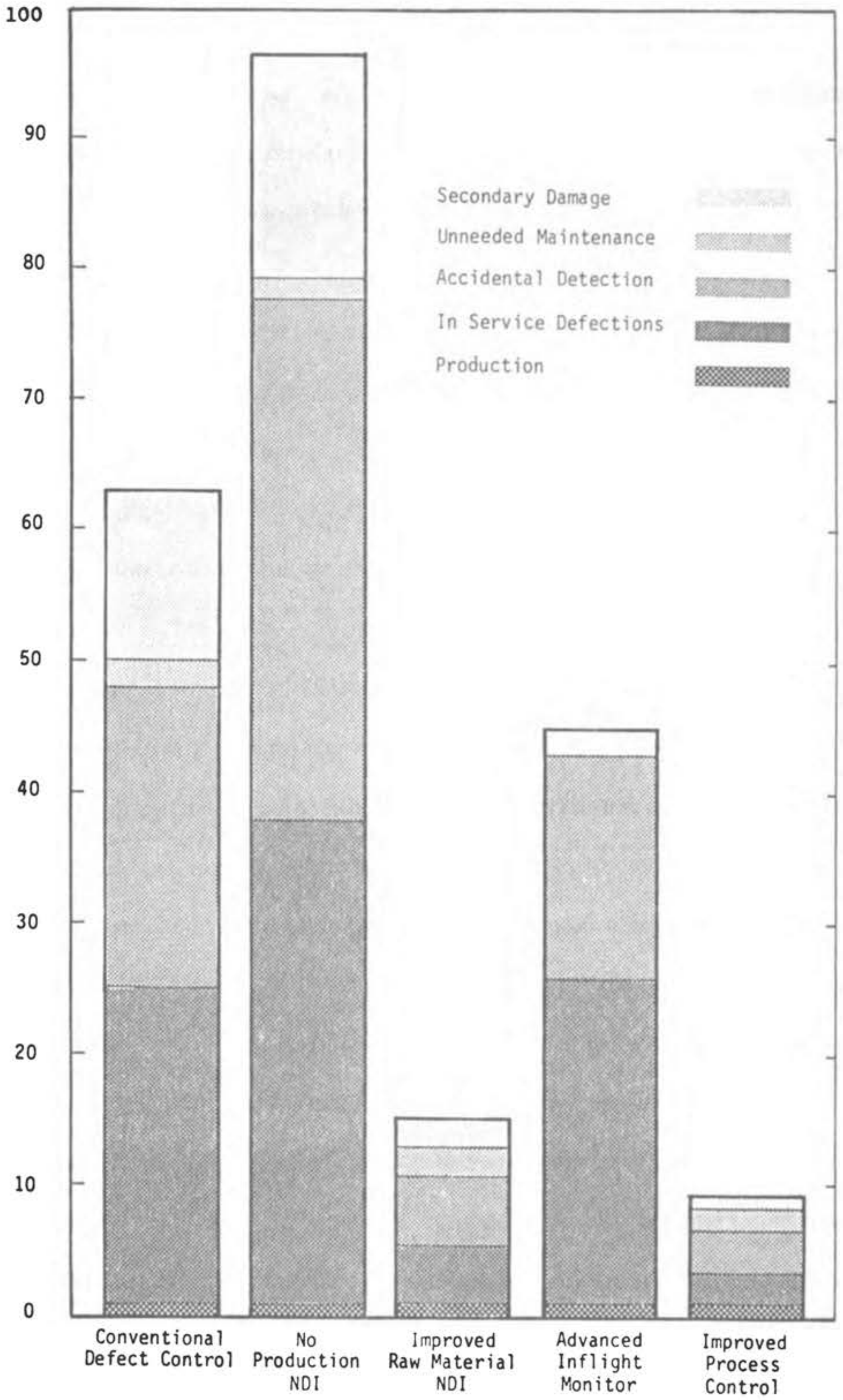

FIGURE C-4 Relative cost performance.

service is dominant. The most obvious direction to take in reducing overall cost is to reduce the frequency of bearing failures. Modification in production that, for example, would double the bearing production costs would be justified if these modifications led to as little as a 2 percent reduction in the frequency of bearing failures.

Given the high bearing failure rate and cost impact experienced by the exemplar engine, a question might arise as to the cost effectiveness of the conventional NDI used to eliminate defective parts before they enter service. These magnetic particle inspections cost less than 2 percent of the bearing production cost or 0.04 percent of the total bearing costs (production and failure costs). The calculated effect of removing the magnetic particle inspection would be a 50 percent increase in the total bearing costs because of the resulting increase in the frequencies of bearing failures. Thus, the money invested in present NDI is well spent.

The cost savings that would accrue from improved defect screening were investigated by calculating the effect of installing an improved NDI at the raw material level. The inspection performance parameters used were based on expert opinion and metallographic study on what performance has been achieved by an ultrasonic test inspection already developed for inspections of bearing raw material.

The cost of operating this inspection is estimated to be less than 0.04 percent of total bearing cost. The resultant decrease in the total bearing cost due to the consequential improvement in bearing life was approximately 75 percent.

Improved raw material process control also was investigated. Based on data supplied by bearing manufacturers, there are large lot to lot variations in raw material quality. If this lot to lot variation were eliminated, an 85 percent cost reduction would accrue. An improvement in raw material cost by a factor of 10 would be cost effective if it caused as little as a 2 percent reduction in the frequency of bearing failures.

Due to the inaccessibility of the main shaft bearing the cost of removing it is bound to be high. A significant additional cost is incurred if the bearing causes engine shutdown in flight. About 15 percent of bearings removed in service cause in-flight shutdown. By installing a vibration monitor directly on the bearing housing, it is anticipated that the in-service detection reliability can be improved to the point that problem bearings are detected and removed before causing in-flight shutdown. Such a monitor also would detect some bearing problems that might cause engine damage. To test the cost response of the system to such a device, an ideal monitor that would detect all spalled bearings and 90 percent of the problems leading to secondary damage was simulated. The net cost reduction was 25 percent of total bearing cost, which for the simulated engine translates to approximately 13 million dollars per year.

Consideration was given to the question of reducing the bearing failure rate by life limiting the bearings and replacing them automatically either once or twice in the life of an engine. Unfortunately, in the exemplar engine the bearing failure rate is more or less constant because of large variation in material quality. Hence, the replacement of used bearings with new bearings will not significantly affect the bearing failure rate. In fact because new bearings have a somewhat larger initial failure rate than bearings that have survived some time, the introduction of new bearings may actually increase the bearing failure rate.

REFERENCES TO APPENDICES

1. P. M. Besuner and A. S. Tetelman, Probabilistic Fracture Mechanics, EPRI 217-1, Technical Report 4 (Palo Alto, California: EPRI, 1975).

2. American Society for Testing and Materials, Bearing Steels, The Rating of Nonmetallic Inclusions, ASTM Special Publication 575 (Philadelphia, Pennsylvania: ASTM, 1975).

3. R. A. Baughman, Experimental Laboratory Studies of Bearing Fatigue, ASME 58-A-235 (New York, New York: ASME, 1958).

4. E. N. Bamberger and J. D. Marble, The Development of Methods for the Ultrasonic Inspection of Bearings (Contract NOW-63-0383-D) AD-454013, N65-19727 (Cincinnati, Ohio: General Electric Co., 1964).

5. S. W. Hopkins, C. A. Rau, G. R. Laverant and A. Yuen, Effect of Various Programmed Overloads on the Threshold for High Frequency Fatigue Crack Growth, ASTM Special Technical Publication 595 (Philadelphia, Pennsylvania: ASTM, 1976), pp. 125-141.