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Panel on Nondestructive Inspection
Committee on Mechanical Reliability
Air Force Studies Board
Commission on Engineering and Technical Systems

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

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Chapter 1

INTRODUCTION

The Air Force has adopted the Aircraft Structural Integrity Program (ASIP) and the Engine Structural Integrity Program (ENSIP), systems of design and inspection that are intended to ensure that new systems as delivered will be as free from flaws as technology will permit. Materials and designs will be employed that are compatible with state-of-the-art nondestructive inspection (NDI) technology, such that flaws that develop during service will be discovered before they reach critical size and lead to catastrophic failure.

However, ASIP and ENSIP were developed after several important aircraft were placed in service. In many cases these aircraft incorporated flaw-sensitive materials that require NDI technology at the very edge, if not slightly beyond, the state of the art. In order to maintain these aircraft in safe operational condition, extraordinary steps have to be taken to ensure that NDI technology is rapidly advanced or that the very best technology is used by highly trained and motivated people. As new systems are designed, it is important that NDI technology be improved so that higher-performance materials can be used with a high degree of assurance that safe, long-term operation can continue to be achieved.

Thus, we are confronted by a circumstance in which at least one air weapon system important for the present the F-16 aircraft has a nondestructive inspection technology that is satisfactory and effective. Other systems currently in use are confronted by a variety of inspection problems. Some of these have required major redesign of components; others are causing substantial concern. In addition, designers of new systems are currently restricted in their use of some advanced materials and/or component designs because of the inadequacy of nondestructive inspection technology.

The purpose of this study is to look at the Air Force organization for NDI to determine how it is responding to these challenges, and to assess the likelihood that the organization as currently configured can achieve its objectives.

This final report summarizes the conclusions of the Panel on Nondestructive Inspection on the effectiveness of the Air Force NDI program and the responses of the Air Force to the deficiencies cited by the Inspector General.[1] The Panel visited Air Force installations to review at first hand the technical and personnel practices in Air Logistics Center (ALC) production inspections and in R&D and other organizations. These Air Force practices were compared with those of commercial airlines and other industries, especially with regard to the inspection reliability levels necessitated by structural integrity requirements. Appendix A lists the Panel's meetings and the organizations visited.

The importance of NDI to the Air Force in terms of strategic readiness and costs of overhaul and maintenance is obvious. The benefits of increased support for NDI equipment, personnel, and R&D may not be as obvious. However, the Panel recognizes that NDI is only one element in the availability of a weapon system and that its members may not see issues from the standpoint of Air Force priorities. The Panel has therefore focused its deliberations mainly on the effectiveness with which NDI technology is transferred to ALC application and how well the technology supports ASIP and ENSIP. Deficiencies in funding levels are noted to the extent that they affect NDI program efficiency, stability, and ability to meet requirements in a timely way. The Panel has limited its study to the peacetime operations of the ALC; special inspection problems would arise during a prolonged military conflict.

Chapter 2

RECOMMENDATIONS AND FINDINGS

The many interviews and visits conducted by Panel members provided a wealth of information. Interpreting this information and condensing it into a few focused recommendations, which are given below, has been a significant task. As noted in the Introduction, no attempt has been made to establish a priority for these recommendations within the existing budgetary structure nor has any attempt been made to pass judgment on the distribution or adequacy of current budgets except to note budget deficiencies that adversely affect the overall efficiency and performance of the Air Force NDI program. A summary of the Panel's recommendations and findings follows:

- The required probabilities-of-detection limits and the confidence limits are specified for minimum flaw sizes by ASIP[2] and ENSIP.[3] However, the reliability of inspection actually achieved in the ALCs and thus the degree of structural integrity ensured are unknown. Cost-benefit analysis of advanced NDI methods and equipment is, therefore, not available in advance of a development program except in the case of the Retirement for Cause inspection system.

- A program called Reliability of Nondestructive Inspection of Aircraft Structures[4] reviewed the results of Air Force nondestructive inspections and indicated unacceptable levels of performance for flaw detection in airframe components. Although these results have been available for several years, indications of poor reliability still exist.[5] The fact that relatively few failures have occurred suggests that this type of study is not the optimum way to address NDI effectiveness for specific inspections.

- Development of a new generation of engineered NDI instrumentation that incorporates automatic decision making should be accorded high priority. By emphasizing the word "engineered," the Panel advocates strong adherence to accepted system engineering design and manufacturing practices to ensure that end-user requirements are well understood and are met in the most cost-effective manner.

- The NDI technology under development is adequate to meet present and anticipated requirements of ASIP and ENSIP, provided adequate attention is given to the overall engineering of the required inspection systems. ASIP and ENSIP establish safe inspection intervals but do not address economic intervals; new technology may be more cost-effective. Current technology is probably not adequate to address corrosion detection effectively.

- From R&D through prototype instrument/system engineering development the NDI technology program of the Air Force Wright Aeronautical Laboratories (AFWAL) needs better continuity. The absence of funding in R&D categories 6.3 and 6.4 ("advanced development" and "engineering development") is a problem. Coordination and continuity to allow the tailoring of applications development programs to the procurement of new weapon systems are essential elements of improved planning.

- The location of the NDI Program Office at the San Antonio Air Logistics Center (SAALC) is an impediment to technology transfer. The office could operate more effectively within the Air Force Acquisition Logistics Division (AFALD) and should be located at Wright-Patterson Air Force Base (WPAFB). A specific program (charter) to ensure the transfer of NDI technology from the Air Force Systems Command (AFSC) to the Air Force Logistics Command (AFLC) should be assigned to this office.

- The Air Force should continue vigorously to review and upgrade its training and certification programs for NDI personnel. It is also important to have an understanding of the results achieved in the training and certification programs of the nuclear power industry and the commercial airlines.

Chapter 3

AN ASSESSMENT OF INSPECTION TECHNOLOGY SUPPORT OF ASIP AND ENSIP

Introduction

Before proceeding to a discussion of the F-16 findings, it is appropriate to review the salient features of the ASIP and ENSIP strategies. The purpose of this section is to document the Panel's findings on how well ASIP/ENSIP have been implemented in some of the Air Force's weapon systems and the impact that inspection technology has had on the successful use of this approach. To gather information for this section, the Panel visited four ALC bases responsible for the maintenance of many aircraft and engines. In addition, we visited several other organizations to gather additional or supportive details. We reviewed Air Force inspection practices used with the T-38, C5A, F-111, A-10. and F-16 airframes. We also reviewed the F-100 engine inspection process. Of these, only the F-16, and A-10 are post-ASIP/ENSIP structures. The F-100 underwent an ENSIP review after design. After reviewing all the material presented, it became obvious that at least one aircraft system of those reviewed had very successfully incorporated the ASIP concept--namely, the F-16 fleet assigned to Ogden ALC at Hill Air Force Base for maintenance management.

Today's damage-tolerant airframe and engine design concepts consider the fact that flaws and defects exist in all structural materials. Structures designed using these concepts can be segregated by fracture-mechanics techniques into two general categories: (1) "fail safe," in which unstable crack propagation is contained locally through the use of multiple-load paths and/or tear stoppers, and (2) "slow-crack-growth" structures, in which flaws are not allowed to reach the critical size necessary for unstable rapid propagation during a specified period of aircraft service. Both design approaches rely heavily on the assumption that all flaws and defects above a maximum allowable size will be detected during fabrication and that none will exist in aircraft that enter service. This assumption places tremendous responsibility on all inspection methods, particularly those involving NDI methods, to exhibit the necessary flaw-detection reliability. Furthermore, the responsibility continues throughout service life for Air Logistic Center (ALC) staff to employ NDI techniques to verify the absence of significant flaws.

The inspection concerns described above are reflected in ASIP and ENSIP requirements for demonstrating the inspectability and fatigue-crack tolerance of each critical structural component. Probabilities-of-detection limits and confidence limits are specified for minimum flaw sizes, and NDI methods and procedures are established to meet these minimum requirements.

Achieving a high probability of detecting flaws of a given size generally requires high enough resolution to detect much smaller flaws; such high resolution, however, can produce uneconomical rates of rejection or repair.[6] Current Air Force procedures do not determine the shape of the curve of detection probability versus flaw size, or in general, the probability that a detected flaw has been accurately sized by nondestructive means. The procedures therefore do not indicate the degree of structural integrity afforded by NDI, and the possibility of cost-benefit analysis (which might provide a basis for procurement and maintenance specifications) is foreclosed. The Air Force has the ability to perform probabilistic lifetime analysis, although this approach is only now being developed (for the F-100 engine Retirement-for-Cause program),[7] and should require component manufacturers to supply probability-of-detection information along with NDI equipment and procedure specifications. Changing from deterministic to probabilistic inspection would remove a major obstacle to communication between equipment and component manufacturers and elements of the Air Force.

ASIP APPLIED TO F-16

The F-16 is a good model to illustrate three key steps that must be combined to achieve a successful integration of NDI technology into an ASIP program. The three key steps are:

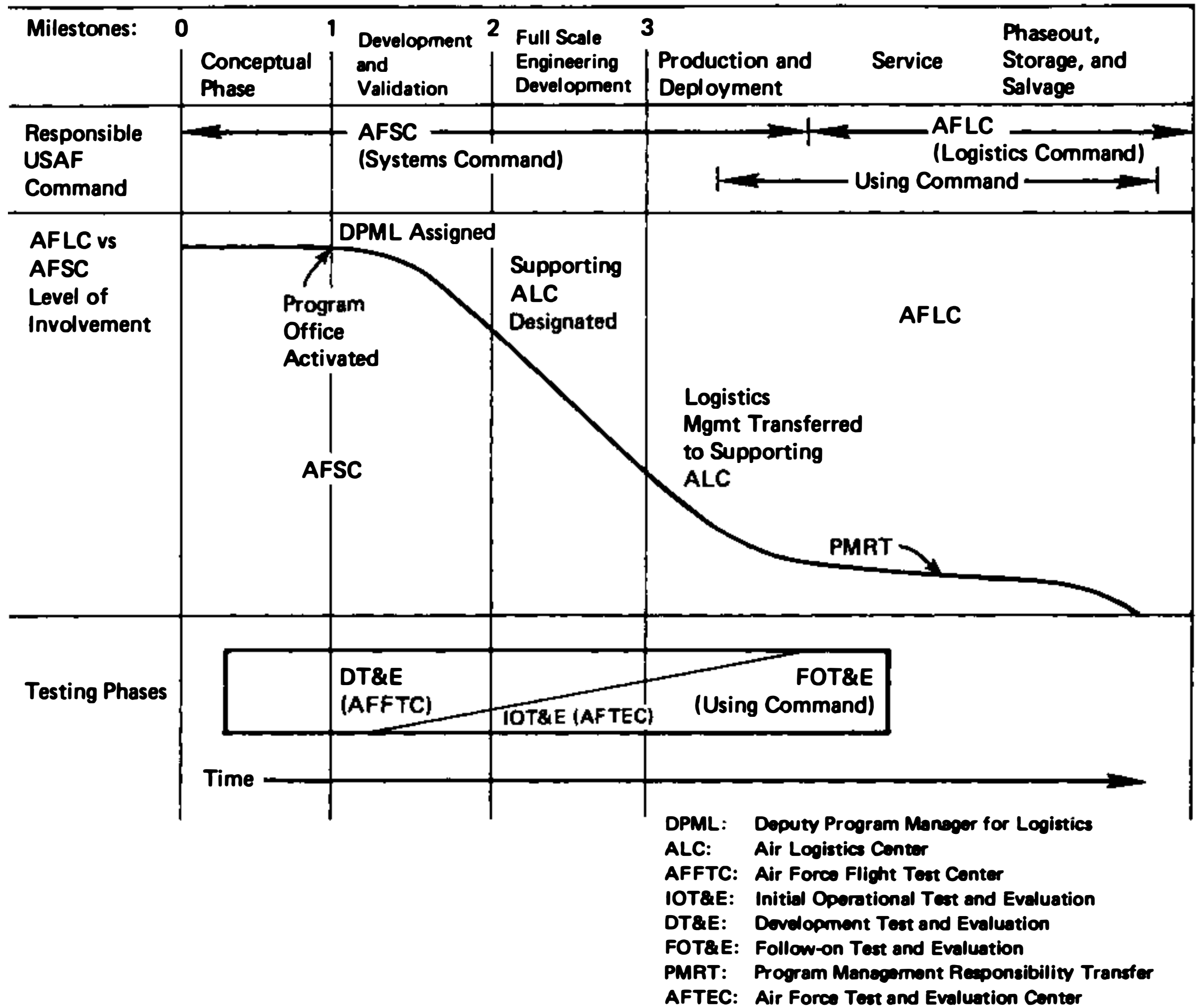
- Early end-user input. The people that would ultimately be responsible for inspecting and maintaining an aircraft after it became operational were involved in the specification development, design, and testing phase of the procurement.

- Critical components. A tolerable critical crack size was selected on the basis of actual demonstrated capability of available NDI technology.

- Concurrent development of a technical manual. The Technical Manual for Nondestructive Inspection of Aircraft Structure and Components (often referred to as the TO-36 Manual) was developed in concert with the procurement process and was completed and available at the time the aircraft was placed in operation.

Each of these items is discussed in more detail below.

Aircraft acquisition, operation, and maintenance are the responsibility of three separate commands within the Air Force. The acquisition and maintenance function is the responsibility of the Air Force Systems Command (AFSC) and Air Force Logistic Command (AFLC), respectively. Figure 1 indicates the responsibilities and degree of involvement of each command as a function of time during acquisition and use. This diagram also serves as a reference for the discussion that follows.



SOURCE: Chart supplied by G.L. Yanker, Director, Logistics Engineering, Deputy for Engineering and Evaluation, Headquarters Air Force Acquisition Logistics Division (AFLC) Wright-Patterson Air Force Base.

FIGURE 1. Relative Involvement of Three Commands for Aircraft Procurement, Operation, and Maintenance

This initial step toward success occurred as soon as the aircraft acquisition process was initiated. At that time the System Program Office (SPO) selected the tentative lead ALC base that would assume maintenance responsibility. Then the inspection personnel from that ALC were requested to participate in the remainder of the acquisition activities indicated in Figure 1. In this manner, knowledgeable field inspection personnel (and personnel likely to be responsible for maintaining the aircraft) were directly involved in setting design specifications, in conducting design reviews and project reviews, and in analyzing component and full-scale testing data as the airframe development progressed. This involvement achieved two important results. First, those responsible for the procurement action had direct information about field inspection capability. Second, the inspection personnel involved acquired a vested interest in the aircraft and its maintainability because they know the probability was very high that they would have ultimate inspection responsibility once the craft became operational.

The presence of the inspection people also contributed to the second key element, establishing an allowable crack size. The allowable crack size established for load-bearing components was based on the available inspection technology. Stated differently, a crack size that could be detected with a specified (and demonstrated) probability at a given confidence level was used as one major criterion for component design. Later, after the aircraft were assembled, they were subjected to full-scale, full-load cycle testing until twice the design life of the aircraft was achieved. If during this period any component cracked, the component was redesigned, manufactured, and retested. As a result, when the testing was completed, there was experimental evidence indicating that the craft could perform throughout its lifetime without component failure. However, if cracking should occur, there was also ample evidence that the flaws could be detected with available inspection technology.

The third key item, a natural outgrowth of the first two, deserves highlighting. The Technical Manual for Nondestructive Inspection of Aircraft Structure and Components, which is required by Technical Order 36 for each aircraft, specifies in detail the inspection method and procedure for each component. Although preparation of the document is required by the procurement contract, the quality of the delivered product is often less than adequate. In the case of the F-16, the TO-36 Manual is of very high quality, describing in great detail the components to be inspected, the NDI technique, and the procedure to be used. All of these details were prepared and the sufficiency of the methods and procedures verified during the design and testing stage. As a result, the document was completed and available when the aircraft became operational.

ASIP FOR OTHER AIRCRAFT

In reviewing other aircraft, the Panel did not observe the same degree of compliance with the ASIP concept. There are several reasons. In some cases an attempt was made to retrofit the ASIP concept to systems or components already designed and in service. In many cases the aircraft were in service before ASIP was developed. As a result, either materials properties, design, or status of reliable inspection technology (or some combination of these factors) fails to satisfy the requirements for a viable system. For example, the material selected may have the critical flaw size that must be detected in the size range where confidence of detection is low. In other cases the delivered TO-36 manuals were inadequate, often late, and required reworking to be useful. Generally, this problem was not discovered until after the aircraft was operational and the need for the manual was urgent. The fact that the TO-36 Manual had not been delivered by the time the aircraft became operational is a clear sign that inadequate attention was given to inspection requirements (i.e., specification, design, and testing) during the procurement process. Table 1 summarizes information about aircraft status and availability of TO-36 manuals for one ALC. When reviewing this table, one must recognize that the ASIP concept was not formulated until about 1966* and was not formally endorsed by the Air Force until 1975.[2]

NEW TRAINER

In July 1982 the acquisition of a next generation trainer (NGT), which has now been designated the T-46A, was announced by the Air Force.+ To ensure the greatest chance of success for this new craft, it is important that the key features of the F-16 experience be repeated. Information indicates that these features are being included, with some variations. The NDI Program Office has the responsibility to provide detailed inspection knowledge for both airframe and engine during the early phases of the procurement cycle. The program office will include personnel from the ALC who will be responsible for aircraft maintenance, i.e., SAALC. This early involvement is a very positive indication that the ASIP and ENSIP approach will be successfully applied.

*ASD TR 66-57.
+On July 2, 1982, Secretary of the Air Force, Mr. Verne Orr announced that the Next Generation Trainer would be built by Fairchild Republic Airplane Company.

TABLE 1 History of Aircraft Managed by SM-ALC McClellan AFB

Aircraft Designation	Development Initiated	Production Procurement Period	Date Entered Service	TO-36 Manual Completion Date
A-10	1970	1973-present	December 1974	1978 (1A-10A) 1982 (A-10) Tentative
T-28	1948	1949-1953	1950	1970
T-33	1947	1948-1959	1949	1971
T-39	1956	1950-1962	1960	1970
F-84	1944	1944-1957	1947-1952 (various models)	1969
F-100	1951	1951-1959	1954-1956 (3 models)	1969
F-104	1952	1953-1961	1958-1959 (2 models)	1970
F-105	1952	1954-1964	1959-1961	1971
F-111	1962	1965-1974	1967-1969	1975
F-16*	1972	1975	1979	1979

*Aircraft based at Hill Air Force Base, Utah.

SOURCE: Table prepared from information supplied by A.P. Rogel, McClellan AFB, and by Gerald L. Yanker, AFLC.

ENSIP

The reviews of the F100 engine maintenance and inspection practice and the preliminary results from the SAALC-sponsored program on reliability of engine component inspection indicate that the engine inspection reliability status is very similar to that of airframe.[5] Because the available information indicates only a remote chance of finding major new insights, additional effort was not devoted to this subject.

Chapter 4

INSPECTION RELIABILITY

Inspection reliability is specified by ASIP. In the case of the F-16 the initial critical crack sizes are detectable by conventional technology with adequate confidence. In other cases, mainly those in which ASIP is being applied retroactively, inspection technology reliability is the weak link. The following discusses this concern.

THE ROLE OF NDI IN ASIP AND ENSIP

ASIP and ENSIP contain requirements for demonstrating the inspectability and fatigue-crack tolerance of each critical structural component. The required probabilities-of-detection limits and confidence limits are specified for minimum flaw sizes, and NDI methods and procedures are established to meet these minimum requirements.

Achieving a high probability of detecting flaws of a given size generally requires high enough resolution to detect much smaller flaws; such high resolution, however, can result in uneconomically high rates of rejection or repair.[6] Current Air Force procedures do not determine detection probability versus flaw size, or in general the probability that a detected flaw has a true size that differs by a specified amount from the indicated size. The procedures, therefore, do not indicate the degree of structural integrity afforded by NDI, and the possibility of cost-benefit analysis, which might provide the basis of procurement and maintenance specifications, is foreclosed. The Air Force has the ability to perform probabilistic lifetime analysis (although this approach is only now being developed for the F100 engine Retirement for Cause program)[3] and should require component manufacturers to supply probability-of-detection information along with NDI equipment and procedure specifications. Changing from deterministic to probabilistic inspection would allow a proper assessment of the improvement in structural integrity that would be afforded by an improvement in inspection technology. Since economy of maintenance is a key issue, the possibility of a net cost reduction as a consequence of the introduction of new NDI methods and procedures may provide the motivation for further Air Force investment in development of new equipment, as is the case in the engine component Retirement for Cause program directed initially at the F100 engine. The Panel is also encouraged by the procurement of a research project on the probability of detection of fatigue cracks in airframe component details.

The Air Force is naturally concerned about the time and cost of generating probability-of-detection (POD) data for each component detail.[9] The Panel suggests that this information can be required for generic materials and geometric configurations as part of the equipment procurement specification. It is acknowledged that POD data should be limited to automated or semiautomated inspections in view of the variability of technician performance.

CURRENT NDI RELIABILITY

Data from the Reliability of Nondestructive Inspection of Aircraft Structures[4] program (a review of the Air Force NDI results) have generally been used to measure the reliability of Air Force NDI. The results of this program, commonly referred to as "Have Cracks--Will Travel," indicate that the average reliability of NDI in the Air Force as of 10 years ago was, and may still be, unacceptably low. While the current validity of the results is subject to question, these results constitute the only available quantitative information and cannot be ignored. Experience in other industries indicates that these results may accurately reflect the low end of the performance spectrum. As such, they indicate the wide variability that is possible when the inspection procedures, personnel training, and management processes are not tightly defined and consistently enforced.

Available inspection results on thick-section carbon steel plate indicated similar variability of results when round-robin reliability tests were conducted.[10,11] More recently, the British Defect Detection Trials (DDT) were conducted on a similar series of thick-section plates containing a variety of realistic flaws. After a well-defined inspection protocol was developed and followed and a very thorough analysis of the signals was applied, the results demonstrated that several ultrasonic approaches could provide excellent results for both detecting and sizing flaws of engineering significance.[12] The results were generated with a well-engineered inspection system consisting of known and available techniques, equipment, and physical understanding, which strongly suggests problems identified in earlier round-robin results can be overcome.

It is tempting to suggest that a second "Have Cracks" program be developed and conducted using lessons learned from the DDT effort and the previous "Have Cracks" project. But although such an effort may show considerably better inspection reliability, its value would be more psychological than real because it would not provide the information useful on specific components that is needed to support ASIP.

Inspection reliability that is component-specific can be demonstrated in a different manner, as has been shown by action mandated by the U.S. Nuclear Regulatory Commission.[13] In that case, representative inspection personnel for boiling water reactor (BWR) nuclear power plants were required to demonstrate that they could detect actual flaws of interest in samples of components containing service-induced flaws before the plants could return to power. The first series of performance-capability demonstrations provided a rapid means of establishing a basic level of inspection reliability on a go-no-go basis. In addition, the series provided valuable information about the relative importance of procedures, training, and experience and about the effective definition of such an exercise. These lessons have been incorporated into the second series of performance-capability demonstrations now under way.[14] In this case an acceptable reliability-threshold detection level of 80 percent of the flaws present was specified.

These demonstrations are significant in terms of inspection reliability. First, the inspection teams had to demonstrate on flawed samples that they could detect these service-induced flaws at or above a specified minimum reliability value. After passing these demonstration requirements, the teams have found the same flaw condition in several plants. There is evidence that this did not occur prior to the demonstration requirement. These exercises also highlighted the need for increased emphasis on automation to provide higher inspection reliability and served as a check on the adequacy of personnel training.

A performance-capability demonstration program such as that called for above also serves as a check on the adequacy of personnel training.

Chapter 5

R&D PROGRAM

In Chapter 3 the F-16 ASIP program was described as very successful. Part of the success is due to basing allowable crack sizes on conventional NDI technology performance. The approach works well for implementing a meaningful ASIP program, as demonstrated by the F-16 performance. However, if designers are to be in a position to use higher performance materials that may fail in the presence of smaller flaws than conventional NDI technology can reliably detect, it is obviously necessary to improve NDI technology. This is a major objective of the Air Force R&D program. If successful, this R&D effort can make a major contribution toward wider use of higher-performance systems.

The Panel found the NDI R&D program elements in funding categories 6.1, 6.2, and 7.8 ("research," "exploratory development," and "manufacturing technology," respectively) well coordinated and planned but limited in effectiveness. This results from several factors. First, the Air Force has many aircraft in operation that were designed before the ASIP approach was adopted. A variety of higher-performance materials are used in these aircraft. Each material/component usually presents a unique inspection problem. Thus, it is a challenge to allocate available and limited resources to solve specific field problems. In some cases, as discussed earlier, the problems are exacerbated by attempts to apply ASIP retroactively. In any case, when new technology is being sought, R&D cannot guarantee the results. A successful solution takes time in the laboratory and even more time before it can be transferred to the field. Another open issue is how the available resources should be divided between providing inspection capability for new-generation materials (i.e., composites) and providing a basis for inspection for older-generation aircraft made from conventional materials. These issues are recognized by those struggling to establish research priorities. They are cited here to call attention to policy matters that must be considered at higher echelons when budget levels and directions are being established. Generating the information necessary to make specific recommendations on these issues was beyond the scope of the Panel.

The effectiveness of the NDI research program is also limited by the contracting process. Presently, as a project proceeds from conception to manufacture, a separate contract must be negotiated for each funding category. This results, sometimes with serious consequences, in a break in the work schedule, and very frequently entails a change in contractors. A change in contractors often results in a loss of corporate memory of the problem and promotes duplication of effort, a highly ineffective process. Another major limitation is the absence of funding in the 6.3 and 6.4 categories ("advanced development" and "engineering development"), which cover the progression of methods and devices from the proof-of-principle phase to the construction of manufacturing prototypes. This deficiency is evidenced by a tendency to initiate manufacturing development projects before the basic technologies have been adequately verified or optimized, a problem discussed in more detail in the chapter on technology transfer. The solution requires closer coupling among all phases of development. Procurement procedures should be modified to favor multiphase, multicontractor programs; such a step would permit greater continuity, lessen the burden on AFWAL program managers, and decrease the risk of confusion in the transition from R&D to manufacturing. In an apparent effort to improve continuity and provide the lacking funding, the SPOs have been requested by the Air Force NDI Program Office to include a description of NDI capability in the procurement stages of new weapon systems.

Even though the F-16 application of ASIP was successful, it was not without penalty. Existing NDI capabilities imposed design limits upon F-16 components. Thus, in some cases the designer cannot take advantage of the full range of material properties and less bulky designs to improve performance and efficiency. Through the development of improved inspection technology and its application to the ASIP and ENSIP concepts such penalties may be reduced. Significant work toward this goal is under way in the AFWAL R&D efforts.

Work in progress on the development of the scientific and engineering technology for quantitative NDI is particularly germane to the full implementation of the ASIP and ENSIP concept. In that program, sponsored jointly by AFWAL and the Defense Advanced Research Projects Agency (DARPA), main research interests include the development of engineering models for various NDI systems (ultrasonic and eddy current), which will permit probability-of-flaw detection curves to be calculated in advance for critical (and other) flaws in specific components and materials, and the development of reliable flaw-sizing algorithms. Both developments are at the core of ASIP and ENSIP requirements. Successful development of the detection models and sizing algorithms will play a significant role in establishing NDI as an engineering technology and generating "smart" instrumentation. The Panel notes this approach was employed by the British while establishing the safety of their proposed PWR reactor system.[15] The Panel encourages the continued development of the quantitative efforts and their application to ASIP and ENSIP problems as soon as is practical.

The Panel believes that Air Force NDI procedures (as is generally true in industry) depend too much on the manual dexterity, visual and sensory acuity, and attentiveness of inspectors. The work in quantitative NDI is consistent with the Panel's belief that procedures should be replaced with a new generation of smart, <u>engineered</u> NDI systems as rapidly as the new technology is developed and evaluated. Engineered NDI systems that emphasize <u>both</u> detection and flaw-sizing reliability (rather than traditional goals such as sensitivity) are the key to realizing reliability in weapon systems and to achieving the cost-benefits possible through the combination of quantitative NDI and fracture mechanics. The current Retirement-for-Cause program is a first-generation step toward this goal. These systems should, further, be automated as much as possible. Other industries are finding that automation is an important step in reducing operator variance. The Air Force should study this issue carefully to ensure that automation approaches are well planned and engineered to fully incorporate appropriate technology, as opposed to trying to duplicate what the manual operator does. The availability of smart instrumentation should help define improved operator training programs.

Finally, the Panel recognizes that it is difficult to decide how to distribute the available R&D budget among the variety of field problems. To improve this process, the inspection problems for the range of aircraft might be placed into a few specific categories by the nature of the error encountered in the NDI application. Such a scheme, for example, is used to help guide R&D efforts for pipe inspection in the nuclear power industry.[16] Three sources of error are used in that instance:

1. Physical: i.e., flaws produce signals too small to be reliably detected with conventional technology.

2. Signal Discrimination: the signal is present and easily detected but errors arise from incorrect discrimination between flaw and nonflaw signals.

3. Procedural: errors arise from improper application of procedure or from improper procedure.

Such a categorization will help demonstrate that R&D efforts have much broader application than might otherwise be apparent.

Chapter 6

TECHNOLOGY TRANSFER

Introduction

"Technology transfer" is an often used phrase with a variety of definitions either stated or implied. For the purposes of this report the term includes all the processes and the financial, technological, and human resources needed to bring a technique or likely solution to a problem from the R&D stage to generally accepted practice. With such an encompassing definition it is very helpful to use a model to address the key parameters in the process. Such a model was presented recently[17] and will be used to focus the remainder of the discussion.

MODEL DESCRIPTION

Technology transfer is a multidimensional process that can be separated and discussed in three different parts. The parts are organic factors (the human element), mechanistic factors (specific development steps that lead from problem definition and research and to technical success), and market factors (transferring the successful technical solution into commercial or routine usage). In the following sections each of these factors will be discussed more fully in the context of Air Force requirements.

ORGANIC FACTORS

The category of organic factors comprises the many elements that have little to do with the technical elegance of the proposed solution but may decide the success of the venture. These factors are strongly influenced by the human element and are a control to implementing a well-planned and financially well-supported project. Table 2 lists some of these factors.

It is doubtful that the exact combination will apply in the same way to more than one project, so the burden of identifying the operative factors in each case, as well as of implementing a strategy to cope with them, falls on the project leader. Thus, the key element is often the project leader's ability and personality because that determines the extent to which the other factors can be successfully identified and accommodated. There is almost universal agreement in the literature that the chances for success age greatly enhanced when the project leader is the champion of the developing technology. Ideally, he leads it through all the stages from conception to field delivery. Note, however, that the project leader is not necessarily the person who conceived the technical solution; in fact, the characteristics of this person are often quite different from those of the average engineer/scientist. Personnel selection for leadership roles in technol-

TABLE 2 Organic Factors That Often Influence Technology Transfer

"Not invented here" (NIH) syndrome
Vested interest in maintaining status quo
Fear of new routine
Negative experience with "new" technology
Scientific statesman that mold opinion
Project leader's missionary zeal
Early user input
Product-liability concerns
Technical bias
Easier to say "no" than "yes"
Regulatory concern
Project management quality
Cost/benefit
Pioneering spirit

ogy transfer may thus require thought and action outside conventional wisdom. Some of these characteristics include the ability to deal with ambiguity, good communication skills, a sense of humor, being a good listener, the ability to perceive a whole process, the ability to make decisions with incomplete information, and the ability to understand end-users bias and requirements. Dr. John S. Toll, President of the University of Maryland, states this very well:

> The transfer of technology requires a special type of talent not always present even in the best of scientists. . . . A successful transfer program must seek out the rare individual with the capacity for looking across disciplines and conventional scientific categories.[18]

The following quotation, attributed to Franklin D. Roosevelt, aptly summarizes the situation: "New ideas cannot be administered successfully by men with old ideas, for the first essential of doing a job well is the wish to see the job done at all."

The Air Force NDI program organization has some built-in obstacles that amplify concern about successful accommodation of the organic factors. The R&D is conducted within AFWAL, the end users are usually the ALCs, and the SPOs are responsible for procurement. Because of this division of responsibility among different command structures, it is difficult to develop and sustain a common pursuit of specific goals without unusual management attention and dedication. There is evidence that the ALCs are becoming involved in planning and reviewing the AFWAL R&D efforts, but the general perception in the ALCs is that the AFWAL program will not help much with daily inspection problems, those with highest priority at the ALCs. The Panel's review of ALCs end-user requirements, AFWAL program overall objectives, and the assessment of available human and financial resources indicates that the ALCs' perception is warranted. This observation should not be used to criticize the AFWAL program; rather, the observation's proper role is to highlight the differences in the motivations and objectives of the organizations.

While it is unrealistic to expect that the R&D people will have the same goals, motivations, etc., as field application people, it is important that a stronger communication channel be established, maintained, and exercised between the two. This will not happen by itself. Rather, an organization must be given the responsibility, authority, and resources (specifically, adequate travel funds for participants) to make this communication occur on a regularly planned basis. With proper direction and adequate resources, the Air Force NDI Program Office could play this role. Additional comments on how this can be achieved are given in the chapter on the program office.

The above statements should not be used to denigrate the efforts of the people involved; they are trying hard to do their job under difficult conditions. Rather, the comments should call attention to some of the constraints imposed by the overall Air Force NDI organization.

Another deficiency noted in the Air Force technology transfer process is a lack of adequate resources in the proper funding categories at the needed times. This can best be illustrated by discussion of the second major element in the technology transfer model, mechanistic factors, which follows.

MECHANISTIC FACTORS

The model referred to earlier presented the different steps that a proposed solution must successfully pass through to satisfy the technology-transfer definition stated earlier. These steps must be passed through in series and must answer such questions as: "Will it work?" (exploratory research), "How will it work?" (engineering development), "Does it work here?" (engineering development), "Will it sell?" (manufacturing technology), and "Will it work here? Will it be used?" (user integration). This process is specifically illustrated for the Air Force's NDI technology development efforts in Figure 2. Table 3 gives the official federal R&D funding categories.[23]

Funding for the shaded areas in Figure 2 was found to be nonexistent for the Air Force NDI R&D efforts. In addition, the Panel found no formal mechanism to promote integration of the new technology into routine ALC use, nor did it find any recognition of the need for such a mechanism. The consequences of these missing items are discussed below.

The lack of funds set aside for categories 6.3 and 6.4 ("advanced development" and "engineering development")[19] means that the crucial steps of systems verification needed to convert laboratory R&D results into products and methods useful in the field are not recognized and addressed. This absence of funds forces dedicated R&D project managers to try performing these functions using category 6.2 or 7.8 funds. Project managers have two options in making this attempt, neither of which is very appealing. The conservative approach is to keep the concept in category 6.2 for an extended time before trying to move it into category 7.8. This reduces the risk of technological failure, but it also delays the introduction of the technology. The probability of success does not necessarily increase linearly with time, and the project competes for funds that could be used on other projects. The second, much more risky approach is to move the technology from category 6.2 to category 7.8 without system verification. The surprises usually experienced in scaling up laboratory results ensure a low success rate for this approach and can lead to reputation problems for the agency responsble for the efforts. The result may be a breakdown of the ALC's ability to maintain weapon systems adequately.

Finally, our investigations did not reveal any organized or funded action to integrate new technology into routine ALC use after the technology has successfully passed through the other development phases. Rather, technology transfer efforts have been pursued on a case-by-case basis. This is a serious omission. Without a formal

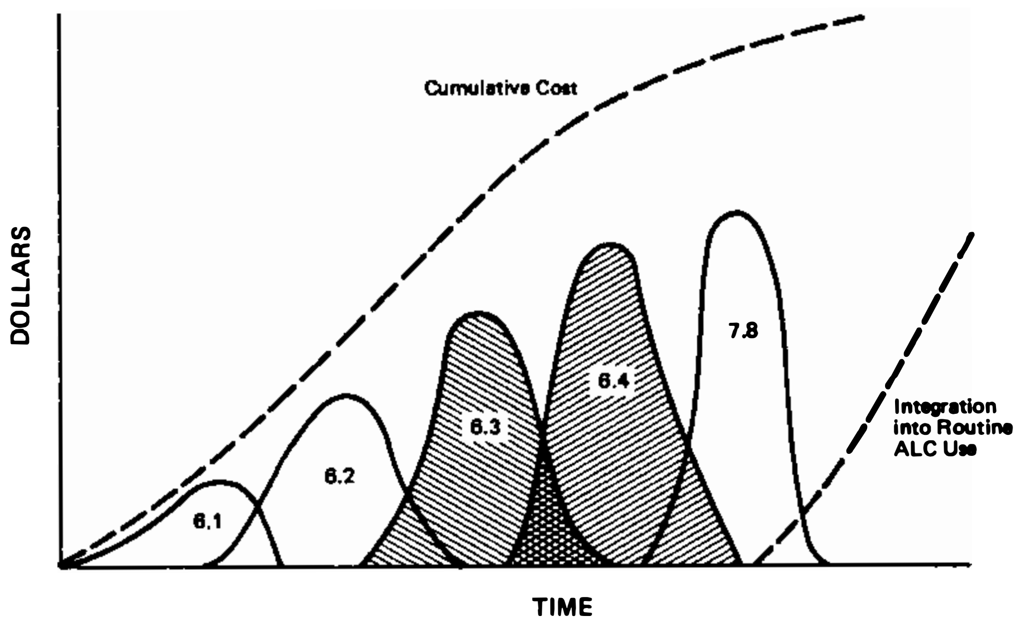


FIGURE 2 Schematic model showing relative cost and sequence of steps in NDI technology transfer.

TABLE 3 Research and Development Funding Categories

Category	Definition
6.1: Research	Includes all basic research and that applied research directed toward expanding knowledge in the several scientific areas.
6.2: Exploratory development	Includes studies, investigation, and minor development efforts varying from applied research to sophisticated breadboard hardware and is oriented to specific military problem areas.
6.3: Advanced development	Includes all projects for development of hardware for experimental test.
6.4: Engineering development	Includes development programs in which items are engineered for military use but that have not been approved for procurement or operation.
7.8: Manufacturing technology	Program to establish and validate the producibility and cost effectiveness of new materials, processes, component designs, etc. based on new state-of-the-art technology.

SOURCE: Blue Ribbon Defense Panel (1970).

effort to integrate the equipment into routine use, completion of the technology-transfer task is left entirely up to the ALCs. If they have had no long-term involvement in the development of a technology from its earliest stages, their commitment to its success may be low. As a consequence, their patience, the time they set aside for familiarization and training, and their tolerance of early failures can be expected to be very low. The result is that the new product must be unusually, perhaps unreasonably, good during its first field use; i.e., it either succeeds or fails on its own, without benefit of a friendly mentor.

The Panel made no attempt to assess the overall adequacy of current funding. We did note, however, that the complete absence of funds in the middle phases of development is a critical problem as is the instability of funding required to obtain a goal. These conditions may often doom an otherwise sound program or project technology transfer in the Air Force NDI program for otherwise sound concepts. Simply supplying more funds is not the answer. As the above discussion indicates, funds must be provided in the right categories and at the right times. This implies planning the entire technology-transfer process from the beginning of the applied research phase. This point is emphasized by Charles Miller:

> One obvious characteristic common to most successful commercialization* cases is that the transfer process is in itself a deliberative endeavor. The activity is planned, staffed, scheduled, and directed, and most importantly, funding is made available.[18]

Market Factors

The final element in the technology-transfer model concerns the market factors. The movement of successful R&D into products available on a large scale, ready for use, with service facilities established, warranties available, etc. is heavily dependent on market forces. The market system for Air Force NDI is a limited market characterized by the following:[20]

- The potential number of units of a particular product or service that may be purchased is limited and the number of purchasers is small.

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*For the purposes of this discussion, commercialization occurs at the point at which routine field use is achieved.

- Financial success is possible for only a limited number of suppliers.

- The decision to purchase a particular product or service is centralized.

Traditional planning models are usually developed for open-market situations; thus, they are usually not appropriate for analysis of the Air Force NDI situation. A new planning model is needed for cases in which the market is limited or the objective is other than making a profit. It is beyond the scope of this review either to specify or develop the appropriate planning mechanism; however, it is important that those responsible for Air Force NDI technology-transfer activities recognize the type of market system and deal with it creatively. Some very useful observations on these points are made in a 1981 report to the Air Force Systems Command.[21] Additionally, S.J. Farmer lists eight elements for the limited-market case that represent a good starting place for those directly involved:[20]

1. Establish the technical objective early.

2. Develop a plan for providing market demand.

3. Earmark sufficient resources to complete the research-development-engineering-production cycle.

4. Ensure that the right people are available.

5. Select contractors with a view to their later ability to perform technology transfer.

6. Establish clear decision points for deciding when the product will or will not be carried through the commercial cycle.

7. Maintain awareness of development of others.

8. Allocate risks of the unpredictable effects of introducing major new technologies.

A key theme that runs through all is to start planning technology transfer as early as possible.

Those familiar with government procurement will recognize the similarity between these elements and the steps taken by a government agency in planning for the sole-source negotiated procurement of a product incorporating new technology.

The development of NDI technology for the electric utility industry has many parallels with the Air Force situation, most notably the limited market feature. Their efforts to promote technology transfer through a dedicated NDI center are appropriate. Considerable information on the center exists and is included in the references.[22-26] A simplified description of the center's operation is given in Appendix C.

Although in operation only since 1981, the center has generated an unusually large number of favorable comments from the utility industry, an industry with operating constraints at least as complicated as those of the Air Force. Thus, the success of the approach strongly suggests review by the Air Force. Such a center would have to be structured to accommodate the requirements of the Air Force, but there is no apparent reason why the concept would not be as successful as in the utility industry.

Chapter 7

PROGRAM OFFICE

The Panel found a variety of opinions about the effectiveness of the Air Force NDI Program Office with little convergence on specific suggestions about how to improve its operation. The lack of convergence reveals part of the Program Office's weakness, i.e., lack of a strong identity with a specific function or mission. The people interviewed looked to the office to provide different types of information and support and were disappointed when it was not forthcoming. Budget restraints prevent it from being all things to all people. Thus, one must either define a scope of activity achievable within the available budget or provide a budget adequate to provide functions defined. The role of the Program Office needs to be restated, needs clearly delineated functions, and it must be operated solely within those boundaries.

Staffing the NDI Program Office, as well as other elements of the NDI program, is an acute problem. Colonel James Griffin, former NDI Program Manager*, has, through the Air Force NDI Steering Committee, increased the Air Force's awareness of the NDI program's special problems and needs. However, the departure of senior staff, the scarcity of skilled NDI engineers, and the federal personnel system's constraints on hiring are of much concern to the Panel. We expect steady improvement in coordinating technical objectives and priorities through the Program Office, but the technical competence to implement new inspection systems must also be available. It appears necessary for the Program Office to provide technical leadership to the ALCs.

The Panel believes that the provision of such technical leadership and coordination is impeded by the location of the Program Office at the San Antonio Air Logistics Center (SAALC). First and most important among these reasons is that the ALCs are geared mainly toward production-item management rather than toward technical-project or program management. Second, the location of the Air Force NDI Program Office deep within the SAALC organization impedes the conduct of its Air-Force-wide coordination function. Figure 3 shows the NDI Program Office relationship within the Air Force. The office must compete within SAALC for travel funds and people and to conform to all local ALC policies and management practices. Since most of this activity must take place with organizations based far from San Antonio (e.g., AFWAL, the ALCs, the SPOs, etc.), adequate travel funds are a necessity.

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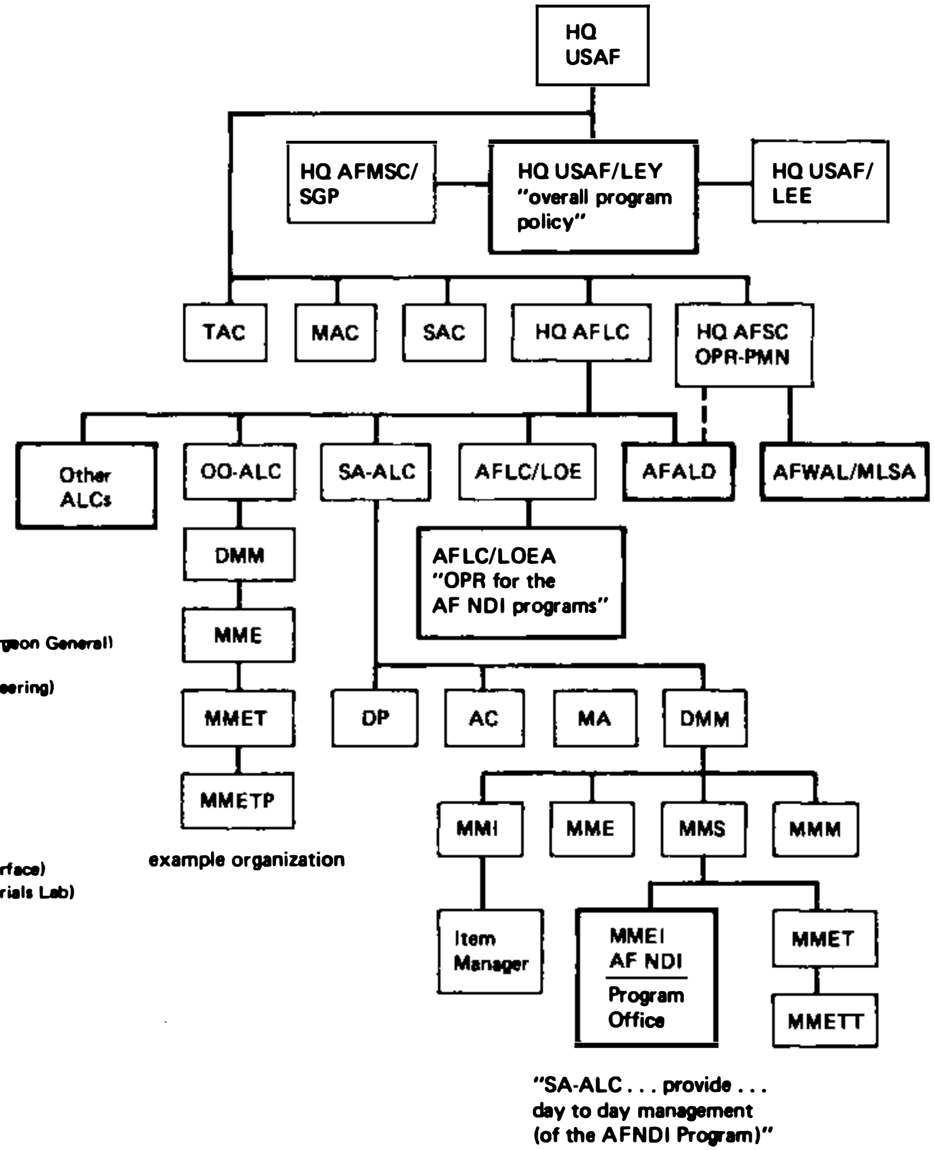
*The present manager is Major Lonnie Phifer.



1. AFLC—Air Force Logistics Command
2. AFSC—Air Force Systems Command
3. HQ AFMSC/SGP—Directorate of Professional Services (Air Force Surgeon General)
4. HQ USAF/LEY—Directorate of Maintenance and Supply
5. HQ USAF/LEE—Directorate of Engineering and Services (Civil Engineering)
6. TAC—Tactical Air Command
7. MAC—Military Airlift Command
8. SAC—Strategic Air Command
9. OO-ALC—Ogden Air Logistics Center
10. SA-ALC—San Antonio Air Logistics Center
11. AFLC/LOE—(Service Engineering)
12. AFLC/LOEA—(Aircraft Division)
13. AFALD—Air Force Acquisition Logistics Division (AFLC/AFSC Interface)
14. AFWAL—Air Force Wright Aeronautical Laboratory (Air Force Materials Lab)
15. DP—Directorate of Personnel
16. AC—(Comptroller)
17. MA—Directorate of Maintenance
18. MM—Directorate of Materiel Management
19. MMI—(Item Management Division)
20. MME—(Engineering Division)
21. MMS—(Systems Division)
22. MMM—(Administrative Division)
23. MMEI—Nondestructive Analysis Branch (AF NDI Program Office)
24. MMET—Varies at the individual ALCs

<u>Source</u>: Chart prepared by H. Solar of DMM at SAALC from AFR 66-38 and AFLC/AFSC Supplement 1, 27 June 1980

FIGURE 3 Air Force organization chart showing locations of major NDI activities.

Figure 3 also illustrates the difficulty SAALC's physical and organizational location presents when it tries to function in an NDI leadership role. Finally access to advice and information on NDI is very limited at the San Antonio Center, and the competition for experienced NDI personnel practically rules out strengthening the office. The Panel concludes that the office should be located at Wright-Patterson Air Force Base in Dayton, Ohio, which is the principal source of NDI expertise and information in the Air Force; and specifically at the Air Force Acquisition Logistics Division (AFALD), which is the most appropriate organization for coordination between the AFLC and AFSC.

If the NDI Program Office is moved, the Panel suggests that expanded responsibilities for it be considered. Possible roles that an expanded Program Office charter could provide are listed below. They resulted from an analysis of views presented on what is expected or desired from the office by various Air Force people.

- Perform as technology-transfer agent/communication coordinator between AFWAL and ALCs.

- Maintain a pool of expensive but seldom used equipment for the ALCs.

- Be responsible for evaluating and qualifying R&D products and provide leadership to integrate new equipment into field.

Chapter 8

TRAINING AND CERTIFICATION OF NDI PERSONNEL

The Panel has been pleased to note a trend toward the appointment of full-time inspectors. The results of the "Have Cracks-Will Travel" program amd the progress of the F100 engine parts inspection at SAALC suggest that motivation of inspectors is as important as formal training or experience (although commercial airline and nuclear industry experience suggests that continued training decidedly enhances NDI capability). There is little question that qualified personnel are very important to the reliability of any NDI program, for if the inspector does not know how the signal from the flaw of interest responds, he cannot be expected to make reliable decisions. An effective training and certification program is a key component of personnel qualification.

The Air Force recognizes the importance of training and certification and has undertaken an effort to analyze its program and redirect it as required. The Panel believes that an independent evaluation of the Air Force's training and certification program would therefore be superfluous and has decided not to pursue the issue. The Panel urges, however, that the intensity of the Air Force study be maintained until shortcomings have been identified and corrective measures implemented.

As indicated in the discussion on reliability in Chapter 4, an effective way to verify the adequacy of training is to implement an inspection performance-capability demonstration, as has been done by the U.S. Nuclear Regulatory Commission.[13,14] Furthermore, at the urging of the Commission the nuclear utilities have formed an ad hoc committee to develop an improved description of the minimum qualification requirements for the three levels of inspection personnel.* This effort may be of benefit to the Air Force.

In addition, it is necessary to note the overall lack of opportunities for educating engineering people at U.S. universities to understand NDI requirements. This is related to the training problem and one which is being addressed only marginally on a national scale. The shortage of graduate engineers who would qualify as true NDI engineers seriously affects the transfer of technology in general and, as stated, is specifically related to the ALC problem.

*Carl Osman (Carolina Power and Light Co.) is committee chairman, while Gary J. Dau (EPRI) is committee coordinator.

Appendix A

PANEL ACTIVITIES

The Panel on Nondestructive Inspection began its study in April 1980. Over the next year* it met in several locations to deliberate and to inspect Air Force and commercial NDI installations. The following is a list of those meetings and their dates:

Study initiated	April 1980
Wright-Patterson Air Force Base	May 16, 1980
Kelly Air Force Base	June 23, 1980
McClellan Air Force Base	Augsut 7, 1980
United Airlines Maintenance	August 8, 1980
Southwest Research Institute	Noverber 19-20, 1980
Kelly Air Force Base	January 14, 1981
Tinker Air Force Base	February 10, 1981
Wright-Patterson Air Force Base	March 24, 1981
McClellan Air Force Base	April 7-8, 1982
Martin Marietta Aerospace	June 1, 1982
Hill Air Force Base	June 2, 1982
Electric Power Research Institute	August 6, 1982

*An interim report was prepared in 1981 but not issued until March 1982.

Appendix B

STATEMENT OF TASK

The Panel on Nondestructive Inspection will examine the factors that influence the effectiveness of nondestructive inspection of aircraft and engine structures as now practiced in the Air Force. It will attepmt to identify those inspection measures, consistent with minimum ownership costs, that can be taken to improve the safety and utilization of Air Force weapon systems.

The Panel will examine in particular the effectiveness of technology and facility transfer from research and development to production inspection at the Air Logistics Centers, reviewing management responsibilities/authority, funding levels and manpower capability. It will also address the communication and collaboration between elements of the Air Force, the proficiency and motivation of inspection teams, and the risks and advantages of automation. The content of developing equipment specifications will be examined from the standpoint of their relevance to the structural integrity of aircraft and engine components.

In pursuit of this task, the Panel will visit the ALCs and review case histories illustrating the successes and failures of technology transfer. The results of similar studies in other areas, e.g., the electric power industry will be examined for their relevance to Air Force NDI practices. Interviews will be held with appropriate AFSC and AFLC personnel.

The Panel will make its preliminary critical report at the end of twelve months. Specific conclusions and recommendations may require additional time, depending upon the final scope of the study.

Appendix C

ELECTRIC UTILITY INDUSTRY'S TECHNOLOGY TRANSFER THRUST IN NDE

In 1973 the U.S. electric utility industry formed the Electric Power Research Institute (EPRI) to formulate and manage major research and development activities needed by the utility industry as a whole. A major effort in NDE is one element of the overall program. An advisory task force is used to provide guidance on the R&D thrust conducted by EPRI.

After a few years' experience, it became obvious that more specific input was needed from the utility community on inspection problems, so a Nondestructive Evaluation (NDE) Subcommittee was established as part of one of the Nuclear Power Division's task forces. This group consists of people directly responsible for the inspection activities of power plants. The committee meets three times a year to review and advise on proposed R&D efforts, reviews ongoing R&D efforts, and provides insights on where future problems can be expected. In turn these meetings provide the EPRI staff a forum to communicate information on new developments, explore options possible within resource limitations, and develop an understanding of the reasons for the response of different utilities to the same problems (e.g., economic, regulatory, political, etc.).

Frustration with the vagaries of technology transfer within this group led to formulating and implementing a concept for a function dedicated to promoting technology transfer. This function is embodied in the EPRI Nondestructive Evaluation (NDE) Center located in Charlotte, North Carolina. It is operated for EPRI under contract by J. A. Jones Applied Research Company.

The purpose of the NDE Center is the application of new technology developed by EPRI contractors and others to utility inspection problems. The primary functions of the center are technology transfer, training, and resource development.

The product from an EPRI NDE R&D contract is delivered to the center as the first step of the technology transfer process. The center staff then starts evaluating the item as if they were the end users. As shortcomings are noted, the problems are either corrected or recycled to the original contractor for reworking. This process continues until the center is satisfied that the product is field-ready. At that time the user-integration phase is started by field people under the center's supervision and initially its support. As the technology continues to show field readiness, the operation is turned over to operations personnel in specific steps. When the center staff is satisfied, the technology is deemed field qualified. At this time, training programs are initiated for other users. When the center completes its tasks, the following has been accomplished:

- The new technology has been demonstrated on realistic test items and in field environments.

- A performance data base has been established.

- Field personnel are trained in use of the new technology.

- The new technology is given support during its integration into routine field use.

Another intangible benefit from the above process is that the center has developed good rapport with both the R&D and the applications communities. This rapport serves as a valuable communication catalyst, as well as providing fresh insight to EPRI regarding R&D needs. Both items are very important to successful development of needed technical innovation and its rapid application.

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