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The problems and opportunities in the NDE of composites are covered in formal papers and a summary of the discussion which took place at a Workshop held in Dayton on February 13-14, 1974. The recommendations arrived at by an NMAB Committee, on flaw detection, composite strength, standardization and design information, and research on composite degradation are stated.

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PROCEEDINGS OF THE WORKSHOP ON STRUCTURAL COMPOSITES AND NONDESTRUCTIVE EVALUATION

February 13-14, 1974

Imperial House North
Dayton, Ohio

Arranged by the

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The assistance of chairmen and co-chairmen of the Workshop in summarizing the findings of their sessions is noted with thanks as is the aid of Mr. Richard Rowand and others from the Materials Laboratory, Wright-Patterson Air Force Base, who helped materially in making arrangements and by providing projection equipment and similar services.

CONTENTS

I. INTRODUCTION

The National Materials Advisory Board (NMAB) was asked by the Department of Defense to conduct a workshop to identify technology gaps, problems, and opportunities in the nondestructive evaluation of composites. A workshop planning committee was organized to establish the program, suggest participants, and provide a list of individuals to whom invitations would be sent. To conduct the workshop the NMAB then established an ad hoc Committee on Nondestructive Testing of Composites, each member of which presented a theme paper related to the workshop which followed. The committee stayed on to write a series of recommendations and were helped in this by the chairmen and co-chairmen of the workshop sessions who summarized the discussion of their session.

The problems of inspecting advanced composites were placed in perspective by the presentations made by members of the NMAB ad hoc Committee on Nondestructive Testing of Composites and these five talks comprise the bulk of this report. The larger part of the workshop--discussion by the participants--is summarized on the next few pages.

Based on the discussion, as reflected in the summary, four principal recommendations--concerning flaw detection, measurement of strength, standardization, and research--were derived by the Committee. They have been stated simply; therefore, exceptions undoubtedly exist. It is believed, however, that the recommendations are valid for the majority of typical applications and should be considered seriously by the Services in the planning of their programs.

These recommendations and the workshop discussion summary were written in a few hours immediately following the meeting with the belief that prompt publication and fullness of recall would be preferable to elegance of expression.

II. RECOMMENDATIONS

A. FLAW DETECTION

1. No additional work on improving the sensitivity of flaw detection in composites should be supported until a need has been demonstrated. However, work to automate, decrease inspection costs and establish sensitivity should be undertaken. The critical flaw size in composites, which is large compared to the critical flaw size in homogeneous materials, should be established.
2. When the required resolution to discover discontinuities is known, the cost and reliability of detection should be optimized. There are obvious opportunities for automation, particularly on large production runs such as blades.

B. COMPOSITE STRENGTH

1. Methods to predict the nominal (unflawed) strength of composites and the interlaminar (cohesive) bond strength should be developed.
2. Such work should be carried out on materials in use today.
3. Concern regarding environmental influence on bond strength should be recognized. Nondestructive evaluation methods should be developed to predict the residual strength of composites in which environmental exposures (to temperatures, cycling, moisture, etc.) have resulted in the growth of flaws.

C. STANDARDIZATION AND DESIGN INFORMATION

1. Universally accepted reference standards are required.
2. The Advanced Composite Design Guide (3rd Edition, Jan. 1973)* should be brought up to date.
3. There is need for standardization of interpretation of instrument output. Signal processing techniques that could assist in this should be developed.

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* Qualified requesters may obtain this 5-volume report from the Defense Documentation Center, order No. s AD916-679L, -680L, -681L, -682L, and -683L.

D. RESEARCH ON COMPOSITE DEGRADATION

Failure mechanisms and strength degradation associated with impact, aging, and fatigue effects should be studied utilizing nondestructive evaluation (NDE) techniques as a research tool.

III. WORKSHOP SUMMARY

A. NDE TODAY

1. Effectiveness of Current Technology

a. Present NDE methods have the necessary capability to detect significant discrete discontinuities in structural composites.

b. Development efforts to increase defect detection sensitivity are not especially important at this time since the critical flaw size is generally large. Programs may be needed to establish and to verify the tolerable sizes of flaws in various types of structures.

c. Techniques for the nondestructive determination of nominal composite strength are not available. Similarly, it was the consensus that it is not possible to measure the strength of a bond by any NDT technique. Until modes of failure are understood and characterized, it will not be possible to define the adequacy of current NDE technology.

2. NDE Influence on Composite Design

a. Close communication is required between workers in stress analysis, design, materials, and NDE. The influence of defects on the modes of failure in composites need to be defined for the specification of acceptance criteria.

b. Designers must be made aware of NDE limitations, capabilities, and costs. Areas in complex structures not inspectable because of geometrical constraints must be designed such as by incorporating redundancy.

3. Quality Assurance and Process Control

a. Since current NDE technology cannot measure inherent composite strength or localized bond strength, process control tests are required to verify the effectiveness and consistency of the manufacturing processes. Even with a well-defined process, it is unrealistic to assume that human errors will not occur. Therefore, the development of NDE test methods, particularly to establish the intrinsic bulk strength of composites and the strength of bonds, is needed.

b. The need for definition and development of NDE standards for composite configurations is significant, and these standards must be relevant to practical applications. Universally accepted standards are presently not available.

4. Additional Considerations

A handbook on the NDE of Composites, or an expansion and updating of that portion of the Composites Design Guide, would be useful for disseminating presently available information.

B. THE EFFECT OF FLAWS ON MATERIAL PERFORMANCE

1. The Criticality of Flaws

In contrast to isotropic materials in which criticality of flaws is principally governed by applied load and crack length, the criticality of flaws in composites depends upon a large number of parameters. These include complex loading conditions, lamination geometry, orientation of flaw with respect to laminate, and flaw geometry itself. In present applications, flaws that are easily detectable are relatively stable and not describable by classical isotropic fracture mechanics theory. On the other hand, specific combinations of lamination geometry, crack orientation, and loading condition exist under which certain flaws propagate catastrophically. These observations emphasize the necessity of predicting the criticality of flaws in terms of the variables listed above. Costs for implementing required critical flaw programs may be quite high. New approaches are therefore certainly required.

2. Characterization of the Criticality of Flaws

The criticality of flaws in anisotropic composites can be characterized by a suitable blending of strength theory with stress analysis of flaws. Such an approach can both predict catastrophic crack propagation and confirm the conditions for nonpropagation. Such mathematically operational analysis can be used as feedback to structural design and materials development. Extension of such an approach to establishing the criticality of flaws under environmental and service conditions should be explored in conjunction with definitive experimental verifications. Such information will be beneficial in determining whether proof tests are required or whether proof testing actually will be detrimental to service life of the structure.

3. Relaxation of Minimum Acceptable Flaw Size

Since the application of composites is in its infancy, there is a tendency to impose overconservative minimum acceptable flaw size requirements, which can have a detrimental effect on the general acceptance and application of composites to engineering structures. With a rational understanding of the quantitative parameters that characterize the criticality of flaws, it is hoped that the minimum flaw size requirement can be relaxed and also that the performance confidence level can be defined.

C. COMPOSITE CHALLENGE FOR NDE

The following problem areas were identified:

1. Measurement of the intrinsic strength of composites.
2. Detection of poor (low strength) adhesive bond and interlaminar bonds.
3. Detection of low level (<2%) moisture absorption.
4. In-service monitoring of structural strength and quality, including monitoring of degradation of material and fiber-matrix debonding.

5. Generation of valid, universal reference standards.
6. Detection and evaluation of impact damage.
7. In-service inspection after exposure to environments not previously encountered, for which no NDE standards nor experience exists.
8. Comprehensive summary of the state of the art of advanced composite NDE.

Approaches to these problems arose spontaneously during the discussion. While they should not be considered well thought out or all-inclusive, they are presented below keyed to the identified problem areas:

1. Proof loading by using an electromagnetic field (problem area 2).
2. Spectral analysis and signal processing (problem areas 2 and 3).
3. Neutron gaging (problem area 3).
4. Acoustic emission, thermal emission (problem area 4).
5. Professional societies, industry, and government activities (problem area 5).
6. Holographic interferometry, thermal emission (problem area 6).
7. Sonic scattering or attenuation (problem area 5).
8. Preparation of an NDE of composites handbook to supplement the Air Force Design Guide (problem area 8).
9. Design for in-service inspection, e.g., incorporate reflective or conductive layers (problem area 4).

In addition to the above, the communications situation between those in the NDE (what can we detect) field and those in the structural design (what do we have to detect) field was aired briefly, but no consensus as to its resolution was achieved.

IV. PRESENTATIONS

E. L. Caustin
NMAB - Dayton
February 1974

NONDESTRUCTIVE EVALUATION TODAY FOR ADVANCED COMPOSITES

This Workshop has been designed to determine needed, new paths of development for NDT in its application to advanced composites. Therefore, the present situation of NDT applied to advanced composites should be reviewed.

From the quality assurance point of view, five major concerns are associated with nondestructive testing:

1. It is used to screen parts; that is, to separate the bad from the good. Many consider this usage to occur too late in the process for best effectiveness.

2. No single method will accomplish the total inspection task. Two, and sometimes three, techniques must be employed for a given product.

3. Quality assurance is being continually pushed to obtain greater sensitivity. The state-of-the-art is constantly being expanded to new horizons, with attendant mounting expense.

4. Usually one of the methods employed is time-consuming, and time represents money with the products that are being developed today.

5. Management considers NDT an excessively expensive inspection tool. The necessity for NDT is acknowledged, but there are demands to reduce its costs.

The numerous available reports on NDT and advanced composites indicate that practically all the known methods have been tried, at least in the laboratory, to determine their capabilities on the various advanced composites, such as metal matrix and boron graphite resin laminates. Ultrasonics, radiography (both X-ray and neutron), microwaves, holography, eddy current, liquid crystals, penetrants, acoustic emission, and sonic vibration techniques have been applied. All have shown success of varying degrees. As a result, one must select the NDT methods to be used by considering the engineering criteria and the capabilities of the particular method.

The most generally capable technique, with its various modes of operation, is ultrasonics. Ultrasonics has been the workhorse for nondestructive testing. Through-transmission, attenuation C-SCAN recording is probably the most sensitive and reliable technique for detecting macro defects of the delamination, inclusion, and void types, and for density evaluation. Figure 1 shows a typical setup. The technique employs two transducers, aligned one on each side of the part. One transducer sends the signal, and the other receives it. Figure 2 is a typical recording of a defective area

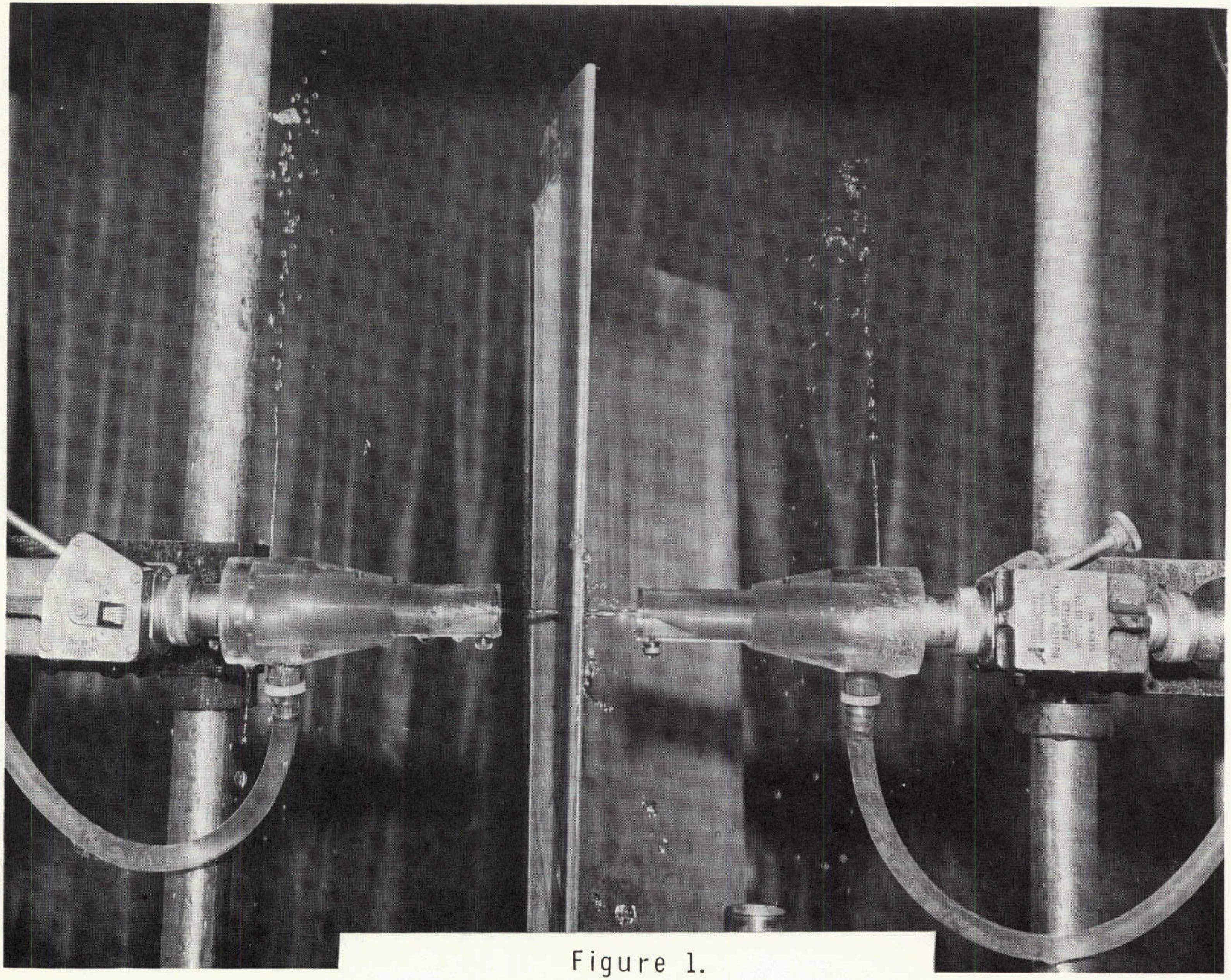


Figure 1.

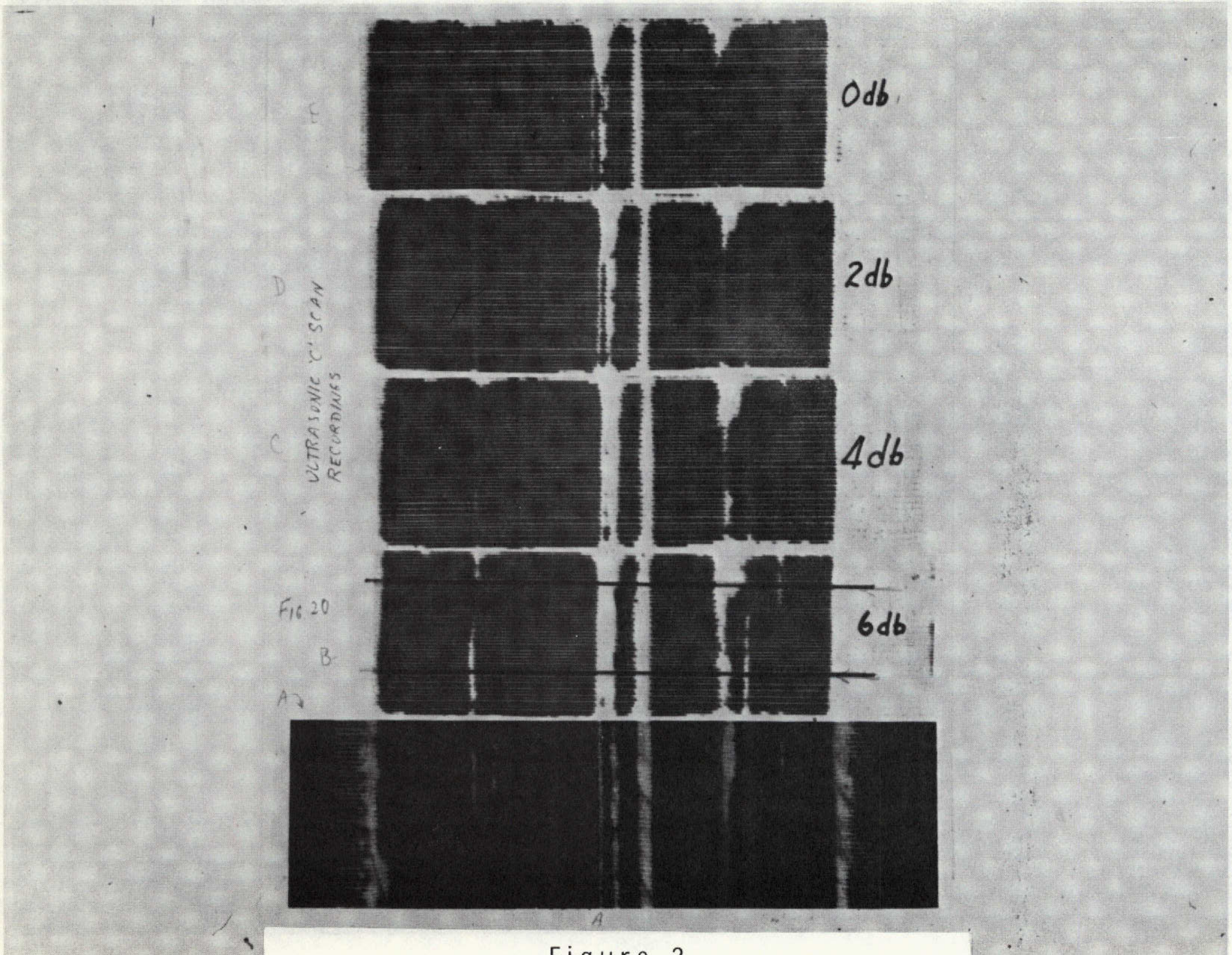


Figure 2.

with various levels of attenuation. The equipment's attenuator settings are noted in decibels (db). This technique works well on thin parts--3 plies of thickness of the metal matrix or resin laminates--and on parts of 235 plies of the boron resin laminate-type structures, with sensitivities ranging from 1/16-inch to 3/8-inch in diameter, respectively. However, it is expensive and does not provide depth location. Pulse-echo is probably the most popular technique of ultrasonics employed for defect detection. Figure 3 shows a typical pulse-echo setup. Pulse-echo ultrasonics uses a single transducer to transmit the signal and receive reflected signals from the part. The method is slightly less sensitive than through-transmission, and does not have the same range of thickness, but it is less expensive. Other ultrasonic methods such as shear wave, surface wave, and interval velocity have been used with composites. These methods, apparently, have been employed mainly in laboratory investigations for density and modulus measurements, and have not seen real production use. Most ultrasonic methods require liquid couplant. Water is the most common, which requires the parts to be protected by sealing of their edges and, for some parts, a drying operation.

Radiography employs X-rays and neutrons. Figure 4 illustrates the difference between neutron radiographs and X-ray radiographs. Neutrons pass readily through metallic objects but are attenuated by halogenated materials such as the cigarettes in the cigarette case, whereas X-rays are attenuated by the metallic portions of the case and not by the cigarettes themselves. X-ray radiography is a well-established production technique and is used primarily to detect broken and misaligned filaments and metallic inclusions. However, because of the confusion factor caused by many filaments, this application is limited to relatively thin parts, 8 to 10 plies maximum. Radiography is also usable for sandwich structure to determine internal damage or shifting of internal parts. Delaminations are sometimes detectable, but not reliably. Neutron radiography has been hampered for production use by the size, cost, and lack of portability of the equipment. The method is as sensitive as X-ray radiography and has the same limitations. Gamma rays have been used frequently in the laboratory to measure density and porosity and filament volume, but production use has been very limited. A major disadvantage of radiography is the hazard to personnel.

Use of holography and liquid crystals on a production basis has been very limited, probably because their detection capability is mainly for gross defects near the surface. Each, however, has been the subject of considerable research and laboratory testing. Figure 5 shows the complexity of a holographic setup with the laser beam and the optics required. In this case, heat is applied to cause a thermal load which provides the distortion necessary for holograms. Figure 6 is a typical hologram where the interference fringes show a defective area.

Microwaves have been used in some production applications for thickness measurements and void detection in plastic sandwich structures. They have

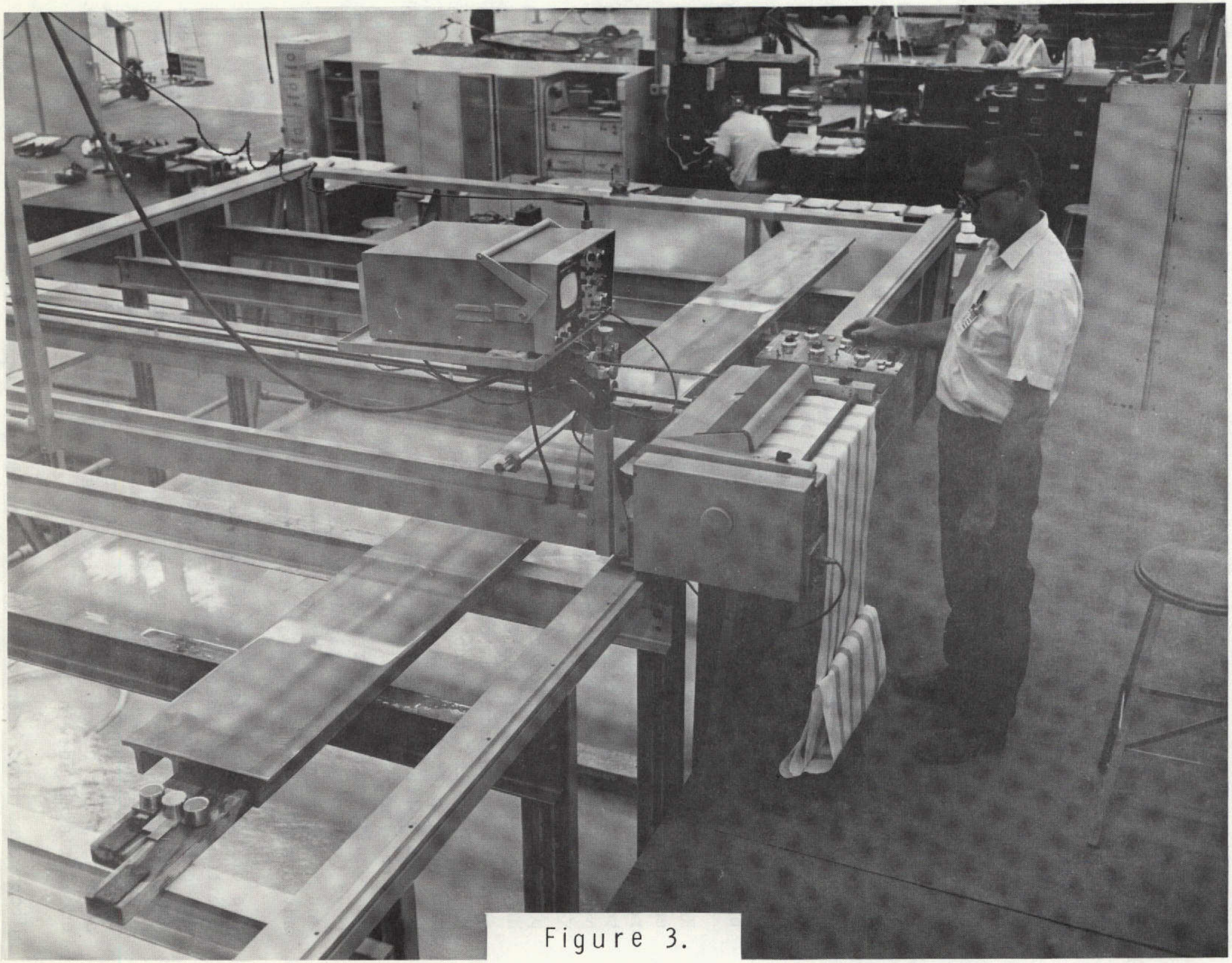
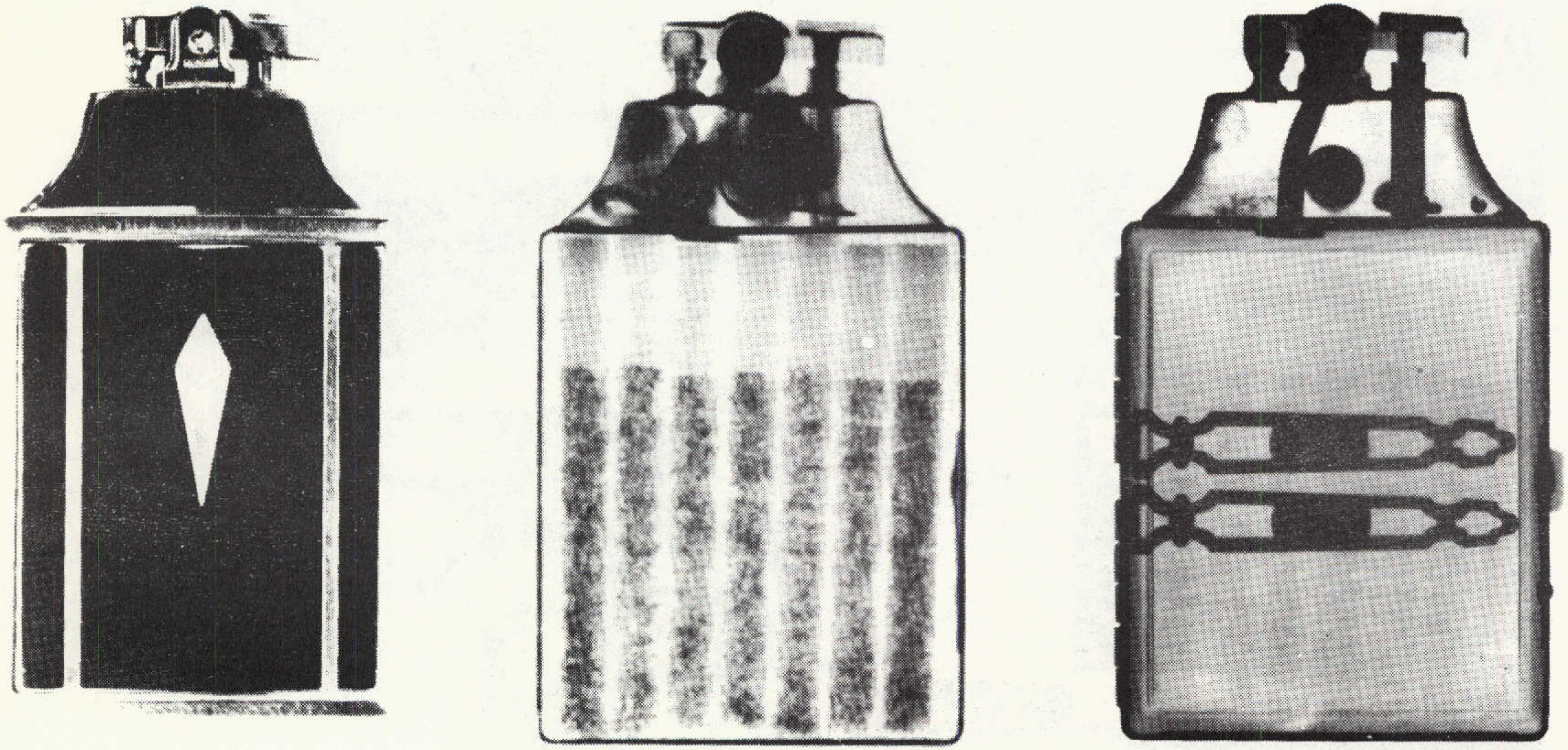


Figure 3.

COMPARATIVE RADIOGRAPHS OF CIGARETTE CASE



PHOTOGRAPH NEUTRON RADIOGRAPH X-RADIOGRAPH

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Figure 4.

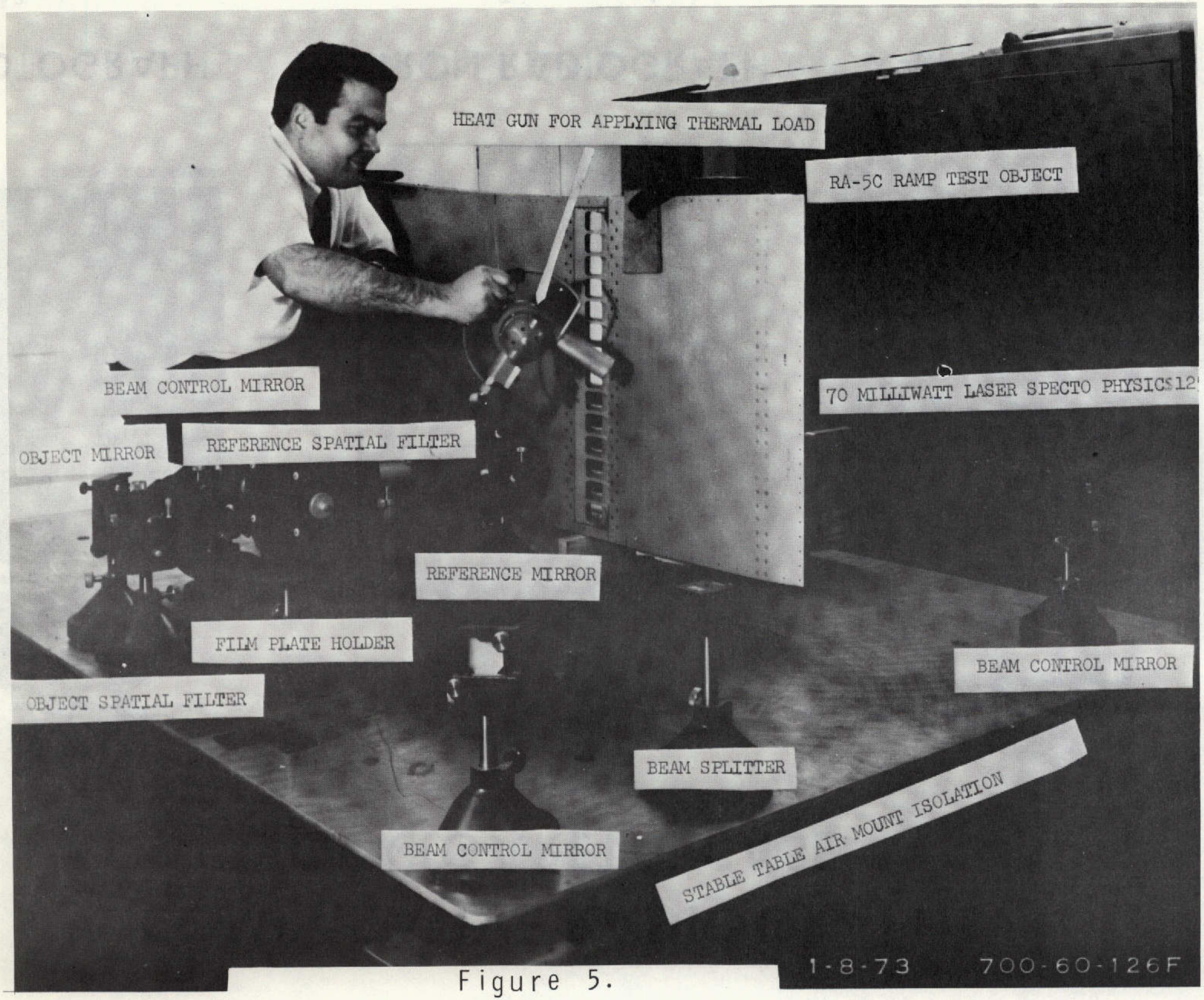
HEAT GUN FOR APPLYING THERMAL LOAD
RA-5C RAMP TEST OBJECT
BEAM CONTROL MIRROR
70 MILLIWATT LASER SPECTO PHYSICS 12
OBJECT MIRROR
REFERENCE SPATIAL FILTER
REFERENCE MIRROR
FILM PLATE HOLDER
BEAM CONTROL MIRROR
OBJECT SPATIAL FILTER
BEAM SPLITTER
STABLE TABLE AIR MOUNT ISOLATION
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Figure 5.

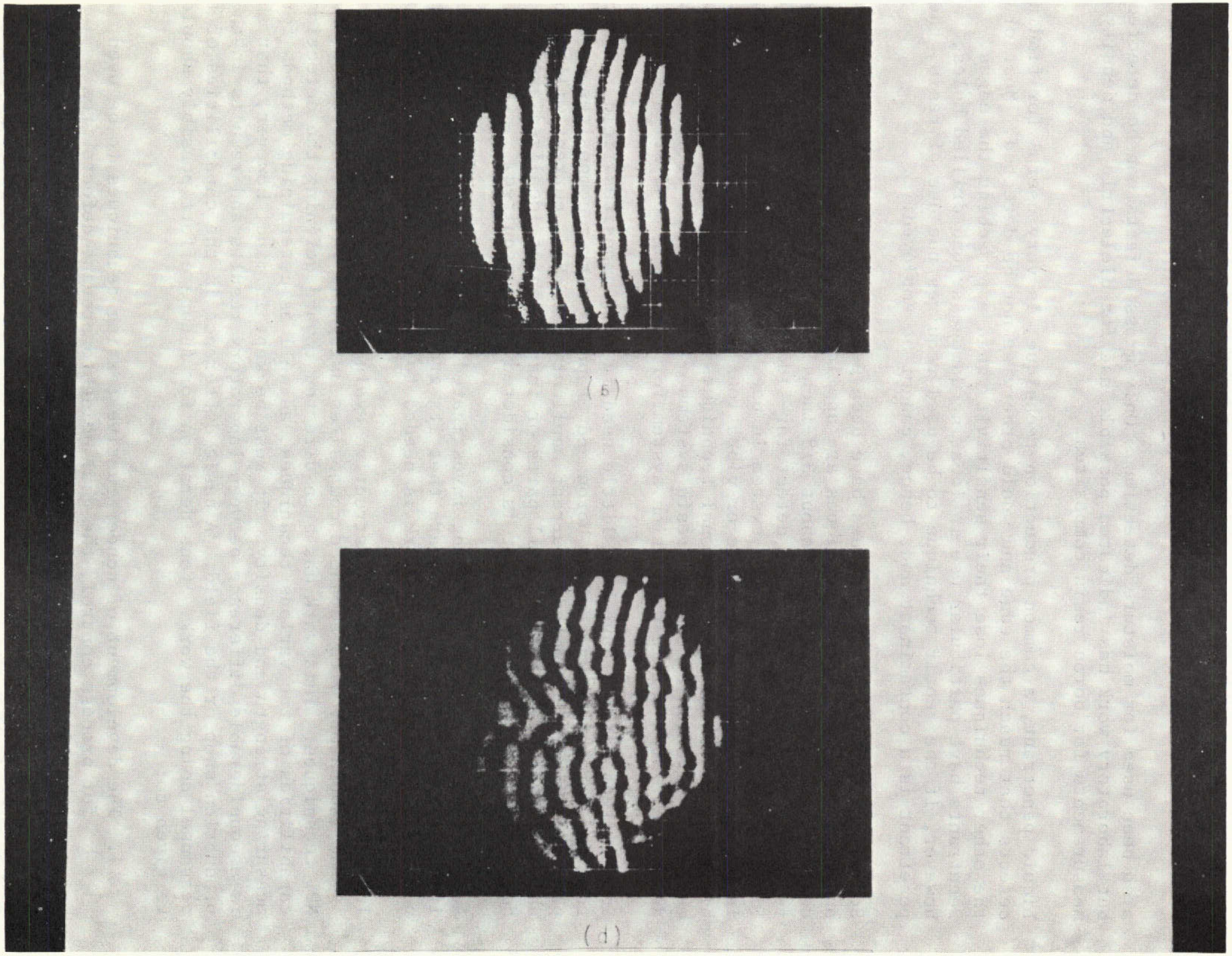

Figure 6.

also been used for moisture detection. Only gross defects can be detected, but laboratory work has indicated possible use for dielectric and density measurements for boron resin composites.

Liquid penetrant, a common production technique, is very useful for finding defects that reach the edge and would otherwise not be detected. Most of the other techniques lose their sensitivity when approaching the edges. Penetrants have particular use in locating damage around drilled holes; however, if the repair technique to be used requires the use of resin, the penetrant is a contaminant and, hence, cannot be employed.

Sonic, or vibrational, techniques have been used extensively in production and in the field. These techniques are applicable for detecting gross defects, voids, and disbonds--about 3/8-inch in diameter and larger. Some techniques have the ability to detect far-side defects in sandwich structures. Figure 7 shows a typical sonic system in use. Note that no liquid couplant is required. Many of the sonic or vibrational techniques have this capability. Studies using vibrational techniques have shown the possibility of measuring strength of certain resin systems. Part complexity still inhibits development of a usable production system for measuring bond strength.

Eddy current methods have been little used in the composites field. Laboratory testing has shown certain boron and graphite matrix composites to be possible candidates for eddy current applications. Eddy current will probably be more applicable to small parts or inspection of localized areas. However, additional development is considered to be required.

Acoustic emission is still being investigated in the laboratory to determine its test application. It appears that its greatest value will be for field nondestructive testing, but work is needed to develop practical applications.

In summary, considerable nondestructive evaluation work has been accomplished in the laboratory with advanced composites using the various aforementioned NDT techniques. This work has been directed toward defining the detection capabilities of the various techniques, as well as determining methods for measuring strength and density. It must be kept in mind, however, that there is a considerable difference between laboratory results and results in the production shop or the field. A basic difference is the capabilities of the personnel doing the work. Consideration for future effort possibly should be given to:

1. The development of nondestructive testing techniques to be used for process control, the goal being to prevent defects from occurring or to detect them early enough in the process to enable easy correction.

2. The need for standards, which is very noticeable. Processing defects normally expected under production and field situations

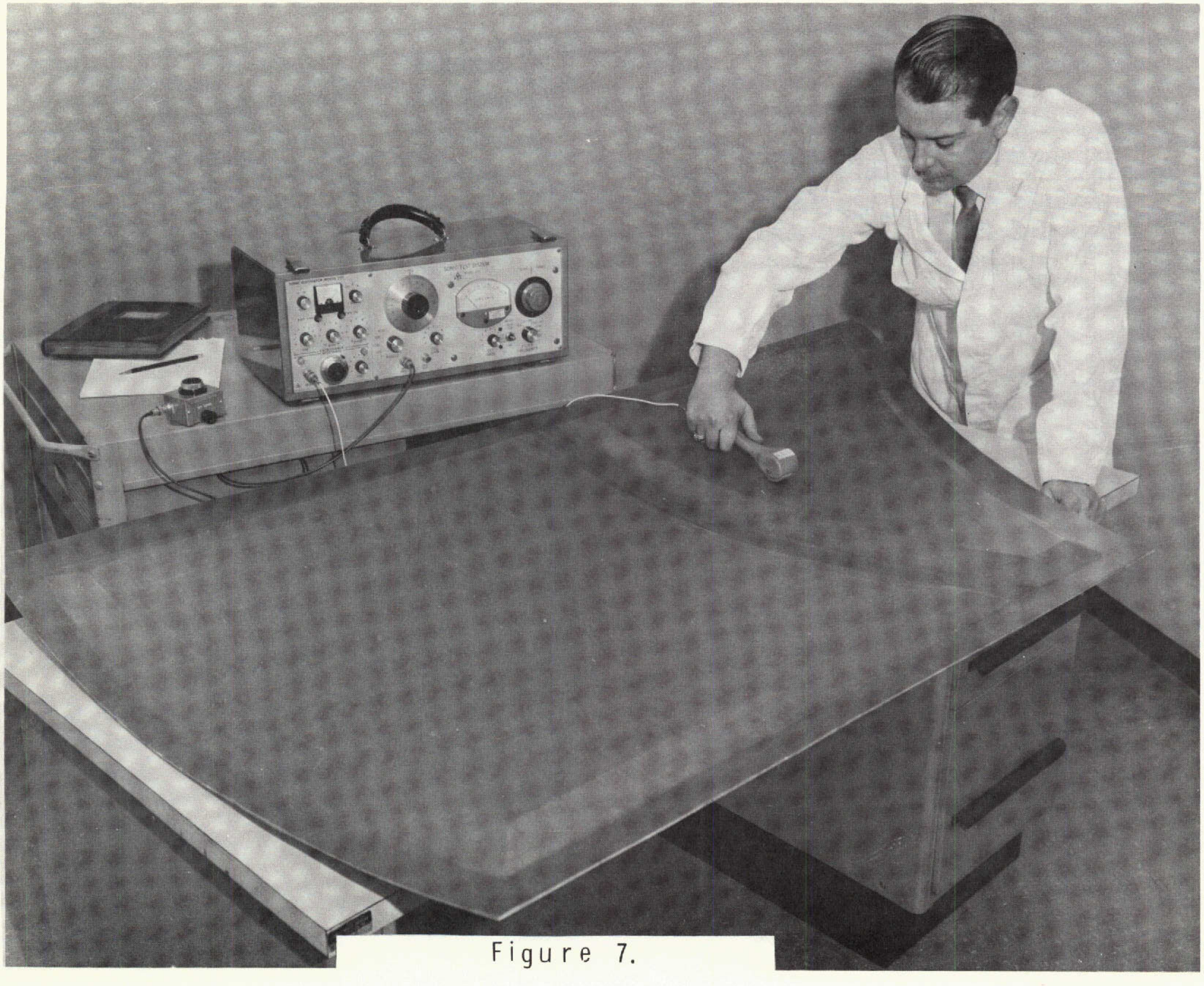

Figure 7.

should be developed into known standards that can be used to control the various testing techniques being used by all organizations.

3. The establishment and demonstration of production and field procedures for the specific applications of those nondestructive testing techniques considered the most promising. Production and field personnel should be used in the demonstration.

4. The development of high-powered transducers to overcome losses in the thicker laminates, and the development of dry couplant media to eliminate the need for water and oil. Figure 8 illustrates an elastomer material used as a couplant in the form of a tire on a roller probe. Figure 9 shows results obtained with this material as a couplant.

5. The development of systems with rapid scanning capability to speed up the inspection function. Perhaps a computer-controlled dispositioning system is the answer. Figure 10 shows the use of a computer to record the complex ultrasonic signals of a standard pulse-echo system. By use of the computer, the recorded ultrasonic signal can be recalled and analyzed, as shown by Figure 11.

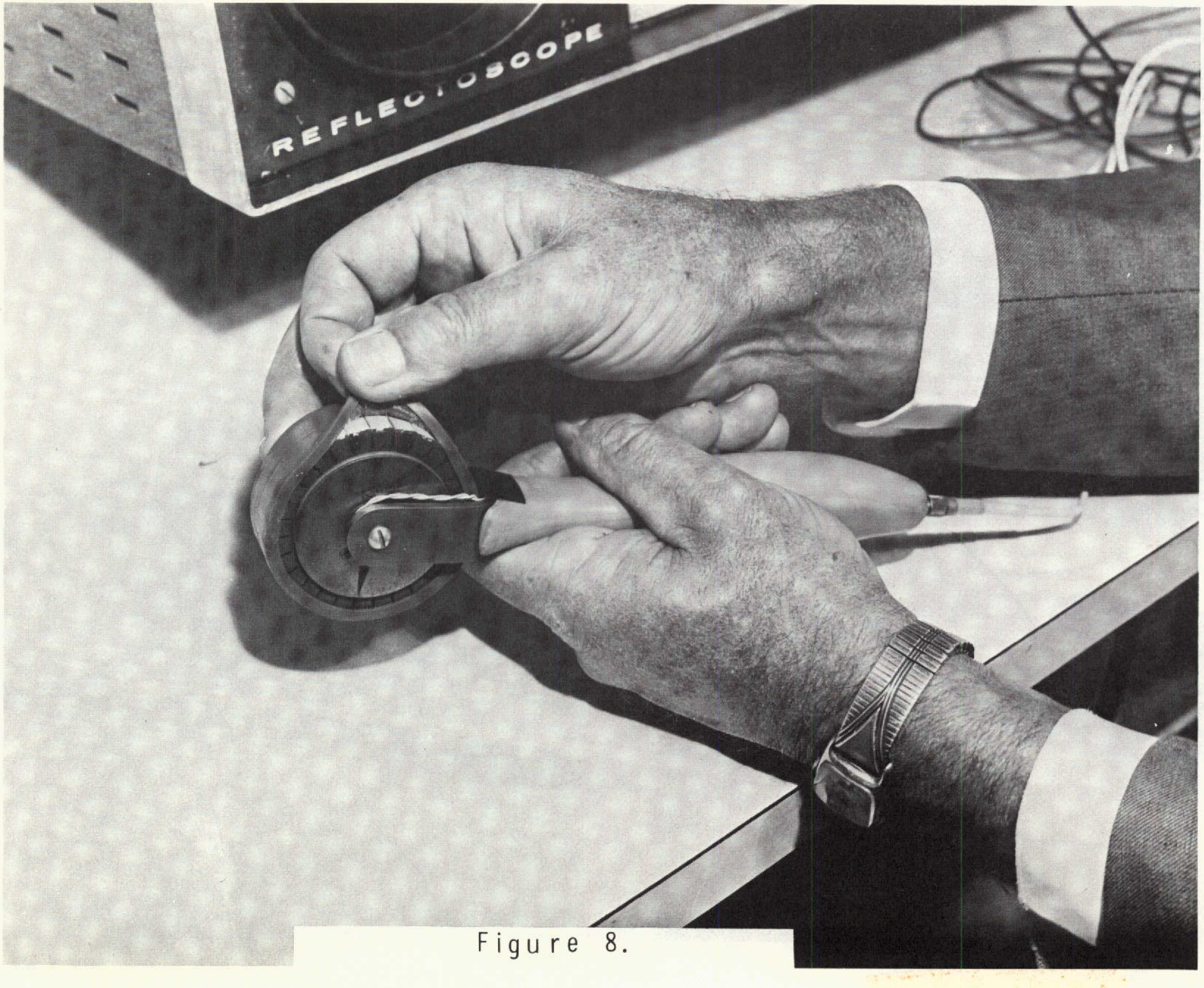

Figure 8.

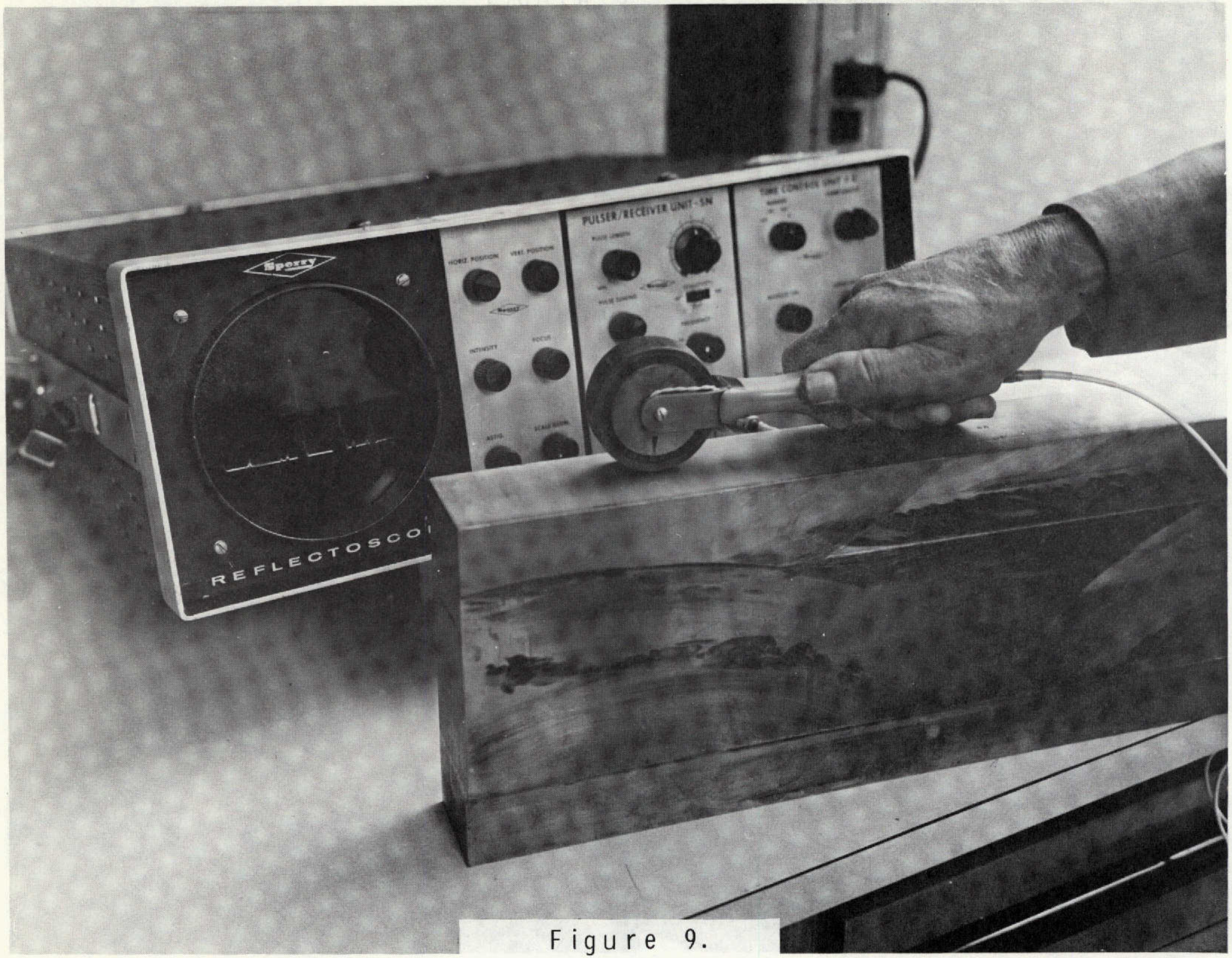

Figure 9.

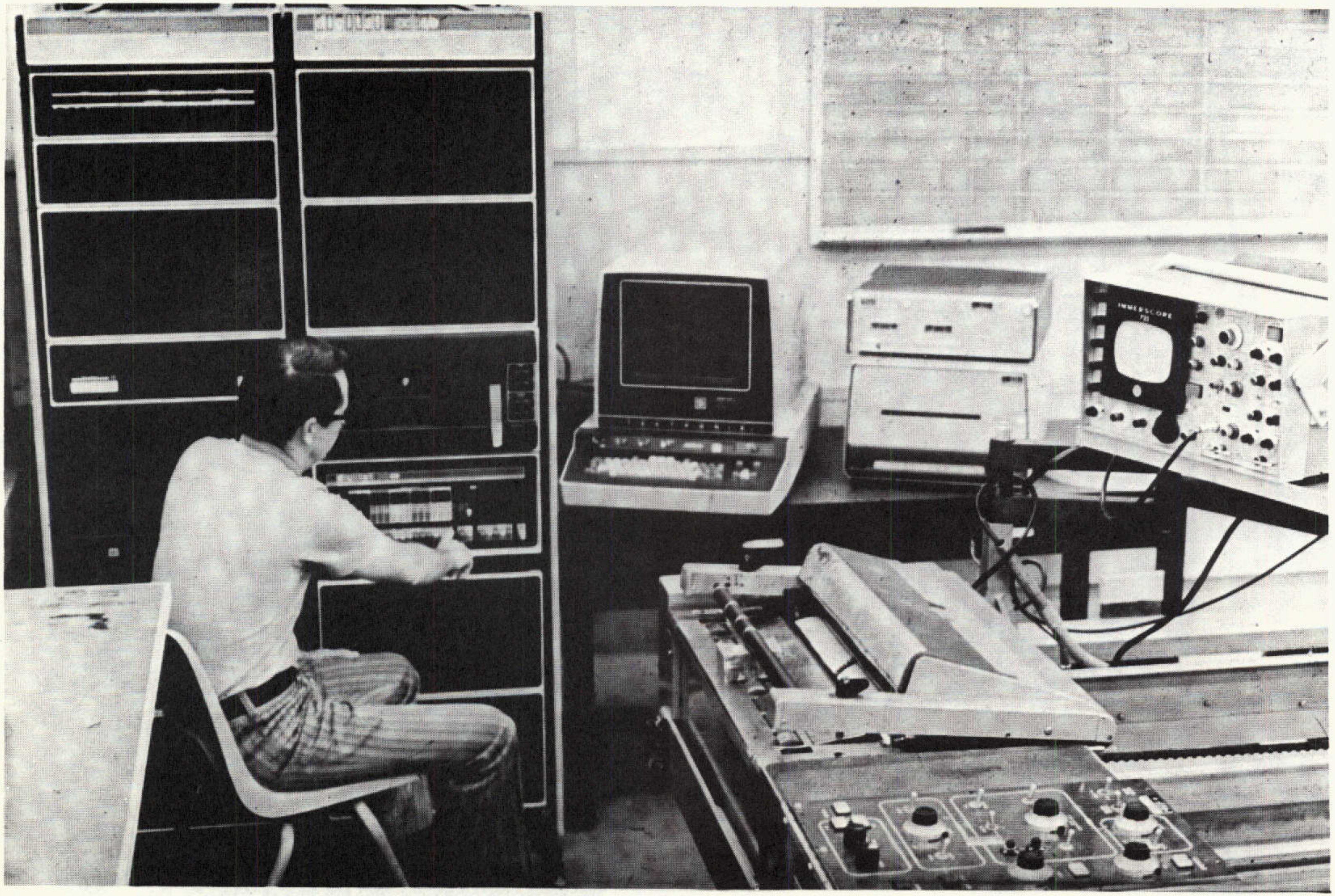

Figure 10.

Figure 11.

J. E. Ashton
NMAB - Dayton
February 1974

COMPOSITE DESIGN AND NDE

This paper presents an assessment of the composite designer's needs with respect to inspection and attempts to address the areas requiring further effort in NDE of composites, as well as to indicate areas that are well in hand. Subjects such as designing to allow inspection and to accommodate available NDE are not addressed since the need for such design approaches is obvious and primarily a matter of good design practice and communication with inspection personnel. The author thus has little to suggest that would be constructive in this area.

Three general areas of inspection requirements will be addressed:

1. Raw material and in process
2. As fabricated and
3. In service

Raw Material and In Process

A designer is interested in inspecting the raw material for a part and in inspecting the fabrication process at intermediate points for two reasons. Firstly, as a matter of economics, he would like to eliminate poor materials and poorly fabricated parts with a minimum amount of value added. Secondly, given the present state-of-the-art for inspecting completed articles the best available approach to insuring the quality of completed articles is often tight acceptance and process control. The present inspection capability appears reasonably adequate for the above needs. For most fibrous composites we have acceptance testing which is adequate to confirm the quality of the raw materials. Furthermore the normal "do it like the planning" inspection is reasonably acceptable for process control insofar as we understand the variables to control. As part of this process control, standard practices utilize a significant number of process control specimens which are destructively tested to confirm that the processing parameters used on the part were appropriate. This use of process control specimens provides useful information and serves as a good quality check as long as the specimens are themselves carefully designed. For example, a laminate that tapers from 100 plies at a root end attachment point to a few plies at the outboard end may require several tab specimens of different thicknesses for reasonable process verification since the different thicknesses respond differently to process variations.

As Fabricated

Except for the economic issues addressed above the designer actually only requires that the part as fabricated has the properties with which it was designed. Thus in the case of composite laminates the designer needs to be able to confirm that the laminate has the strength and stiffness represented by his allowables. He would like to be able to confirm this directly by nondestructive evaluation of the fabricated laminate rather than by total dependence on doing it right (I. E., good process control). Unfortunately the present capability for NDE of composite laminates does not allow such a direct determination of strength. We can find discontinuities in otherwise continuous media, that is, we can find voids and delaminations. If the voids and/or delaminations are large enough or numerous enough, that is, if the inspection reveals that the part is "bad enough," the part may be rejected since the voids and delaminations are an indication of poor processing. However, in many cases the voids or delaminations cannot be shown to be harmful by themselves and in other cases a badly processed laminate that is understrength may not posses significant voids or delaminations. The techniques we use depend upon finding an anomaly in the propagation of some elastic response. If the medium remains continuous (does not have voids or delaminations) no apparent anomaly is likely to be found. In light of the above observations it should be apparent that a fruitful area for research is in the determination of low strength but fully bonded laminates. This, of course, is the same problem which has plagued adhesively bonded joints for many years. In this author's opinion, this area of research offers considerably more promise than further attempts to improve our ability to discriminate smaller and smaller voids and delaminations.

In Service

The designer's needs relative to in-service inspection is for some a way to confirm that composite parts do not suffer significant degradation during their useful lifetime. In this respect we have largely uncharted waters. Essentially our problem is that we don't know what sort of degradation of strength reduction that we should inspect to find. To clarify this view, I will discuss a few observations of composite behavior.

The fatigue behavior of advanced fibrous composites is quite unlike that of high strength metals. In an unnotched condition, composites exhibit quite flat S-N curves with fatigue lives of 10^7 cycles above 70% of static ultimate. When the same composites are fatigue tested with holes or sharp notches they exhibit even less fatigue damage. In fact, although the static strength may be reduced 20 to 40% with a notch, this strength is usually maintained over 10^7 cycles. Furthermore, when a notched composite specimen is fatigued a small number of cycles the residual strength of that specimen is increased well above the static strength before fatigue (Reference 1).

Many investigators have done research in the area of composite fracture during the last few years. This research has shown that the fracture behavior of advanced fibrous composites with holes and notches can be reasonably pr dicted using linear elastic fracture mechanics. This research has been quite helpful in understanding the behavior of these composites. However, it also seems it has intensified efforts to detect discrete cracks or flaws within these composites so that critical cracks might be detected in-service before a service failure. The author believes the results of the fracture research should lead one in a different direction. As an example, K_{IC} for a $[0\pm45/90]_s$ Boron/Epoxy laminate has been represented as approximately 36,000 psi $\sqrt{in}$ several researchers. Using a relatively high limit stress value for this laminate of 30,000 psi the critical through crack length at limit is approximately 0.9 inch. Such a very large critical flaw size hardly makes one concerned about sophisticated detection methods for discrete defects. If we add to this observation the observation cited above concerning residual strengths (which implies a lack of crack growth but rather crack "blunting") one is led to the conclusion that critical discrete flaw detection is easy in advanced fibrous composites, at least when using typical laminates and typical working stresses, because composites are inherently fracture resistant.

One other conclusion that leads from the above observations is that a proof test of a composite laminate can be a very effective screen since the proof test confirms that the part can safely rake at least that much load and the fatigue life will be very large at any smaller loads. The nearly perfect elastic behavior of composites also removes any concern with high yield deformations and development of "plastic hinges" during high proof loadings.

The above discussion indicates that if a composite laminate is fabricated acceptably, discrete damage in-service should not be a major detection problem. What then do we need to inspect for? This question does not have a clear answer. That is, we do not know of any specific degradation to expect in nominal strength (no discrete defects), yet without an extensive experience base we cannot conclude positively that no degradation will occur. Consequently, an inspection method that could identify a degradation in nominal strength would greatly enhance our confidence in applying these materials for long-term applications. One near-term solution may be to monitor the strain response of critical parts by built-in gages. It is unlikely that strength changes will occur independently of stiffness changes. The alternative appears to be the development of sufficient testing and in-service experience to provide confidence that such nominal strength degradation will not occur.

Applications

As a first example of the kind of inspection procedures deemed appropriate, Boron/Aluminum tubes that will be utilized on the Space Shuttle Orbiter as compression struts will be briefly described. These tubes are unidirectional B/Al tubes with integrally diffusion bonded titanium end collars. After the tubes and end fittings are fabricated the bolt attachment clevis is welded to the tubes collar. The quality control procedures that are planned for these tubes are as follows:

1. The material is being procured to specification minimums for strength and stiffness which will be verified with load tests and a volume percent determination.

2. In Process. Dimensional checks will be provided on both the tooling and the parts. Inspection of the layup procedure is called out in the planning. The titanium to titanium weld will be verified before and after setting up the welding machine each day.

3. Proof Test. Each tube will be tested to 120% limit tension and compression before being used. This proof test should be adequate to show the process was performed essentially correctly. Having passed a proof test at 120% of limit, fatigue results indicate a virtually infinite life time at limit stresses and below, for the tube wall and diffusion bond.

4. In-Service Inspection. The only in-service inspection that should be required for these tubes is an occasional visual examination. This inspection should be adequate since the limit stresses to which the tubes are designed are such that a notch or discrete defect that is large enough to lower the limit properties on the tubes should be easily seen. The titanium end fittings will need to be inspected carefully since they are designed conventionally. The weld area, however, is very conservatively designed (45 KSI ultimate).

As another example, Convair has recently completed the design of a graphite/epoxy wing box for our Model 200 Navy V/STOL aircraft. This airplane is a delta canard configuration. The delta wing is naturally redundant and a relatively low stress level design is inherent. The details of this design are reported in Reference 2. For the present discussion, the conclusion of interest is that the limit tension stresses for the optimized design are well below the 10^7 cycle run out strength of the material <u>with a hole</u>. This sort of design in composites results in virtually no non-visual inspection required in the field and in a virtually infinite life-time for the wing skins. Except for the elusive problem of nominal strength degradation alluded to above, no future NDE procedures appear needed for in-service inspection of such wing skins.

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Conclusions

Fibrous composite materials have a very good fatigue resistance and are inherently resistant to discrete flaws. These observations lead one to conclude that we do not need to dwell on the development of finer discrimination of discrete defects in these laminates. On the other hand, composite laminates can have strengths significantly below nominal without any observed discrete defects. We cannot at the present time identify such off-normal laminates nondestructively. For both of these potential applications of NDE (discrete defects and off-nominal strengths), we first need to define what damage or degradation is, and then determine methods to find it.

References:

1. Halpin, J. D., Jerina, K. L., and Johnson, T. A., "Characterization of Composites for the Purpose of Reliability Evaluation," Analysis of Test Methods for High Modulus Fibers and Composites, ASTM STP 521, American Society for Testing and Materials, 1973, pp. 5-64.

2. Wennhold, W. F., "Conceptual Design of Navy Wings," CASD-NSC-73-006.

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QUALITY ASSURANCE AND PROCESS CONTROL OF STRUCTURAL COMPOSITES

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INTRODUCTION

Quality assurance and process control have important roles in the production and use of structural composites. The relative newness of composite structures and limited service experience as compared to metal structures makes the use of proven quality assurance and process control procedures a necessity. This helps provide confidence in the use of structural composites.

DESCRIPTION OF COMPOSITE STRUCTURES

The quality assurance and process control procedures applied to production structural composites is discussed. McDonnell Aircraft Company is manufacturing composite stabilator and fin torque boxes, and composite rudders for the F-15. These are all full depth honeycomb structures with boron/epoxy skins. In addition, under Air Force contract, a composite static test wing is now being assembled and a flight test composite wing is planned.

The configurations of and materials used in the stabilator and fin torque boxes are shown in Figures 1 and 2. Both use boron/epoxy skins with titanium frames, full depth aluminum honeycomb core, titanium spars, and fiberglass closure ribs at the tips. In Figure 1, note the areas where the geometry of the structure changes. Note the core splices and, in Section A-A, note the titanium steps in the skin, the skin-to-spar joint and the foam adhesive joint between the core and the spar. These changes in geometry are typical of what is encountered in actual structures. Most effort on developing and/or defining the capabilities of NDT methods fails to take into account such areas of changing geometry. When actual structures are produced, it is found that most discontinuities which need to be found with NDT occur in these changing geometry areas. Therefore, NDT development work done on simple, flat specimens is of little value when it comes to solving problems in NDT of actual structures. Future investigations on NDT should be applied toward providing useful information for the NDT of production structures and must take into account typical changing geometry areas.

The F-15 rudder assembly uses boron/epoxy skins reinforced with titanium splice plates in the areas of the titanium hinge attachment. Full depth aluminum honeycomb is used. Closures (ribs and spar) are fabricated from fiberglass.

Figures 3 and 4 show the F-15 flight test composite wing. Note the variety of geometries and materials in this structure such as the boron/epoxy and aluminum honeycomb core skins and the graphite hats, tees, ribs, and spars. The skins are fabricated in a single operation, cocurring the boron/epoxy and boron/epoxy-to-core bonds in one operation. The graphite parts are fabricated as details and then assembled to the rest of the structure. The hat and tee stiffeners are bonded to the skins.

DOCUMENTATION

In dealing with composites materials, it is important to initially establish engineering requirements for quality assurance and process control.

This is normally done as a cooperative effort by the structures, design, and material and process engineering personnel. It is their responsibility to define the quality assurance and process control requirements and issue documents containing these requirements. Principal documents are material specifications, process specifications, Engineering drawings, and detailed written NDT procedures.

To provide the proper NDT input for inclusion in these documents, it is necessary to perform a preliminary NDT analysis. This requires reviewing the preliminary engineering drawings and specifications and defining special equipment requirements to insure that the equipment is available when it is time to perform the test. It is also very important to design reference standards that can be used for performing the specific inspection. And last, but not least, this preliminary analysis should specify when to inspect the part.

Material Specifications

Material specifications are used to control all of the basic materials used to fabricate structural composite assemblies. Typical of materials controlled are the boron/epoxy prepreg tape, the aluminum honeycomb core, the titanium, and the adhesives.

The material specification will first define all the requirements the material is to meet. For example, for boron/epoxy prepreg tape, the minimum mechanical properties, the fiber and resin contents, and thickness per cured ply are specified. Next, the material specification outlines the qualification tests that a vendor must perform and submit the resultant data in order for his material to be qualified for a given specification. Often these tests will be run on several lots of material, and the data will be used as a basis for defining acceptance criteria for later vendor batch certification tests and incoming inspection tests. Typical batch certification tests that are specified for boron/epoxy prepreg tape include the thickness per cured ply, the resin content, infrared analysis of the resin, and determining the epoxide equivalent of the resin. Incoming inspection tests specified include mechanical property tests and resin content tests.

The material specification then defines in detail all of the test methods to be used for the qualification, vendor batch certification, and incoming inspection tests. Finally, preparation for delivery, and storage requirements are specified. For example, boron epoxy prepreg tape is required to be stored at 0°F, and records are kept of time out of 0°F storage.

Process Specifications

Figure 5 outlines the contents of process specifications. Process specifications are used to control both the fabrications and the NDT of structural composite assemblies.

The materials and solutions used in the process are specified and controls for the solutions are given. For example, make up and control of the titanium cleaning solution used for the titanium bonded to boron/epoxy is specified. Personnel qualification requirements are given. All bonding personnel are qualified by training and written examinations. NDT personnel are qualified in accordance with the guidelines of the American Society for Nondestructive Testing recommended practice SNT-TC-1A and applicable supplements. Requirements and controls for equipment, such as ovens and autoclaves used in bonding and ultrasonic and radiographic NDT equipment, are specified. Facility requirements are also included. For example there are bonding room controls prohibiting any machining or operation of internal combustion engines in bonding areas. Close control of the Ti cleaning facility is obtained by using a Ti cleaning facility exclusively for preparation for bonding.

The process specifications include the general procedures to be used for the fabrication and NDT of the composite structures. There will be technical requirements such as the dimensional and physical properties (verified by process control specimens) of the completed assembly. Figure 6 shows typical technical requirements from the specification for radiography of composite structures. The maximum kV's as a function of thickness for various materials are specified. It is important to keep the kV values relatively low as shown in the figure in order to obtain maximum subject contrast. It has been demonstrated that radiography properly applied at low kV's will find many types of discontinuities in complex geometry areas that are undetectable by other NDT methods.

In addition to procedures, there are defined in the NDT specifications bases for evaluation of indications. What the inspector is to be looking for is defined in detail. There are numerous types of discontinuities that can be encountered and are covered with descriptions and acceptance criteria. For example figures 7-10 show some of the discontinuities that can occur in the core of a composite structure. There can be various degrees of crushed, distorted, and condensed core. There can be blown core as shown in Figure 9. This can occur when a bag bursts, causing a sudden rise in pressure during the cure cycle. There can be discontinuities in the foam adhesive at core splice joints. Figure 10 shows a section through a core splice joint with a lack of adhesive in the center of the foam bond. Each type of core discontinuity has a different structural significance; acceptance criteria

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must therefore be defined for each type.

Acceptance classes or grades are defined in the NDT process specifications in order to assist the design or structures engineer in calling out the specific acceptance criteria for a given part. This eliminates the need for drawing the various flaws that can be tolerated on the drawing for each part. The design or structures engineer need only reference the process specification defined acceptance classes according to the requirements for each particular part. The chart shown in Figure 11 has been developed to define acceptance classes for unbonds and delaminations. The length and width of the unbonds are related to the different acceptance classes. For example, any unbond whose dimensions fall within the envelope defined by the class A line would be acceptable to class A. Any unbond falling outside the envelope would be rejectable.

The bases for evaluation of indications and the acceptance classes were generated by coordination between NDT, Strength, and Design Engineering personnel. It is important that these be defined in detail. If they are not, it ends up that the NDT technician decides the acceptance criteria. Without specific instructions, all he can do is guess at what is wanted. His choice may not be compatible with the real Engineering requirements for the part, and many types of discontinuities could be ignored.

In addition, the NDT process specifications require that detailed written procedure be prepared for each part to be inspected. There are such variations in part configurations that it would not be practicle to cover in a general specification all of the details for every part. The detailed procedures provide for consistent tests and help verify that the specifications are understood and are being worked to. Quality Assurance or Engineering NDT personnel prepare the procedures which are then reviewed for concurrence by the Quality Assurance Engineering staff. Typical information included in procedures is shown in Figures 12 and 13, taken from radiographic and ultrasonic inspection procedures for a composite tee stiffener. The radiographic procedure gives details such as the source-to-film distance, the kV's, ma's, exposure times, and exposure directions. Note the angulated exposures. This provides for coverage of the radius areas between the vertical member and the flange of the tee. Angulated exposures are effective on many different composite structural configurations. They can detect many types of discontinuities which are missed by exposures with normal (90°) beam direction.

Note in Figure 13 the ultrasonic procedure information such as the scan planes, search units, and test methods (thru transmission or reflector plate). The phenolic block is placed on the cap of the tee to prevent the ultrasonic energy from "spilling" around the edge of the cap. Without the phenolic block, even when using focussed search units with the focal points located at the sound entry and exit surfaces of the part, the area of the tee cap within 0.060 to 0.090 inch of the edge ends up a no test zone because of the sound spillover. Since the solid cap area is only 0.170 inch wide, it is important to test the entire width. Use of the phenolic block provides for this. Simple technique refinements such as this provides for more effective inspections.

Engineering Drawings

In order to ensure that the part is inspected in the required areas, it is the responsibility of the structural engineer to define the critical areas and see that this information is placed on the drawing. He must also

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establish the maximum allowable flaw size and reference the applicable acceptance classes. In addition, the Engineering drawing references the applicable material and process specifications and often will include a zoned sketch to indicate varying acceptance classes. A typical zoning is shown in Figure 14 which indicates acceptance classes for a stub wing skin. These classes are the classes defined in Figure 11. For this part, the class A zones are boron/epoxy-to-titanium splice plate bonds; the class B zones are solid boron/epoxy lands; the class C zones are boron/epoxy-to-honeycomb core bonds, and the class D zone is the outboard solid boron/ epoxy area.

PRODUCTION PROCEDURES

Next to be described are the quality assurance and process control procedures applied during the fabrication cycle used for the production of the composite stabilator and fin torque boxes. The skin assemblies are first fabricated, and then the completed skins are bonded to honeycomb core and closure assemblies.

Figure 15 illustrates the various process control and NDT operations applied during fabrication of the skins. First the titanium frame details are cleaned in a facility used exclusively for preparation for bonding. Process control specimens (lap shear) are cleaned along with the parts. In addition, the cleaned parts are checked for water break free surfaces. The titanium is then spray coated with adhesive primer. The dried primer thickness is checked to control the thickness in the 0.0001 to 0.0005 inch range using a special eddy current procedure covered by an NDT process specification. Since the dried primer is rough and has some resilency, multiple readings are taken and averaged and a spring loaded probe is used to obtain constant probe pressure. The eddy current readings are correlated to average thickness by set up on standards whose average thickness has been determined from weight measurements and density data.

Visual inspections, using a back lighted table, are preformed during the lay-up process to check for such things as excessive gaps or overlaps between tapes. Visual inspections are also performed when the plys are put into the skin assembly; orientation and fit-up is checked. The completed lay-up is bagged and then leak checked. Curing in an autoclave follows. Process control specimens are fabricated and cured right along with the part. Double lap shear specimens represent the boron/epoxy-to-titanium bonds. The boron/epoxy laminate properties are checked using sandwich beam specimens to determine longitudinal and transverse tensile strengths at room temperature and 350°F. In addition, one side of titanium lap shear finger panels, coated with a layer of adhesive, are processed along with the skins to be used in later process control tests to represent the titanium edges of the skins which are coated with adhesive and then, in the next stage of assembly, are bonded to the titanium spars. The completed skin is ultrasonically inspected to check for possible delaminations in the boron/epoxy or unbonds between the boron/epoxy and titanium. The immersion reflector plate C-scan method is used. Figure 16 shows a schematic of this test set-up.

The stabilator and fin torque box assemblies are completed by bonding the cured skins to aluminum honeycomb and titanium spar substructure assemblies. Figure 17 illustrates the process. The titanium spars go through the cleaning and priming operations with the same quality assurance and process control procedures used for the skin frame titanium. The assembly is first run through a verifilm inspection to check for proper tooling and fit up. The verifilm inspection consists of placing a plastic film (verifilm) in the assembly in place of adhesive. The assembly is then bagged and heated in an autoclave under pressure. The assembly is then taken apart and the resultant verifilm shows the fit up of the details of the assembly. Differences in fit up tolerance are indicated by changes in thickness of the verifilm. Any areas requiring extra layers of adhesive are noted. The details are then assembled with adhesive, bagged, leak checked, and then cured. Process control specimens include double lap shear specimens to represent the boron/epoxy-to-titanium bonds, single lap shear specimens to represent the titanium-to-titanium bonds, flatwise tension tests to represent the skin-to-core bonds, and beam shear tests to represent the foaming adhesive bonds within the core structure.

The completed assembly goes through ultrasonic and radiographic NDT. The ultrasonic thru transmission test is applied to the skin-to-core bonds. Focussed search units are used with the focal points located at the surfaces of the part. "Squirters" are used for coupling. The results are C-scan recorded. Double layer lead tape discs (3/8 inch diameter are applied to the surface for use as standards. It has been found by correlation with actual defects that when the instrument gain is set to print these to actual size, unbonds will also be printed at actual size. The skin-to-spar bonds and spar-to-core bonds are ultrasonically inspected using hand scanning. Penetrant emulsifier is used as the couplant. The "damping" test is applied to the skin-to-spar bonds. In this test, sound is sent through the bond and the operator damps the ringing signal of the cathode ray tube by applying his finger (couplant wetted) to the back surface of the bond. A ringing test is applied to the spar-to-core bonds. In this test, unbonds (separation of the foam adhesive from the spar) are indicated by an increase in ringing signal on the cathode ray tube. Prior to the ultrasonic tests, all edges of the part are sealed. This is to prevent couplant from flowing into any possible unbond which may be open to an edge. It has been shown that ultrasonic inspection will not detect unbonds or delaminations which are filled with couplant.

Radiographic inspection is applied to check for discontinuities in the core structure (for typical discontinuities, refer to Figures 7 through 10) verify proper fit up of the skins, core, and spars, and check for possible adhesive voids in the skin-to-spar bondlines. Radiographic exposure positions are identical for all like parts. This is assured by preparing a Mylar overlay which shows the locations of all films relative to the part. This overlay is then used to layout the NDT for all articles of the part. The layout of the ultrasonic standard discs and strips are also indicated on the Mylar. In addition to their use as ultrasonic setup standards, these discs and strips also aid in locating the radiographs to the part.

An additional part of the quality assurance and process control was the destructive test of the first article torque box. Mechanical properties were checked, the bond line thicknesses were checked, and the effectiveness of the NDT procedures was verified. In addition, selected areas from this first article were cut up, retained, and used for NDT standards.

REVIEW AND ANALYSIS OF DISCREPANT PARTS

An important part of quality assurance and process control is the review and analysis of discrepant parts. Discrepant parts are reviewed by design, strength, and material and process engineering, manufacturing, and quality assurance. Some of the parts are reworked, some are accepted as is, others are scrapped. Those parts that are scrapped end up getting into an NDT/DT (destructive test) correlation in order to determine if the requirements that have been imposed are satisfactory or if the requirements need to be changed. Drawings, manufacturing procedures, NDT procedures, process specifications, or acceptance criteria may be revised based on the NDT/DT correlation. This also provides an opportunity to verify or revise the detailed procedures as a result of the destructive analysis of parts.

NONDESTRUCTIVE INSPECTION

NDI (nondestructive in-field inspection) is required after the composite structures are installed on aircraft and put into service. It is necessary to identify the areas to be inspected, determine their accessibility and availability, select and develop the NDI techniques, prepare detailed procedures, perform the NDI, and report the results. NDI requirements and procedures are established in a manner similar to that discussed for establishing the NDT requirements and procedures.

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SUMMARY

This discussion of quality assurance and process control of structural composites has emphasized the procedures used on production composite aircraft structures. The importance of establishing and documenting detailed procedures, requirements, and acceptance criteria is emphasized. This requires close coordination of Design, Strength, Material and Process, and NDT Engineers, and Quality Assurance personnel. The quality assurance and process control procedures applied during the manufacturing cycle for empennage composite torque boxes have been described. A combination of process control tests and nondestructive tests helps provide reliable structural composites.

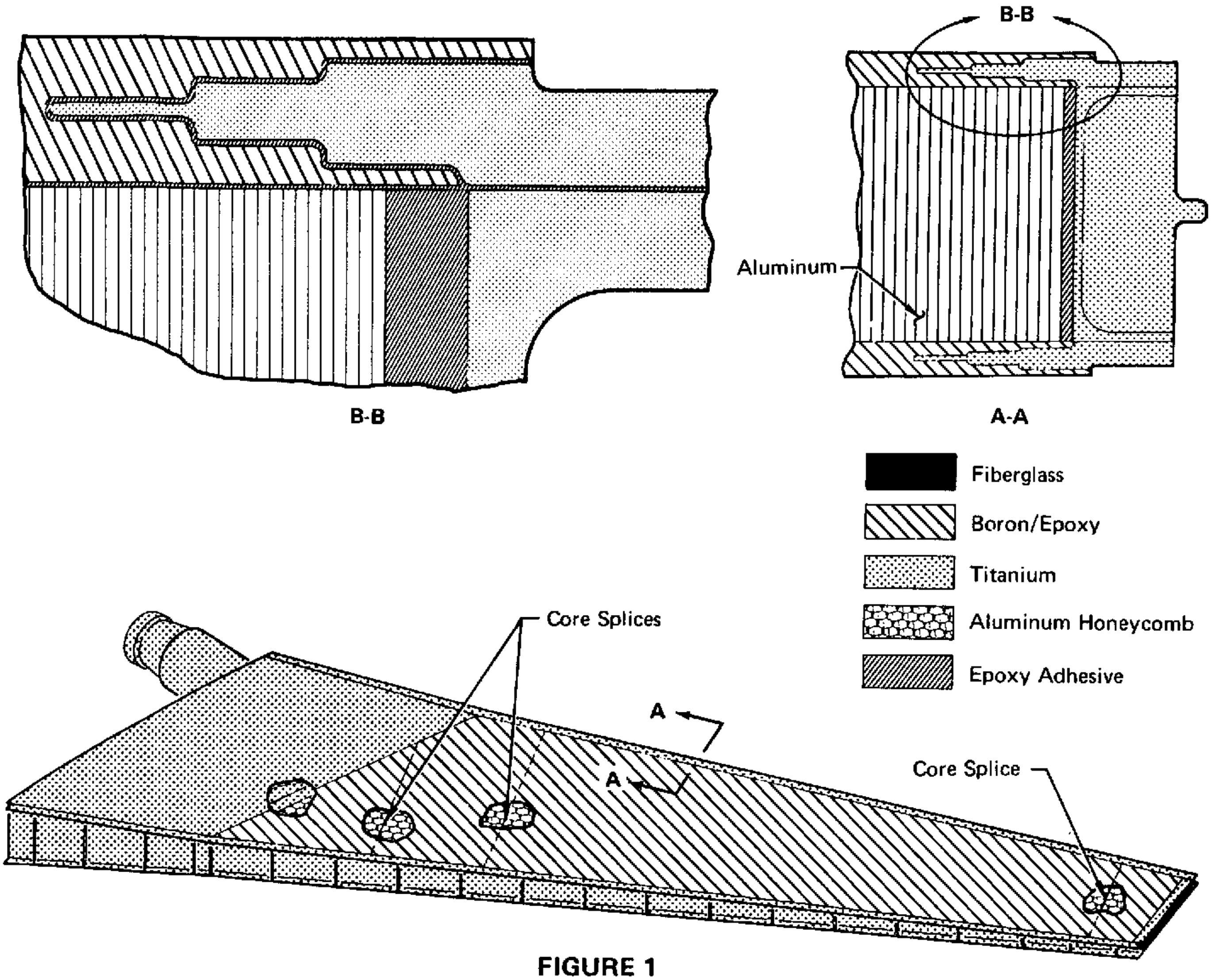

FIGURE 1
F-15 STABILATOR TORQUE BOX

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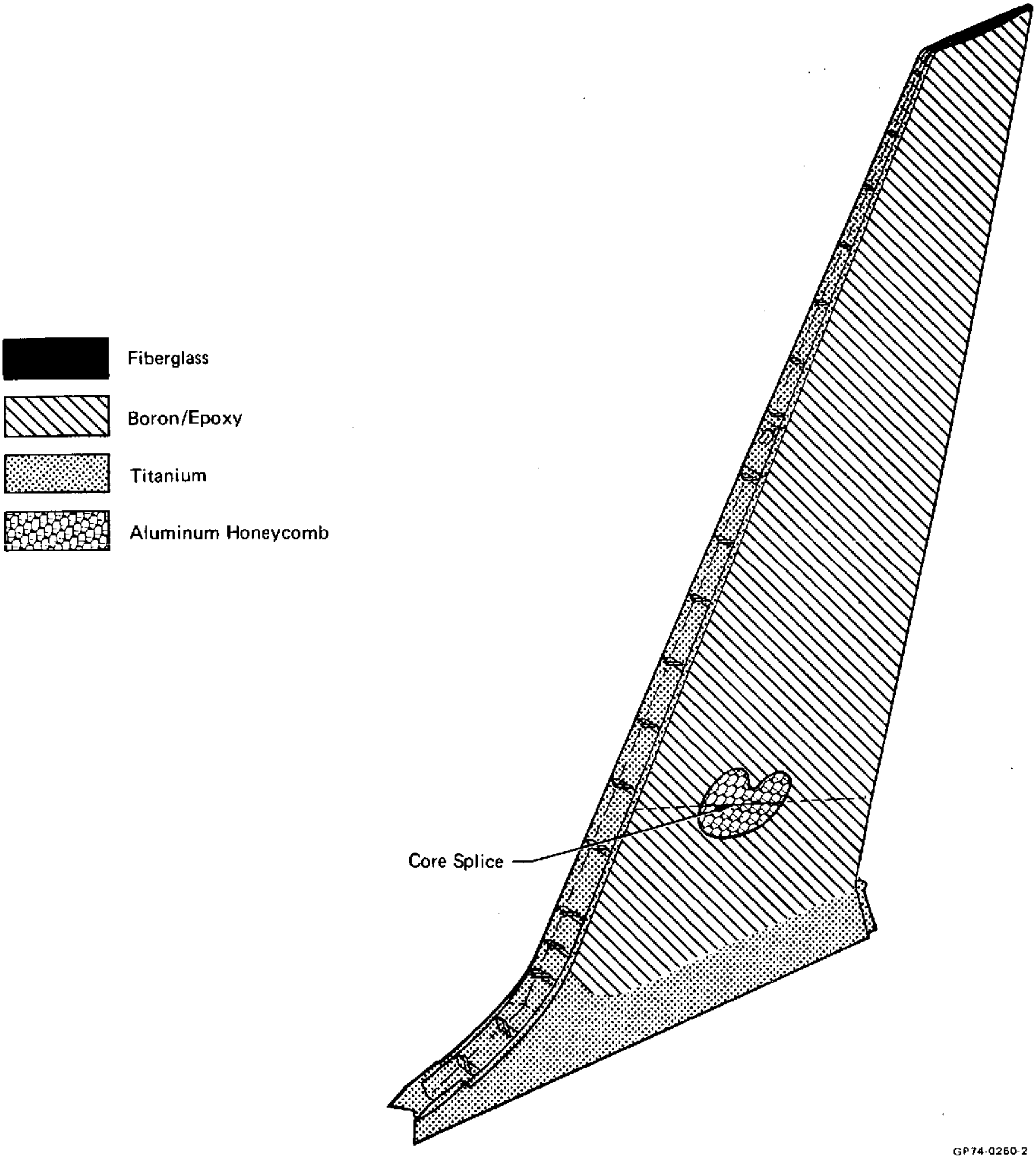

FIGURE 2
F-15 FIN TORQUE BOX

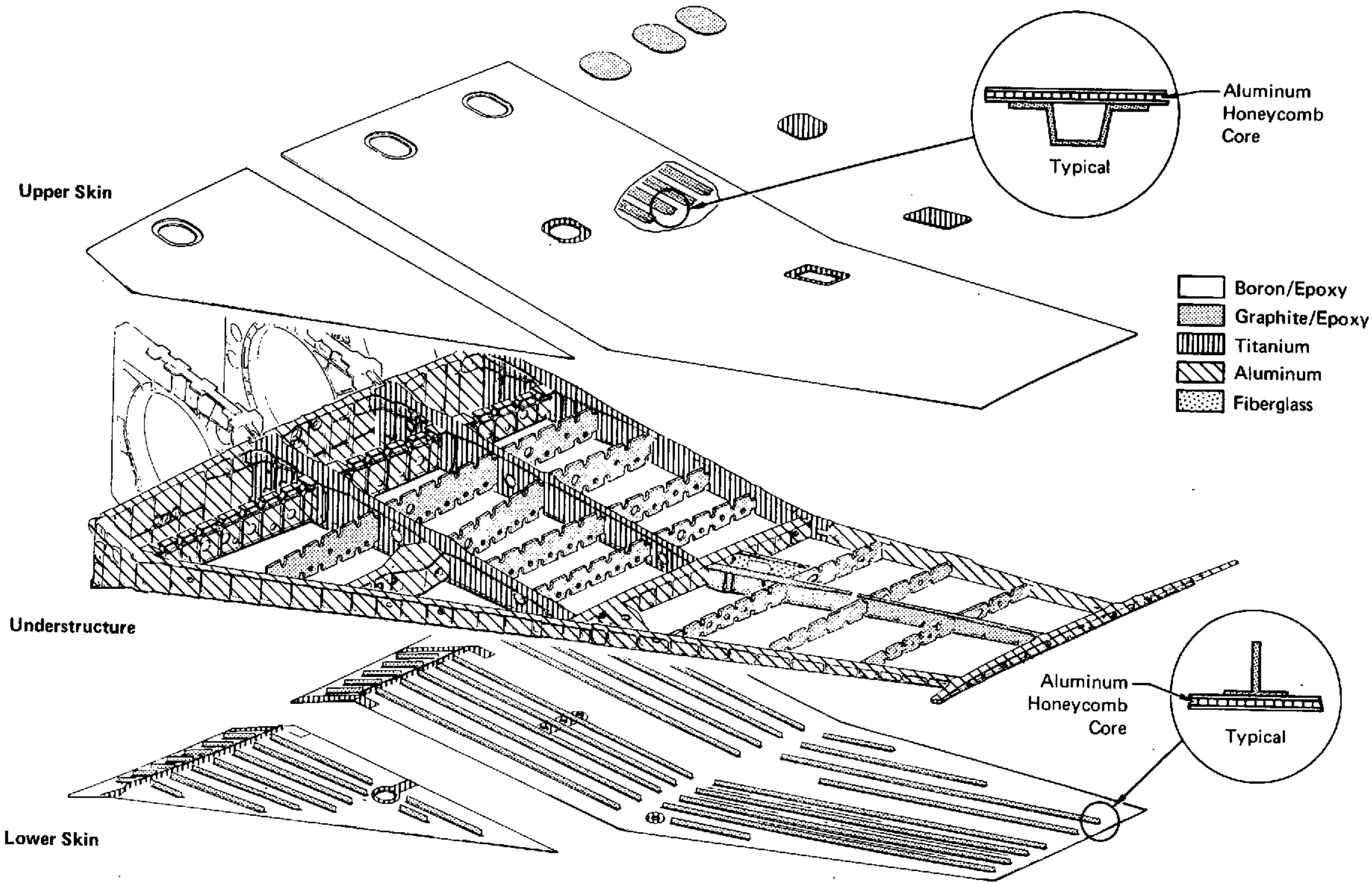

FIGURE 3
F-15 COMPOSITE FLIGHT TEST WING

GP74-0260 3

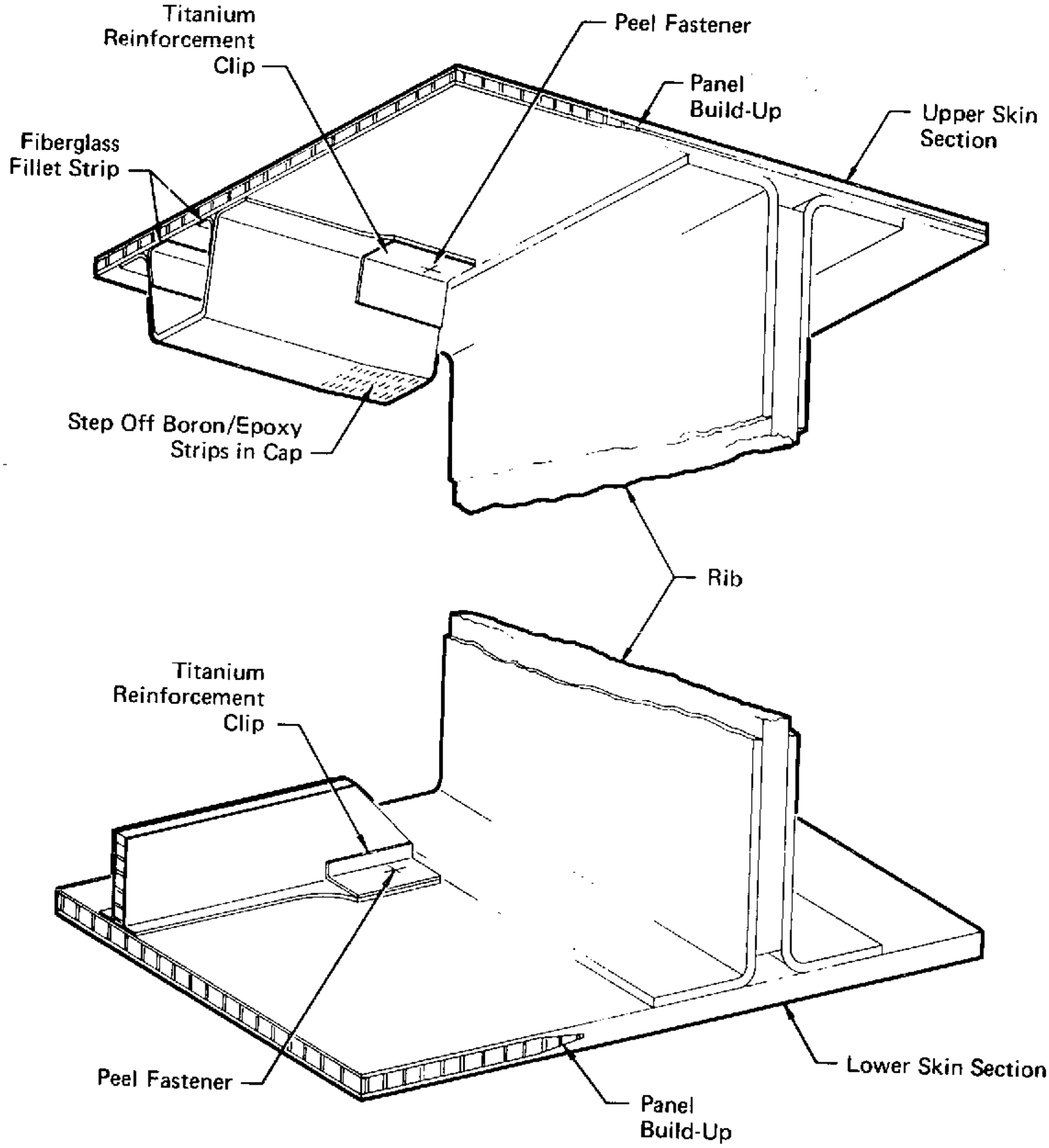

FIGURE 4
TYPICAL COMPOSITE WING CONFIGURATIONS

- Control of Materials and/or Solutions
- Personnel Qualification Requirements
- Equipment Requirements
- Facility Requirements
- Technical Requirements
- General Procedures
- Basis for Evaluation of Indications
- Acceptance Classes or Grades
- Detailed Procedure Requirements

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FIGURE 5
PROCESS SPECIFICATION CONTENTS

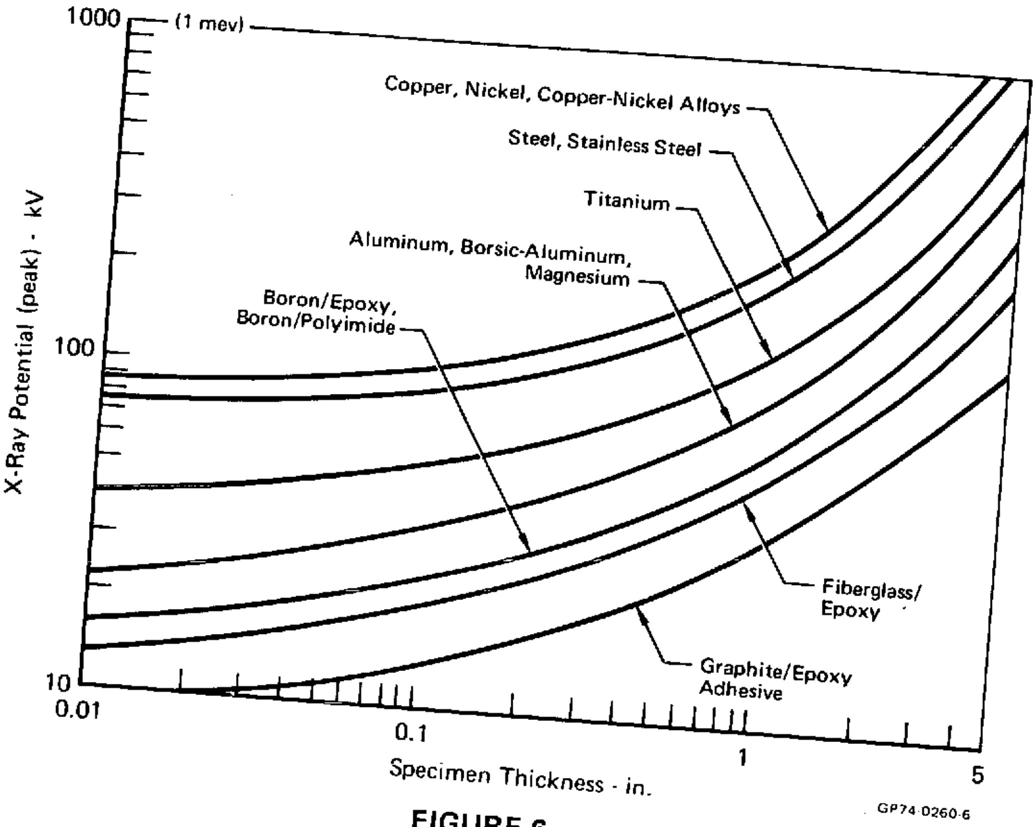
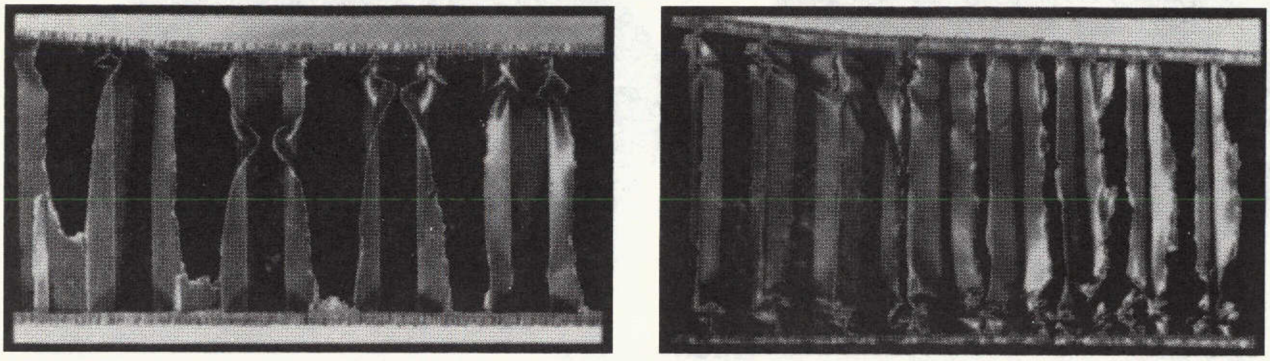


FIGURE 6
NDT SPECIFICATION REQUIREMENTS

Crushed Core



Distorted Core

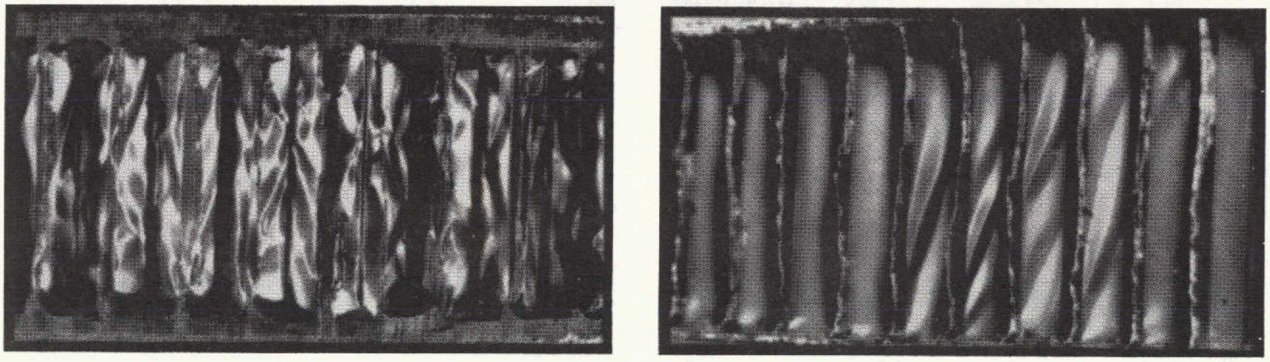


FIGURE 7
CORE DEFECTS

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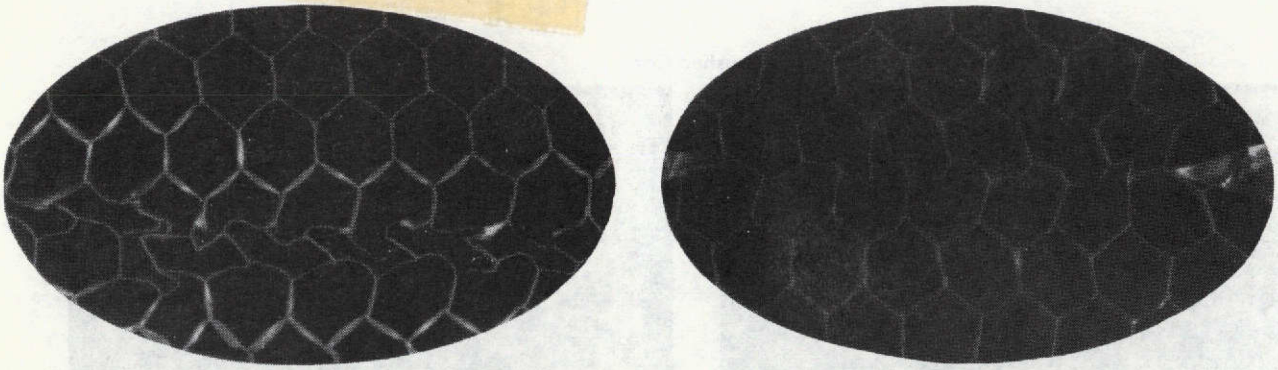

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FIGURE 8
CORE DEFECTS
(Condensed Core)

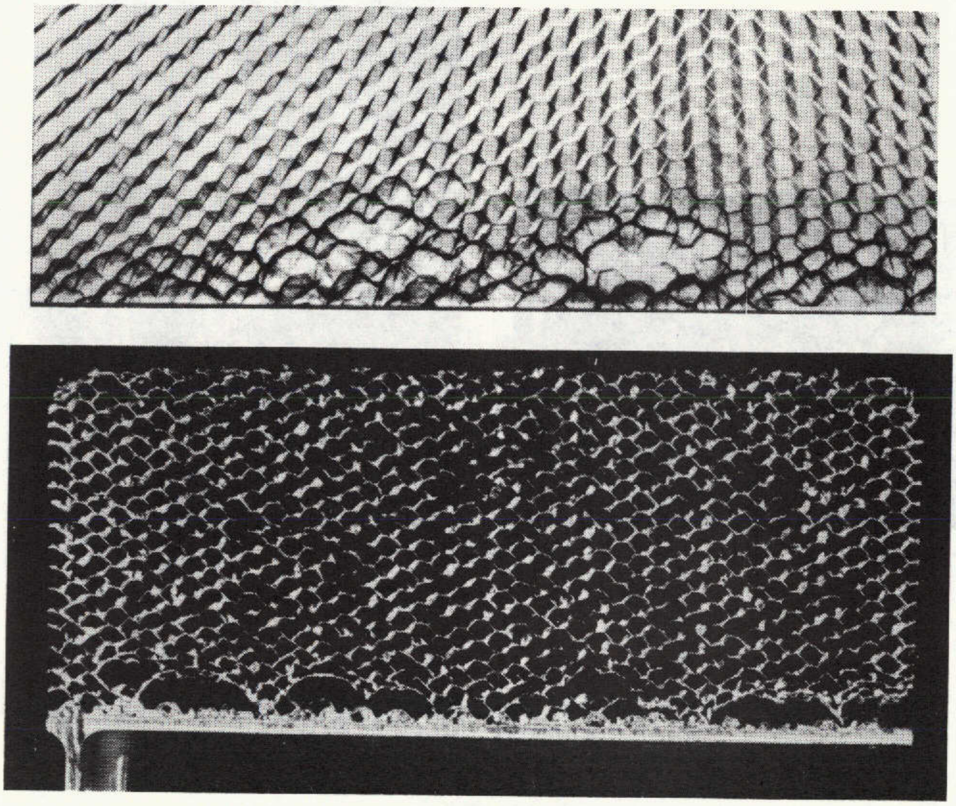

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FIGURE 9
BLOWN CORE

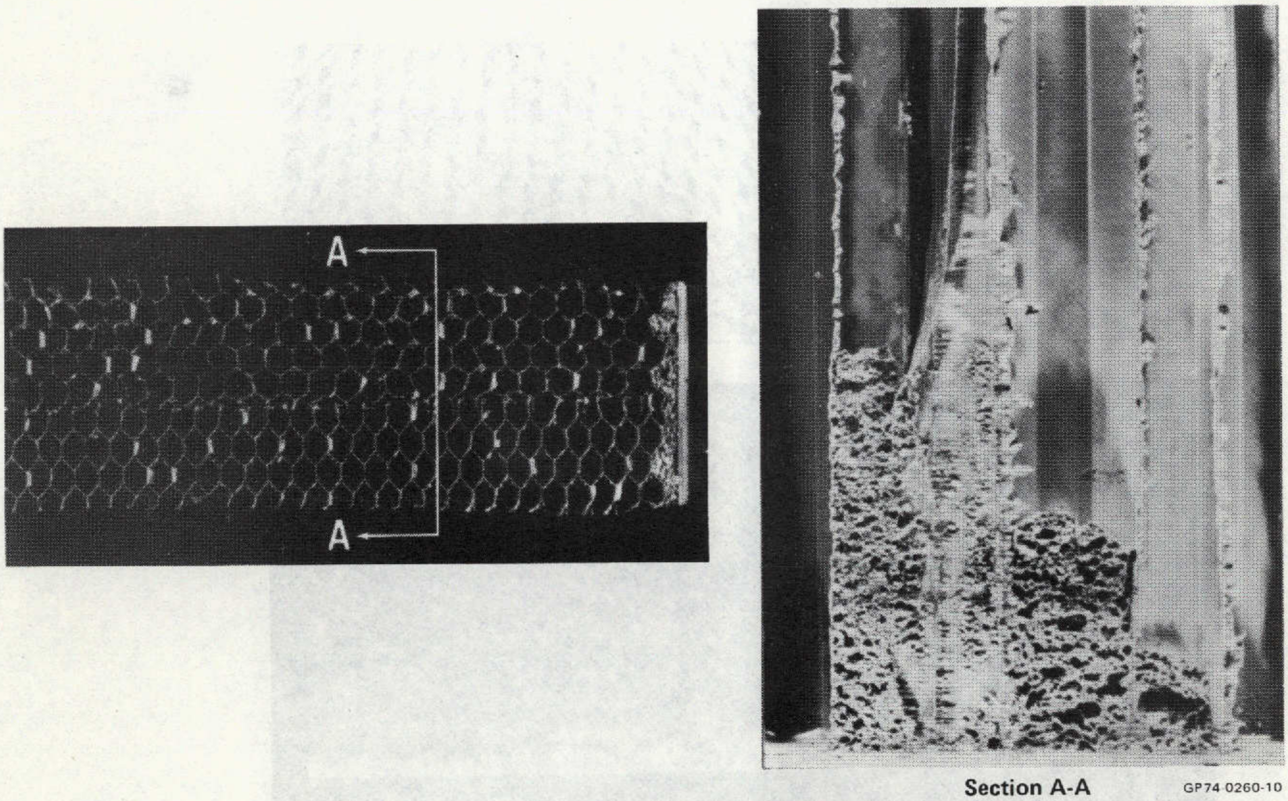


FIGURE 10
LACK OF FOAMING ADHESIVE IN CORE SPLICE JOINT

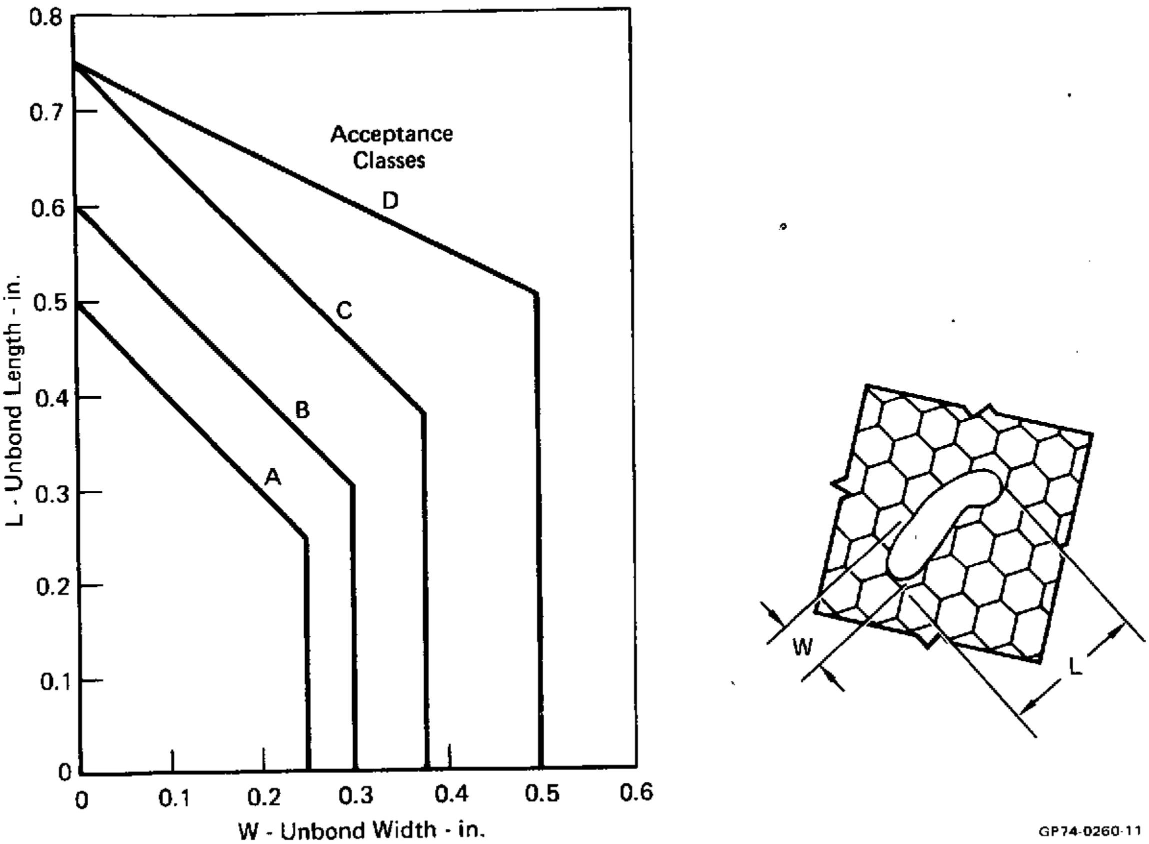
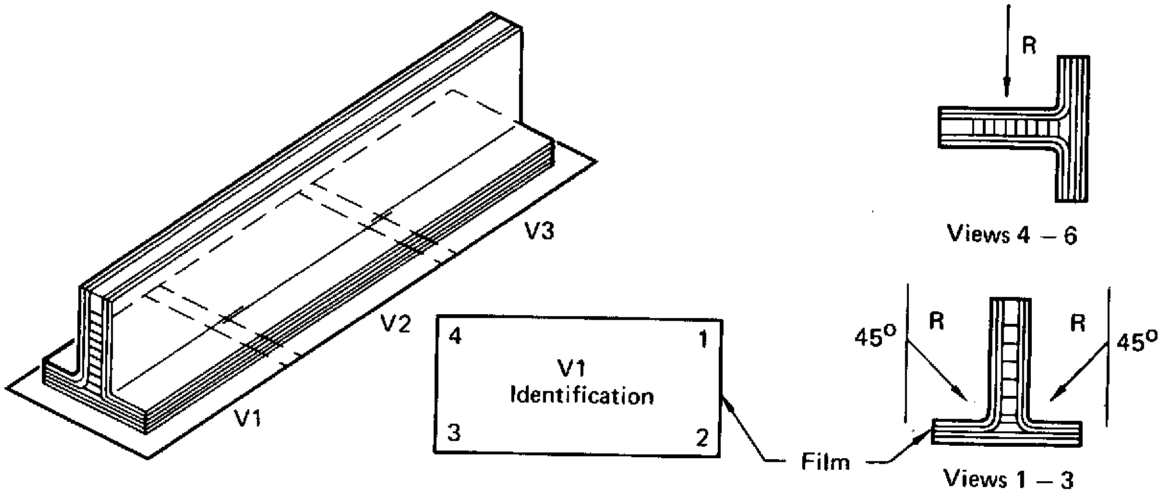


FIGURE 11
ACCEPTANCE CLASSES FOR UNBONDS AND DELAMINATIONS



View	Film Size (in.)	Film Group	Filter	Kilovolts Peak	Milliamps	Density	Exposure Time (min.)	FFD (in.)	Backup Material
V1-V3 $\pm 45^0$	7 x 14	1	BE Window	6	10	1.5 - 3.0	2.5	40	1/8 in. Lead
V4-V6	7 x 14	1	BE Window	10	10	1.5 - 3.0	2.5	40	1/8 in. Lead

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FIGURE 12
RADIOGRAPHIC INSPECTION OF A T-SECTION STIFFENER

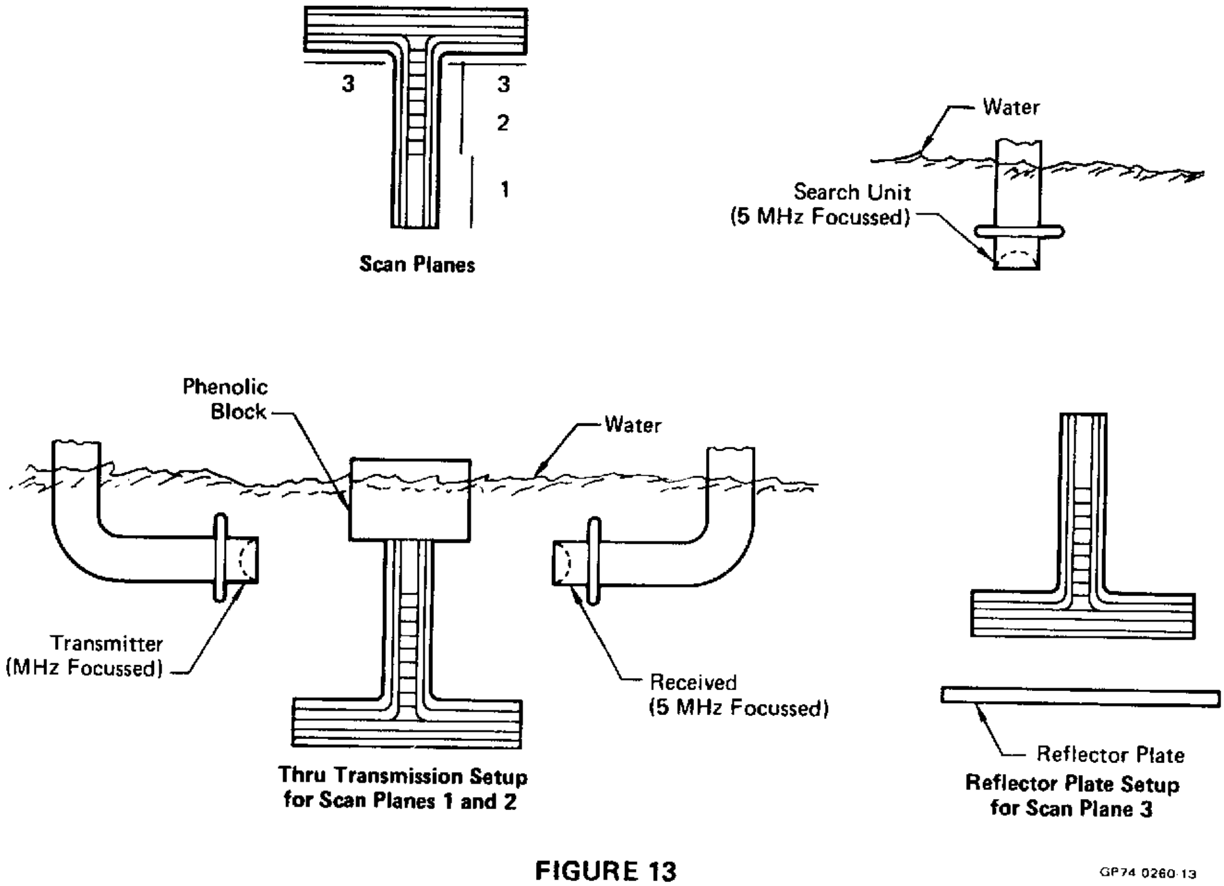

FIGURE 13
IMMERSION ULTRASONIC INSPECTION OF A T-SECTION STIFFENER

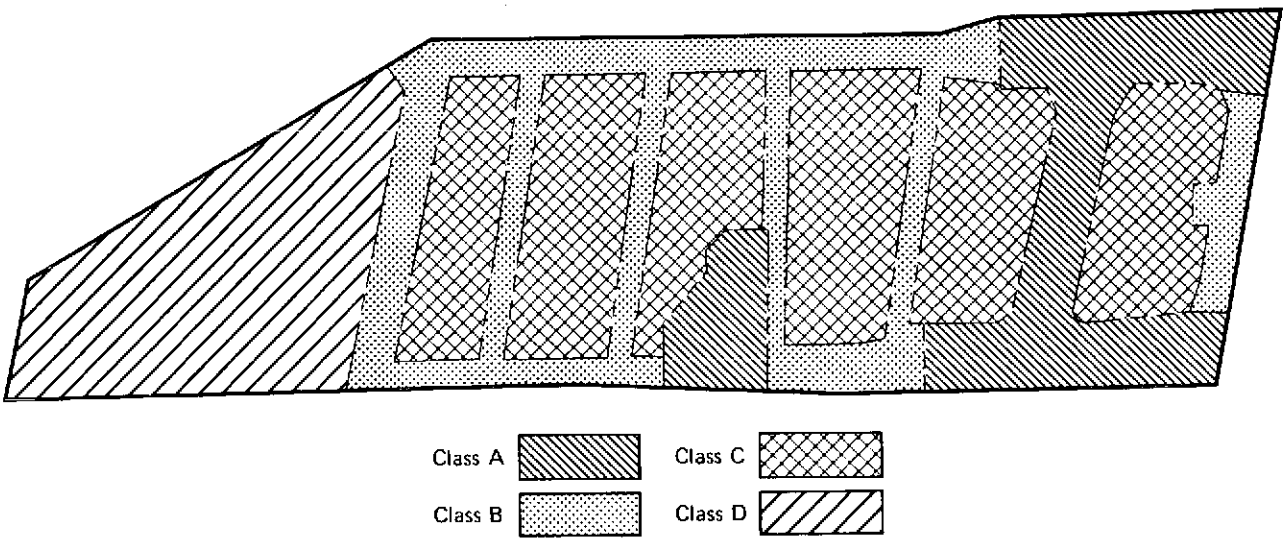

FIGURE 14
ZONING OF STUB WING SKIN

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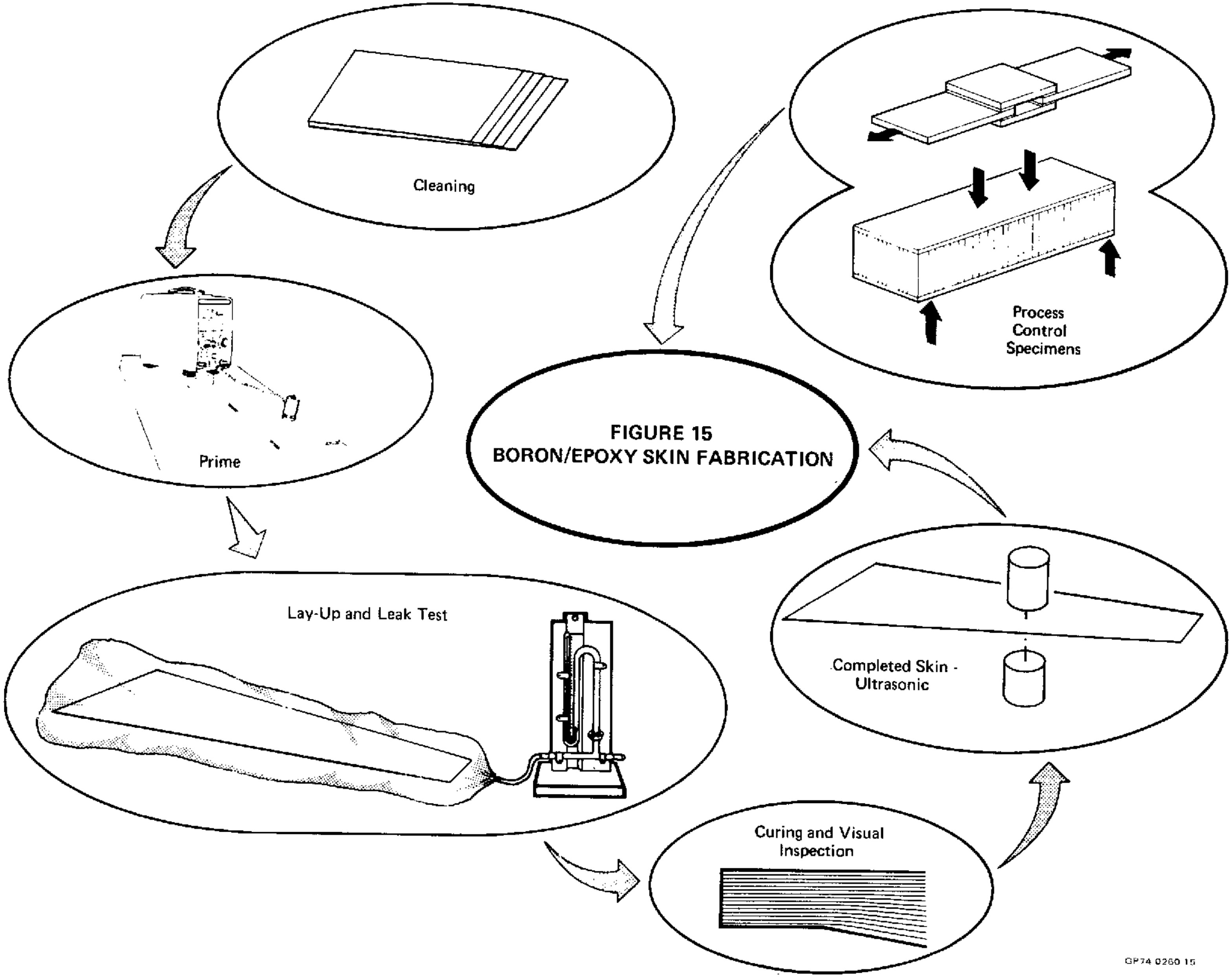

FIGURE 15
BORON/EPOXY SKIN FABRICATION

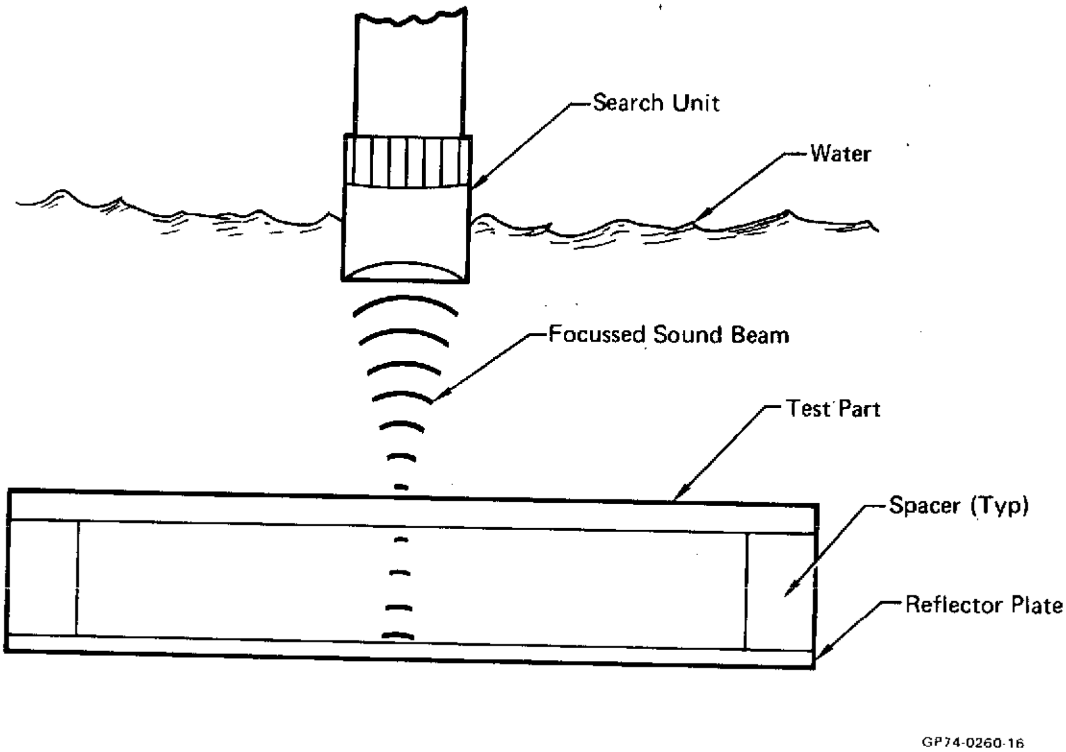

FIGURE 16
ULTRASONIC REFLECTOR PLATE TEST SETUP

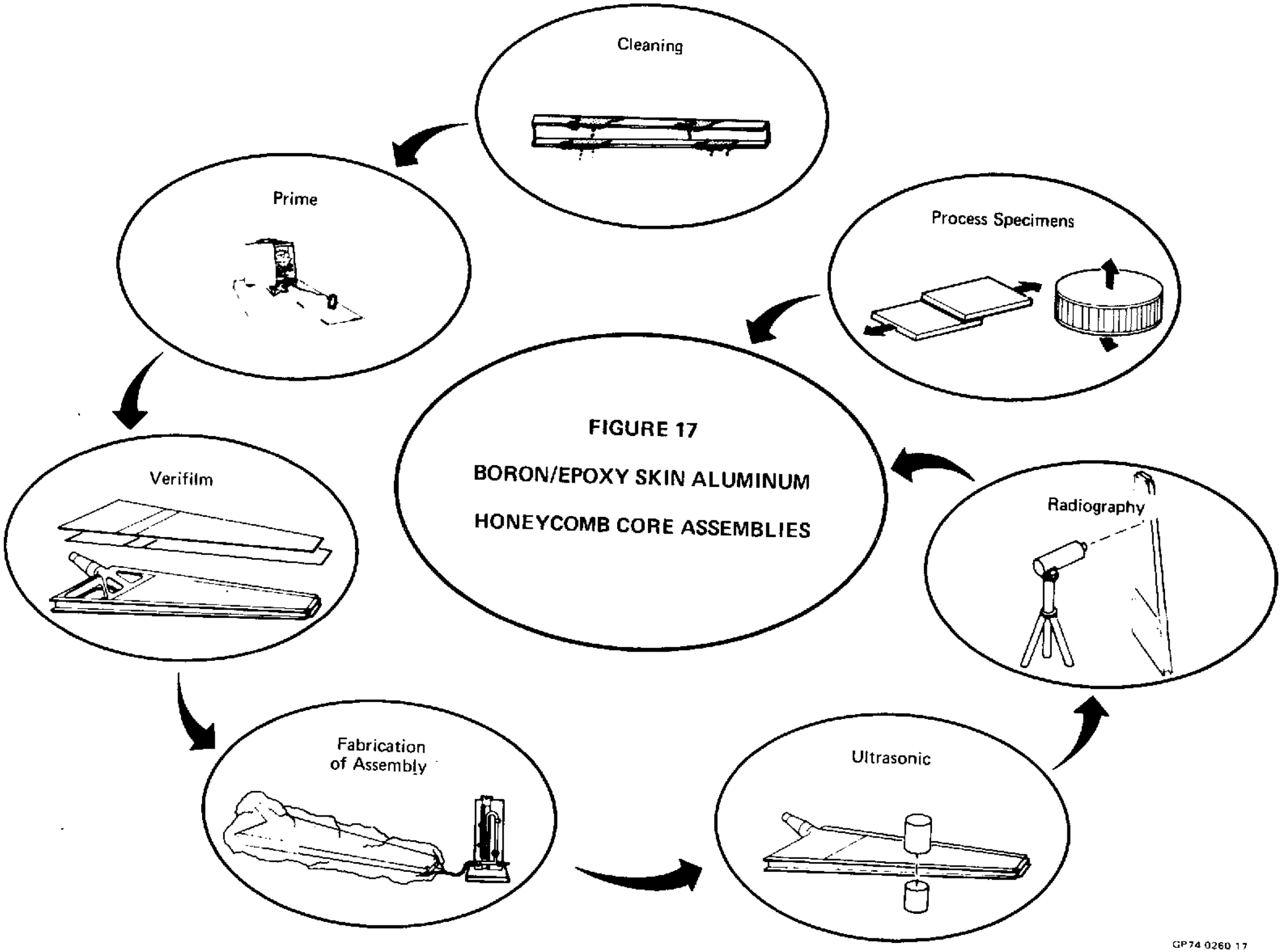

FIGURE 17

BORON/EPOXY SKIN ALUMINUM HONEYCOMB CORE ASSEMBLIES

EFFECT OF FLAWS ON MATERIAL PERFORMANCE

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This paper had not been received by publication time.

J. L. Rose
NMAB - Dayton
February 1974

THE COMPOSITE CHALLENGE FOR NDE

Introduction

Let us consider briefly the materials challenge for Nondestructive Evaluation. As indicated in Table I, the materials challenge for NDE can be considered from two different viewpoints. We must first be able to find and characterize various defects and flaws in a material. Secondly and perhaps more importantly, we must study the effects of specific flaws on system and material performance. This second step allows us to prescribe reasonable and reliable inspection specifications and standards. This problem has confronted engineers and scientists for many years. Much work has already been performed in the past that handles the various aspects of programmed flaws on system performance. Only a few of these programs utilize various aspects of nondestructive evaluation for defect growth characterization. In order to draw proper conclusions on aspects of mechanics, design, and material research, accurate and reliable quality control and nondestructive evaluation programs must be utilized. NDE programs can be used to study defect growth characteristics in fatigue and degradation problems, therefore providing the designer with useful materials and systems design data for structures having a greater capability of resisting degradation and fatigue.

Let us now consider specific problems associated with the Composite Materials Challenge for NDE. Many aspects of the composite challenge have already been considered in the earlier papers. Mr. Caustin discussed principles of several nondestructive evaluation test procedures that are being used in inspection programs today. Various material design considerations associated with nondestructive evaluation were discussed by Jim Ashton. Jeff Cook presented various quality and process control concepts that are required for the new advanced composite materials. The effects of flaws in material performance and various concepts of fracture mechanics were outlined in some detail by Ed Wu. All of these talks included topics that could be considered in the Composite Challenge for NDE. As a result of many discussions with engineers and scientists in both industry and the Department of Defense, I have prepared an outline that depicts topics for consideration in the Composite Challenge for NDE. These items, listed in Table II, are described briefly in the following paragraphs.

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I. Specific Composite Material Problem Must be Solved with NDE.

Items that should be considered in the future are listed as items a, b, c, and d, in Table II. Void regions must be found and studied so that delamination growth and crack initiation in these areas can be understood and handled properly from a design standpoint. Void areas, and resin rich or poor areas are associated with local volume fraction variations in the composite. It is also desirable to develop procedures that could detect misaligned plies in a multi-layered composite. The volume fraction and misaligned angle ply problem along with the material characterization problem could be studied further if wave propagation fundamentals were thoroughly understood. For example work by Smith [1] describes a procedure for measuring wave speeds and elastic constant values in a composite. As shown in Figure 1, the method relies on angle beam ultrasonic analysis, a problem of some difficulty in theoretical wave propagation analysis. Some of the calculated elastic constants are incorrect. The work by Rose and Deska [2], an early attempt to understand the mode conversion problem in composite materials, describes the wave profile analysis problem associated with composite structures. Further work in data analysis and wave propagation is required before the ultrasonic procedure achieves its fullest potential in solving basic problems in material and flaw characterization analysis.

The item of flaw characterization has received much attention in the past. For example, as indicated in the paper by Rose, Carson, and Leidel [3], signal shape and arrival time analysis for flaw characterization is often used in flaw characterization schemes as shown in Figure 2. A sample "C" scan result, taken from [3] is also shown in Figure 3, along with a sample frequency analysis result in Figure 4. Each of these methods is currently being used in flaw characterization analysis, but each is limited by the tedious, time consuming chore of data acquisition and data analysis. Such optical techniques as holographic interferometry are also being utilized in flaw characterization work. A sample result, taken from [3], is shown in Figure 5. Advances in the data handling problems are certainly necessary if reliable flaw characterization procedures are to be developed.

II. Reliable Signal Analysis Techniques must be Developed for Composite Materials.

Items of concern related to this topic are listed in Table II. A new emerging industry, information sciences, will play an important role in the development of reliable signal processing systems. Such topics as pattern recognition and high speed data analysis must be developed and applied to NDE. A technical philosophy on signal preprocessing and processing is presented in a paper by Rose and Meyer [4], basic elements of which are presented in a block diagram shown in Figure 6. A sample problem of the thought processes that enter the signal processing problem area for measuring the thickness of thin films is presented in [5]. Suitable software routines, transducer selection criteria, and the basic physics of nondestructive evaluation must be understood before one can reliably generate suitable software routines for data analysis. For example, the dependence on ultrasonic pulse shape is pointed out in [5]; this particular problem was neglected for many years in the past. The possibility of developing automatic tuning and compensation networks for ultrasonic transducers should also be considered. The problem of selecting suitable reference standards, other than the classic flat bottom hole described by Ellerington [6], must be approached.

III. The Effects of Flaws on Systems Performance can be Studied with NDE.

Several items associated with this topic are listed in Table II. NDE can be used to study such problems as crack arrest mechanisms, critical crack sizes, resistance to impact, etc. A sample result showing cracked fibers from a fatigue test, taken from work by Owsten [7] is shown in Figure 7. NDE could show which cracks are present initially as well as to describe the growth characteristics during a particular test. A paper by Rose and Shelton [8] describes several interesting facets of radiography and ultrasonics as applied to the inspection and damage analysis of composite materials.

The problem of adhesive bond inspection should also be studied from an NDE viewpoint. A formidable list of several of the many variables in adhesive bond inspection, taken from a paper by Rose and Meyer [9], are included in Table III. Rather than study the effects of each one of the variables listed in the Table, it is proposed to study correlation techniques between specific NDE parameters and the performance of the adhesively bonded system.

IV. How can an Awareness of NDE Help the Designer and the Process Control and Quality Control Engineers?

Several topics under this heading, most of which are self explanatory, are listed in Table II. Educational programs by way of seminars and handbooks, group cooperation in the problems of the designer and NDE inspection, and other problems of human engineering must receive some attention.

Concluding Remarks

Strides toward advancing the state of the art in composite materials inspection and study with NDE have certainly been made during the past few years. In order to achieve the best results, great efforts of cooperation and teamwork between the material supplier, mechanics engineer, NDE engineer, physicist, the electrical engineer and mathematician for their signal processing skills, and many other people in different fields of study must be made. Careful planning, thinking and program implementation is certainly needed.

REFERENCES

1. Smith, R. E., "Ultrasonic Elastic Constants of Carbon Fibers and Their Composites," Journal of Applied Physics, Vol. 43, No. 6, June 1972.

2. Rose, J. L. and Deska, E., "New Analytical Concepts in Ultrasonic Angle Beam Analysis," to be published in Materials Evaluation, (Presented at the 1973 Fall meeting of ASNT in Chicago).

3. Rose, J. L., Carson, J. M., Leidel, D. J., "Ultrasonic Procedures for Inspecting Composite Tubes," Analysis of the Test Methods for High Modulus Fibers and Composites, ASTM STP 521, American Society for Testing and Materials, 1973, pp. 311-325.

4. Rose, J. L. and Meyer, P. A., "Signal Processing Concepts for Flaw Characterization," to be published in the British Journal of Nondestructive Testing.

5. Rose, J. L. and Meyer, P. A., "Ultrasonic Signal Processing Concepts for Measuring the Thickness of Thin Layers," submitted to Materials Evaluation.

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7. Owston, C. N., "Carbon Fibre Reinforced Polymers and Nondestructive Testing," British Journal of NDT, January 1973, pp. 2-11.

8. Rose, J. L. and Shelton, W., "Damage Analysis in Composite Materials," Presented at ASTM Composite Reliability Conference, Las Vegas, April 1974.

9. Rose, J. L. and Meyer, P. A., "Ultrasonic Procedures for Predicting Adhesive Bond Strength," Materials Evaluation, Vol. 31, June 1973.

Table I - The Materials Challenge for NDE

A. Find and characterize the flaws

B. Study the effects of specific flaws on material performance.

Table II - The Composite Challenge for Nondestructive Evaluation

I. Specific Composite Material Problems must be solved with NDE

a. Volume fraction determination and evaluation of void content

b. Specific ply orientation, characterization and location

c. Material characterization and geometrical inspection

d. Flaw and crack characterization (shape, size, orientation, and location)

II. Reliable Signal Analysis Techniques must be developed for composite materials

a. Are the standard NDE methods suitable for inspecting composite materials?

1) Are suitable software routines for data analysis and signal preprocessing available for effective digital and image signal processing?

b. Should new NDE methods for inspecting composite materials be developed?

c. Can the human engineering problems of signal interpretation, procedure, and reference standard selection be solved?

III. The effects of flaws on system performance can be studied with NDE

a. Environmental and fatigue effects

b. Impact damage analysis and new design considerations

c. Fastening and joining techniques

IV. How can an awareness of NDE help the designer and the process control and quality control engineers?

a. Accessibility; can it be improved?

b. difficulties attaining reliable NDE can be appreciated

c. suitable joint designs for specific applications can be selected

d. proper material selection and ply orientation for impact resistance or environmental resistance, etc. can be made

Table III - Variables Affecting Adhesive Bond Strength.

Various processing parameters that affect the strength characteristics of an adhesive bond include:

a) bondline thickness
b) joint type and geometry
c) shear and tensile modulus of adhesive
d) composition of adhesive with respect to base and accelerator ratio
e) adhesive type
f) strain rate effects for loading
g) surface preparation and roughness
h) plastic and elastometric substrate qualities
i) humidity variation in manufacture
j) electrical and thermal properties of adhesive and adherend
k) interfacial resistance properties
l) substrate surface free energy
m) residual stress in the adhesive
n) contact angle of a liquid drop on the adherend surface

Several variables that affect the in-service performance characteristics of an adhesive bond in addition to those presented above, are listed next:

a) aging
b) environmental degradation and corrosion
c) heat and moisture cycling
d) load fatigue
e) the cohesive or adhesive nature of failure
f) temperature
g) material handling problems
h) dynamic impact resistance
i) stress concentrators in the interface

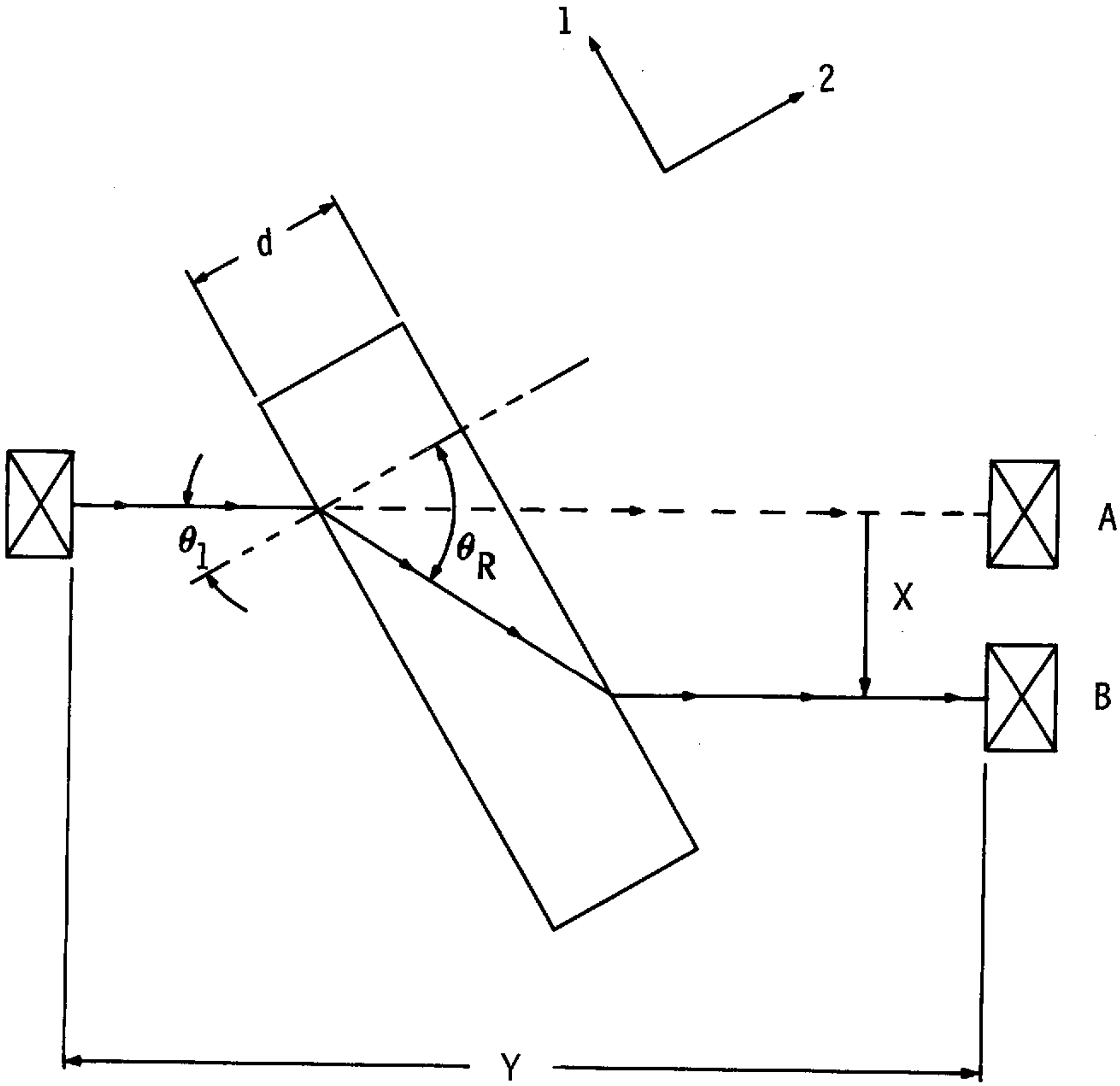
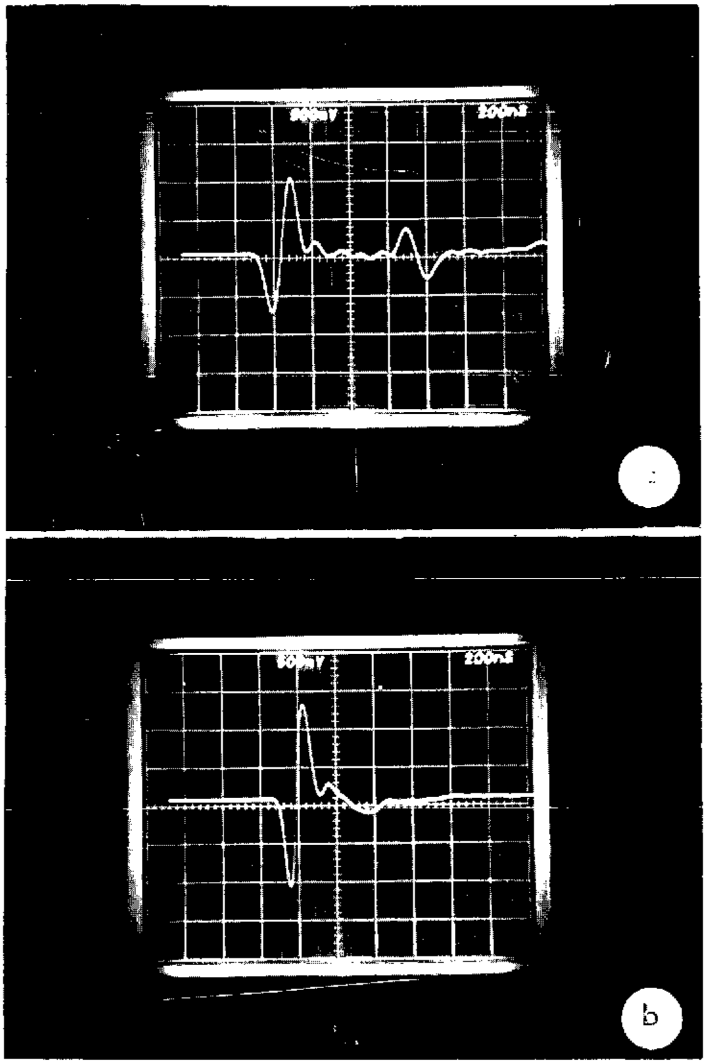


Fig. 1 - Composite material property determination with ultrasonics



(a) Plot showing back wall echo over the good area.

(b) Plot showing the defect echo over the flaw area.

Fig. 2 - Oscilloscope trace of a pulse echo ultrasonic signal in the glass-epoxy composite tube.

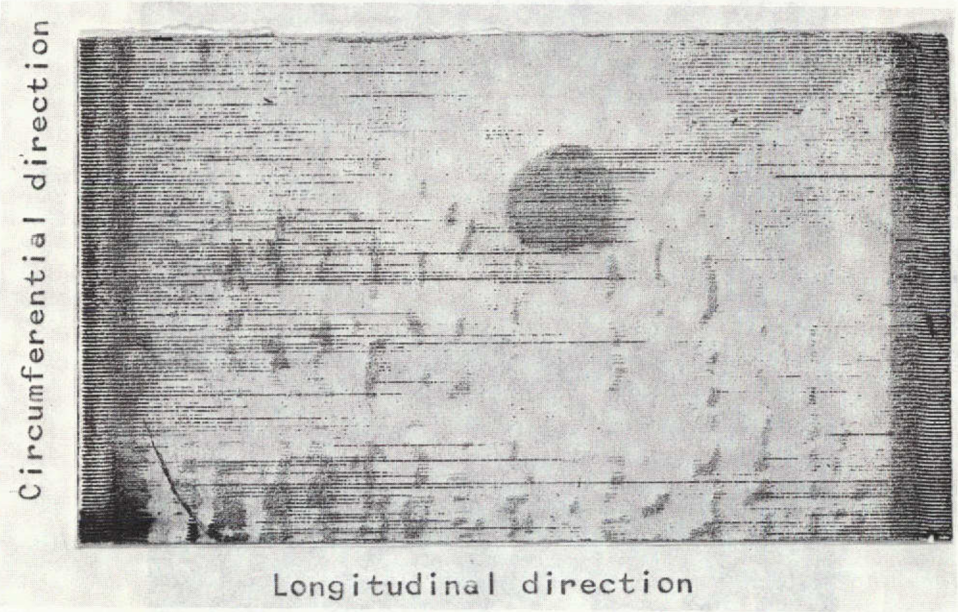
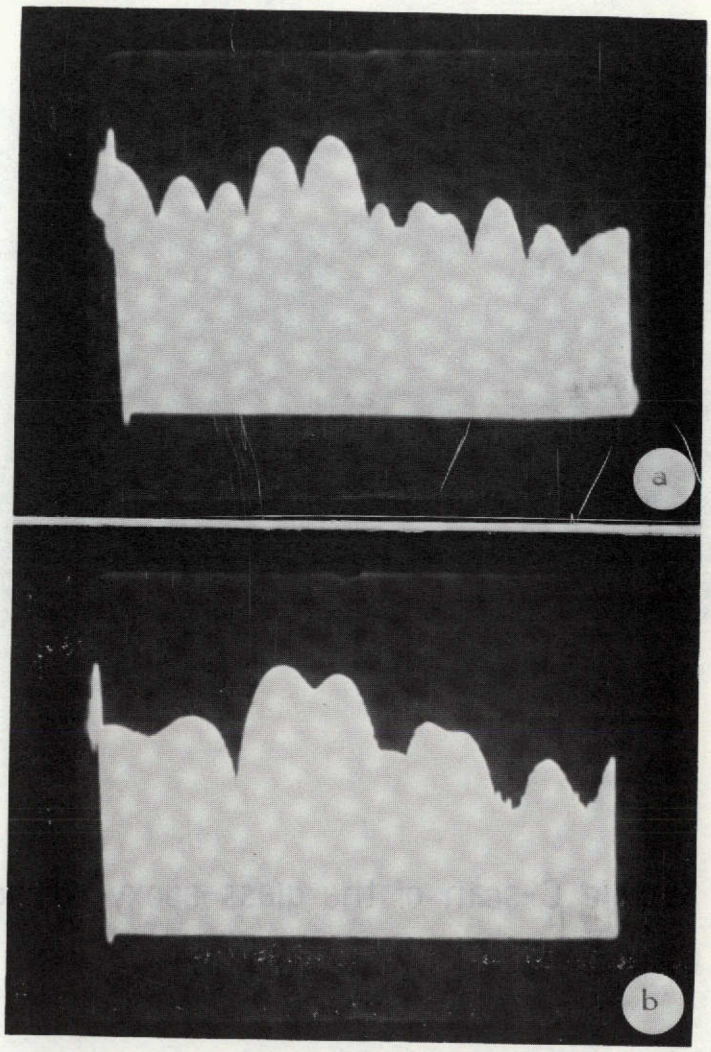


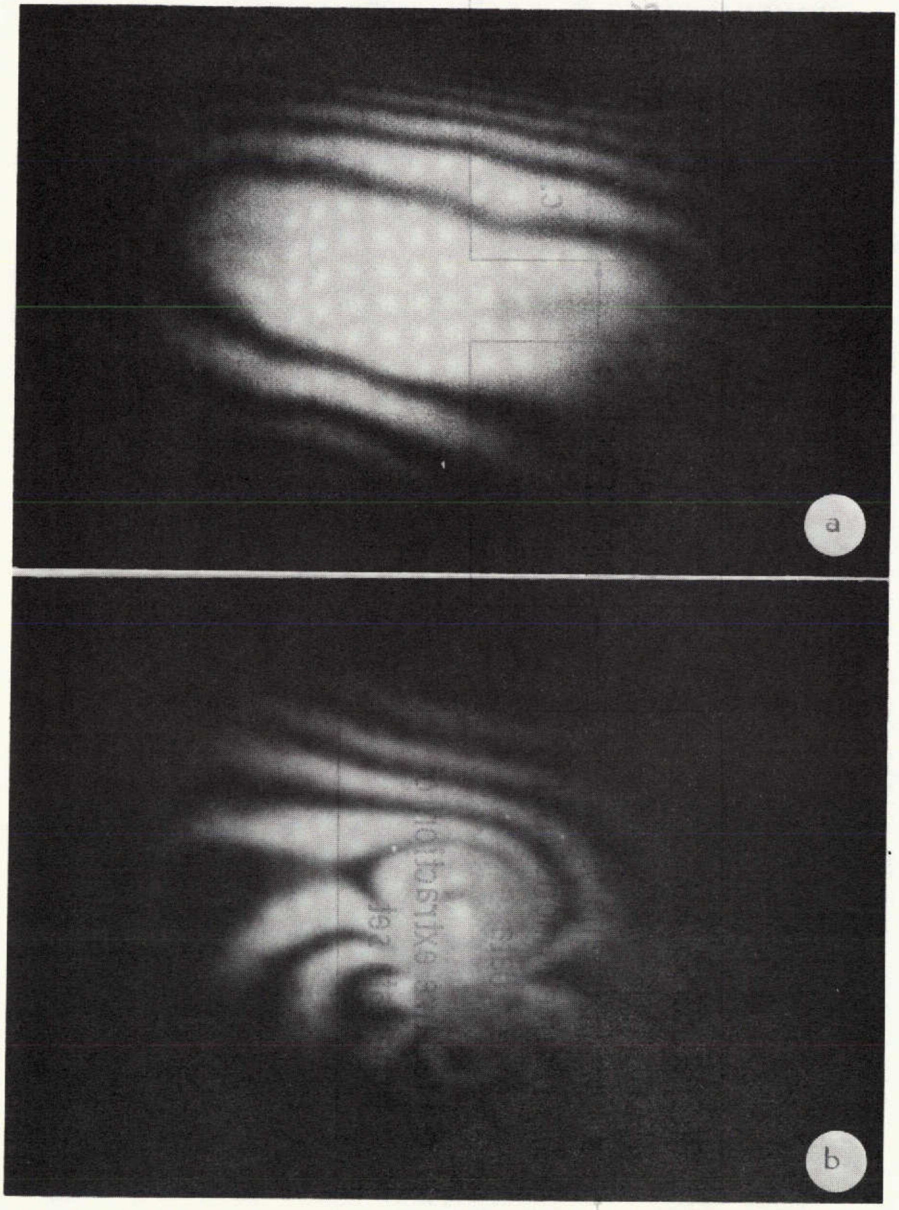
Fig. 3 - Sample C-scan of the glass-epoxy composite tube
(flaw indicated by the dark area).



(a) Over the good area.

(b) Over the flaw area.

Fig. 4 - Spectral analysis comparisons of areas in the glass-epoxy composite tube (band width 0 to 20 MHz with center frequency of 10 MHz).



(a) Over the good area.

(b) Over the flaw area.

Fig. 5 - Holographic fringe pattern for the glass-epoxy composite tube subjected to internal pressure.

SIGNAL PROCESSING

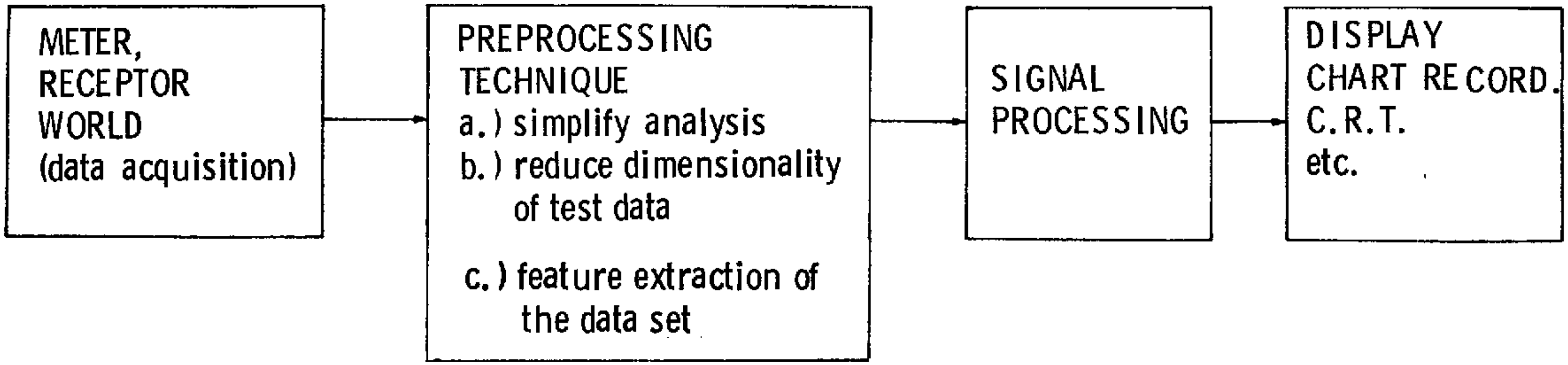


Fig. 6 - A signal processing system

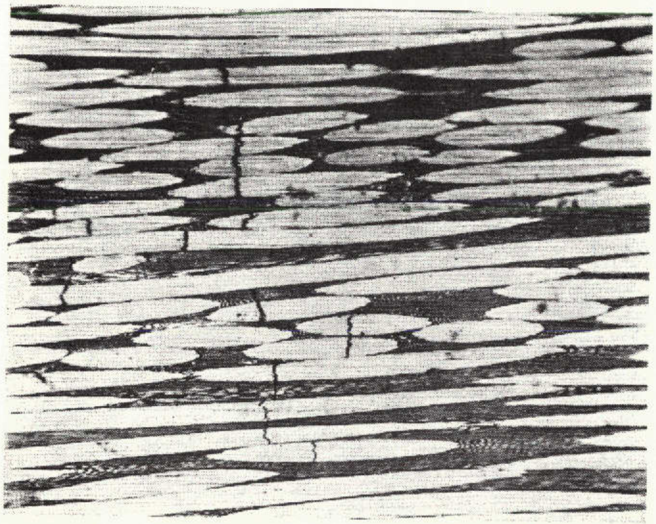


Fig. 7 - Close-up of longitudinal section of CFRP showing fibres cracked during a fatigue test

APPENDIXES

APPENDIX A

WORKSHOP PROGRAM

February 13, 1974

PRESENTATIONS

9:00

GOAL OF THE WORKSHOP

Joseph R. Lane
Staff Metallurgist
National Materials Advisory Board

9:05

NDE TODAY

Edward Caustin, Director
Quality & Reliability Assurance, B-1 Division
Rockwell International Corporation

9:30

COMPOSITE DESIGN & NDE

James Ashton, Director
Structures & Design, Convair Aerospace
Division of General Dynamics Corporation

10:00

Coffee Break

10:30

QUALITY ASSURANCE & PROCESS CONTROL

Jeffrey F. Cook, Senior Engineer, NDT
McDonnell-Douglas Corporation

11:00

EFFECT OF FLAWS ON MATERIAL PERFORMANCE

Edward M. Wu, Professor
Washington University

11:45

SUMMARY: THE COMPOSITE CHALLENGE FOR NDE

Joseph L. Rose
Assoc. Professor, Drexel University

12:00

Lunch

WORKSHOP SESSIONS

1:30

NONDESTRUCTIVE EVALUATION TODAY

Dana Moran
Battelle-Columbus Laboratories, Chairman

Harold Hatch
U.S. Army, Co-chairman

Effectiveness of current technology
NDE influence on composite design
Quality assurance and process control
- What do we want to measure
- Transition to plant use
- Reference standards and inspection specifications

3:00

Coffee Break

3:30

THE EFFECTS OF FLAWS ON MATERIAL PERFORMANCE

L.B. Pritchett
Boeing Company, Chairman

Robert L. Crane
AFML, Co-chairman

Correlative data: NDE/Properties/Service life
Critical flaw identification for fracture mechanics
Impact damage

5:00

Cash Bar - Conversation

February 14, 1974

9:00

COMPOSITE CHALLENGE FOR NDE

Richard Chance
Grumman Aerospace Corporation, Chairman

S. Friedman
Naval Ship R&D Center, Co-chairman

Environmental and fatigue effects
In-service inspection
Joining and fastening
New problem areas
Design improvement through enhanced inspectability
New techniques
Signal analysis and presentation

10:00

Coffee Break

11:00

SUMMARY OF DISCUSSION

Joseph L. Rose
Workshop Chairman

12:00

ADJOURN

APPENDIX B

WORKSHOP PARTICIPANTS

ADELMANN, Louis - Bell Helicopter Company, Ft. Worth, Texas

ALERS, George - Rockwell International Corporation, Thousand Oaks, Ca.

ANDERSON, R.T. - General Dynamics/Convair, San Diego, Ca.

ASHTON, James - General Dynamics/Convair, San Diego, Ca.

AVERY, John G. - Boeing Aerospace Company, Seattle, Washington

BEATTY, W.M. - General Dynamics/Convair, Ft. Worth, Texas

BETZ, Robert A. - Pratt & Whitney Aircraft, East Hartford, Conn.

BOISVERT, Bernard - SAAMA, Kelly Air Force Base, Texas

BOWLES, Kenneth - NASA-Lewis Research Center, Cleveland, Ohio

BUDNICK, Morris L. - U.S. Army Natick Laboratories, Natick, Mass.

CARSON, James - U.S. Air Force Academy, Colorado

CATALANO, Sam - U.S. Army Tank-Automotive Command, Warren, Mich.

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CHWIRUT, Daniel J. - National Bureau of Standards, Washington, D.C.

CLEMENS, R.E. - Northrup Corporation, Hawthorne, Ca.

COLLINS, Richard - Grumman Aerospace Corp., Bethpage, N.Y.

COOK, Jeffrey F. - McDonnell-Douglas Corp., St. Louis, Mo.

CORNISH, Rodney - IIT Research Institute, Chicago, Ill.

CRANE, Robert L. - U.S. Air Force Materials Lab., WPAFB, Ohio

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EDELSTEIN, Harold - Naval Ship R&D Center, Annapolis, Md.

EVERS, Ronald V. - Army Aviation Systems Command, St. Louis, Mo.

FETHEROFF, C.W. - TRW, Inc., Cleveland, Ohio

FRIEDMAN, Seymour - Naval Ship R&D Center, Annapolis, Md.

GARDNER, C. Gerald - Southwest Research Institute, San Antonio, Texas

GIESKE, John - Sandia Laboratories, Albuquerque, N. M.

GUPTA, Y.P. - Advanced Technology Center, Inc., Dallas, Texas

HANBY, Kenneth R. - Battelle-Columbus Laboratories, Columbus, Ohio

HARRISON, Robert W. - General Electric Company, Cincinnati, Ohio

HARRY, Douglas R. - Naval Ship R&D Center, Bethesda, Md.

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HATCH, Harold - Army Materials & Mechanics Research Center, Watertown, Mass.

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KEBLER, Richard W. - Union Carbide Corporation, Indianapolis, Ind.

KOCZAK, Michael J. - Drexel University, Philadelphia, Pa.

KRASKA, I.R. - General American Transportation Corp., Niles, Ill.

KREIDER, Kenneth - National Bureau of Standards, Washington, D.C.

LAKE, W.W. - Army Aviation Systems Command, St. Louis, Mo.

LANE, Joseph R. - National Materials Advisory Board, Washington, D.C.

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MOORHEAD, Paul - NASA-Lewis Research Center, Cleveland, Ohio

MORAN, H. Dana - Battelle-Columbus Laboratories, Columbus, Ohio

NELSON, Paul T. - TRW Systems, Redondo Beach, Ca.

OAKS, Arthur - General Electric Company, Philadelphia, Pa.

PEARS, C.D. - Southern Research Institute, Birmingham, Ala.

POMERANTZ, J. - Air Force Office of Scientific Research, Arlington, Va.

PRITCHETT, L.B. - Boeing Company, Seattle, Washington

RAMSEY, S. David Jr. - Stanford Research Institute, Menlo Park, Ca.

REIFSNIDER, Kenneth - Virginia Polytechnic Institute, Blacksburg, Va.

ROSE, Joseph L. - Drexel University, Philadelphia, Pa.

ROTH, Peter A. - Eastman Kodak Company, Rochester, N.Y.

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STINEBRING, Russell - General Electric Company, Philadelphia, Pa.

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THORP, John M. - Army Aviation Systems Command, St. Louis, Mo.

TOTH, Istvan J. - TRW Equipment, Cleveland, Ohio

VINSON, Jack R. - University of Delaware, Newark, Delaware

WALKER, William J. - Air Force Office of Scientific Research, Arlington, Va.

WU, Edward M. - Washington University, St. Louis, Mo.

ZURBRICK, John R. - General Electric Company, Cincinnati, Ohio

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