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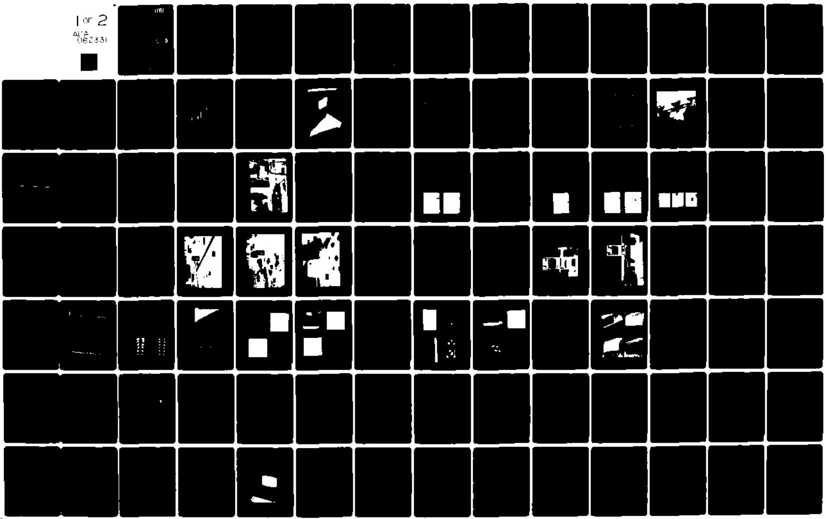

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IN-SERVICE INSPECTION OF ADVANCED COMPOSITE AIRCRAFT STRUCTURE

GENERAL DYNAMICS
FORT WORTH DIVISION
P.O. BOX 748
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Final Report for Period 1 March 1978 – 31 December 1978

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GROVER L. HARDY
Project Engineer

BENNIE COHEN, Acting Chief
Materials Integrity Branch
Systems Support Division

FOR THE COMMANDER

W. P. JOHNSON
Assistant Chief
Systems Support Division

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This report describes the work accomplished under a 12-month program conducted for the purpose of developing a reliable and practical inspection and data recording capability for service induced, or propagated flaws in composite aircraft structure. The basis of the developmental work was a portable C-scan recording system developed by General Dynamics to be used in hand-scan ultrasonic inspection on F-16 production line. In that system, a unique sonic microphone digitizing system was used to receive low-frequency ultrasound

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generated by a cursor attached to the ultrasonic transducer for position indication. In this program, a laboratory mock-up system was assembled to detect and record implanted flaws and impact damages in fabricated specimens, using modified and improved ultrasonic techniques. Preliminary design of a prototype system incorporating improvements from the laboratory mock-up system was completed. A cost analysis was conducted to allow an evaluation of the performance of the prototype system in the preliminary design against its cost.

FOREWORD

This final report is prepared by the Fort Worth Division of General Dynamics under Air Force Materials Laboratory Contract No. F33615-77-C-5206 covering the period from March 1 to December 31, 1978. The objective of the program is to develop a reliable and practical inspection and data recording capability for service induced flaws in advanced composite aircraft structure. The project engineer at AFML is Mr. G. L. Hardy. The program is being conducted at the Materials Research Laboratory of General Dynamics under the leadership of Engineering Chief of the Laboratory, Dr. B. G. W. Yee. The project leader is Dr. F. H. Chang. Personnel directly involved in the program are Dr. F. H. Chang, J. R. Bell, A. H. Gardner, G. P. Handley and C. P. Fisher. Contributions to the program by R. H. McDaniel, J. S. Green, L. C. Spruill, B. W. Lee, W. M. Beatty, T. B. Hollar, K. W. Hammer, and D. D. Dingler are gratefully acknowledged.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTD.)

LIST OF TABLES

LIST OF TABLES (CONT.)

SUMMARY

This final report describes the work accomplished from March 1, 1978, to December 31, 1978, under a 12-month program to develop a reliable and practical inspection and data recording capability for service-induced or propagated flaws in composite aircraft structure. The basis of the development of this capability is a portable C-scan recording system developed by General Dynamics to be used in hand-scan ultrasonic inspection on F-16 production line. A unique sonic microphone digitizing system is used to receive low-frequency ultra sound generated by a cursor attached to the ultrasonic transducer for the purpose of position indication.

All the tasks delineated in the program have been successfully completed. A laboratory mock-up system was assembled (Task III) to detect and record implanted flaws and impact damages in fabricated specimens (Task I), using ultrasonic techniques developed in this program (Task II). Preliminary design (Task IV) of a prototype system incorporating improvements from the laboratory mock-up system was completed. A cost analysis (Task V) was conducted to allow an evaluation of the performance of the prototype system in the preliminary design against its cost. The mock-up laboratory system can produce hard-copy real-time plots and post-inspection C-scans. Flaw locations had an accuracy of better than 0.64 cm (0.25 in.) over a minimum area of 0.61 x 0.61m (2 x 2 ft.) with a contour surface of a maximum radius of 1.22m (4 ft.). Post-inspection flaw magnification, flaw-amplitude listing, and RF waveform digitization are the major features of the post-inspection analysis capabilities of the system. Inspection data can be stored in floppy disk unit. The system can be operated by one person.

A system tryout demonstration was held successfully in August 1978. Areas of improvement were identified and incorporated in the preliminary design of the prototype system. The preliminary design will be the basis of the prototype system design in the follow-on program - the In-Service Composite Inspection System Producibility (Contract No. F33615-78-C-5152).

I. INTRODUCTION

Advanced composite materials have been used extensively in primary and secondary structures in modern aircraft. These materials offer distinct advantages in terms of reduced weight, increased performance, lower cost, and higher structural reliability. The fiber/epoxy material systems currently in service in Air Force aircraft include boron/epoxy (B/E), graphite/epoxy (G/E), and a hybrid comprising the two systems. The structural configurations generally consist of composite skins attached to metallic or non-metallic structures by bonded or bolted joints. The skins may be tapered composite skins and the substructure may be in the form of metallic spar or rib stringer reinforced by honeycomb structure. The G/E skins in the F-16 vertical stabilizer are bolted to an aluminum substructure. The G/E skins in the F-16 horizontal stabilizers are bonded to a titanium spar reinforced by fasteners. Aluminum honeycomb cores serve as the reinforcement in areas not covered by the titanium spar. Other advanced Air Force combat fighters use B/E and G/E materials with similar designs in empennage components and speed brake.

The complexity of the advanced composite structures increases the degree of difficulty for nondestructive testing (NDT) and inspection. The major NDT techniques for composite structure inspection are ultrasonics and radiography. For in-service inspection, ultrasonic techniques generally involve an operator scanning the structure manually with a hand-held transducer. They are not considered cost effective for inspection of large areas for small flaws or for monitoring areas containing known small flaws which may propagate during service. The inadequacy stems primarily from the lack of devices for position locating and recording of flaws. A need exists for an in-service inspection system for composites that will record the flaw location in a pseudo-real time C-scan while minimizing the operator effort to attain a high level of inspection reliability.

The objective of this program is to develop a reliable and practical inspection and data recording capability for service-induced or propagated flaws in composite aircraft structure. The basis of the development of such a capability is a portable C-scan recording system developed by General Dynamics to be used in hand-scan ultrasonic inspection on F-16 production line. In this system, a pair of sonic microphones is used to receive low-frequency ultra sound generated by a cursor attached to the ultra-sonic transducer for the purpose of position indication.

The duration of this AFML-sponsored program is twelve (12) months. From the contract go-ahead date of March 1, 1978 to December 31, 1978 all the tasks delineated in the program were successfully completed. This final report outlines the accomplishments achieved in these tasks and the difficulties encountered which are relevant to the design of a prototype inspection system. A program schedule and expenditure chart is shown in Figure 1.

The preliminary design of a prototype inspection system will be the basis of the In-Service Inspection System (ISIS) Prototype design, to be conducted in a follow-on program, "In-Service Composite Inspection System Producibility", AFML Contract No. F33615-78-C-5152 (Reference 1).

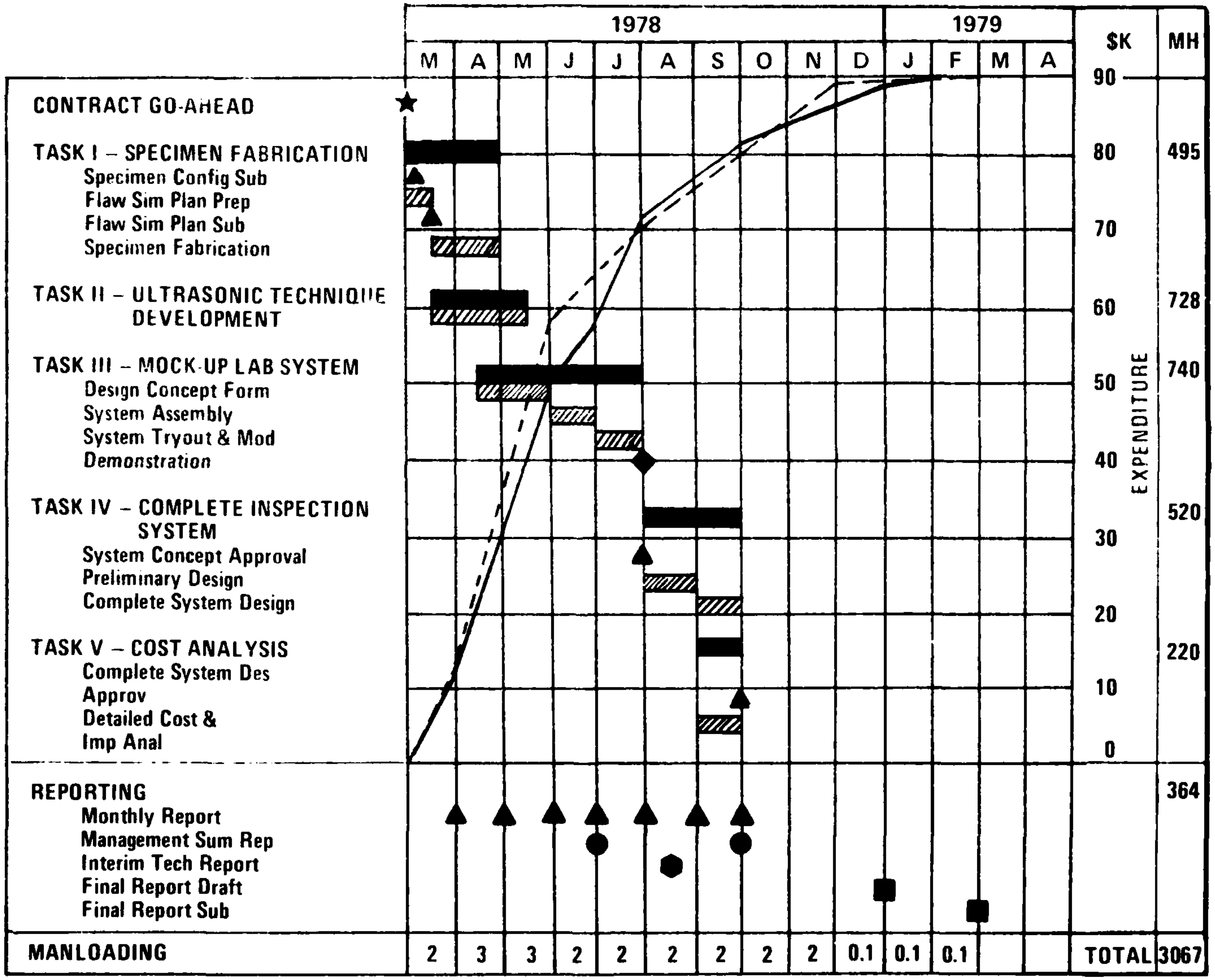


Figure 1 Program Schedule and Expenditure Chart

II. SPECIMEN FABRICATION

A basic specimen configuration of tapered composite laminates adhesively bonded to a Ti channel substructure and aluminum honeycomb core (HC) was selected for this program. The laminates consisted of B/E, G/E, and a hybrid of B/E and G/E. The B/E laminate contains a Ti stepped bar and a Ti shim as reinforcements. Painted and Al flame-sprayed surfaces were chosen as representatives of aircraft exterior surfaces. Flat-bottom-holes (FBH), Kapton film implanted defects, naturally occurring flaws, and impact damages were the representative types contained in the test specimens. Three existing specimens (A-1, A-2 and A-3) and three fabricated specimens (B-1, B-2, and B-3) contained a variety of flaw type and structural configurations. Detailed descriptions of these specimens are outlined in the following paragraphs.

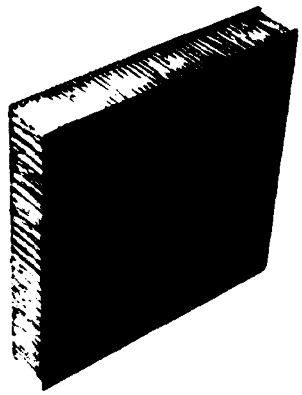
2.1 Specimen Configuration

Selection of specimen configurations was based on typical structural design of in-service production aircraft which use advanced composite materials. The configuration of tapered composite laminates adhesively bonded to Ti channels and Al HC substructure was selected. This configuration represents the structural design of the horizontal stabilizer of the F-16 and the vertical stabilizer of the F-15. It also represents the areas on the composite components on the F-16 with the most complex geometry and, thus, will be of most concern to the field service inspectors. In addition, a root section of the F-16 vertical stabilizer skin was bolted to an Al substructure, simulating the high-stress area in the vertical stabilizer. Impact damages were inflicted on different areas in this component with bolted joints.

The Quality Assurance Department of General Dynamics adopted similar configurations in the fabrication of reference specimens for the production inspection of F-16 horizontal stabilizers. Three of these existing specimens, shown in Figure 2, were used in this program. Specimen A-1 was a G/E skin-fiberglass-Ti multilayered structure with dimensions of 7.62 x 47.63 cm (3X 18-3/4 in.). The T-300/5208 laminate tapered from 52 plies at one end to 4 plies at the other end. A 1.58 cm (0.62 in.) diameter FBH was drilled at each two-ply dropoff of 1.9 cm (3/4 in.) interval on the Ti side to the fiberglass layer, simulating voids and delaminations at the fiberglass/Ti interfaces. Specimen A-2 was a 15.24 x 15.24 cm (6 x 6 in.) Al HC structure with G/E skins adhesively bonded on both sides. The skin on one surface tapered from 16 to 4 plies with a

SPECIMEN A-1

SPECIMEN A-2



SPECIMEN A-3

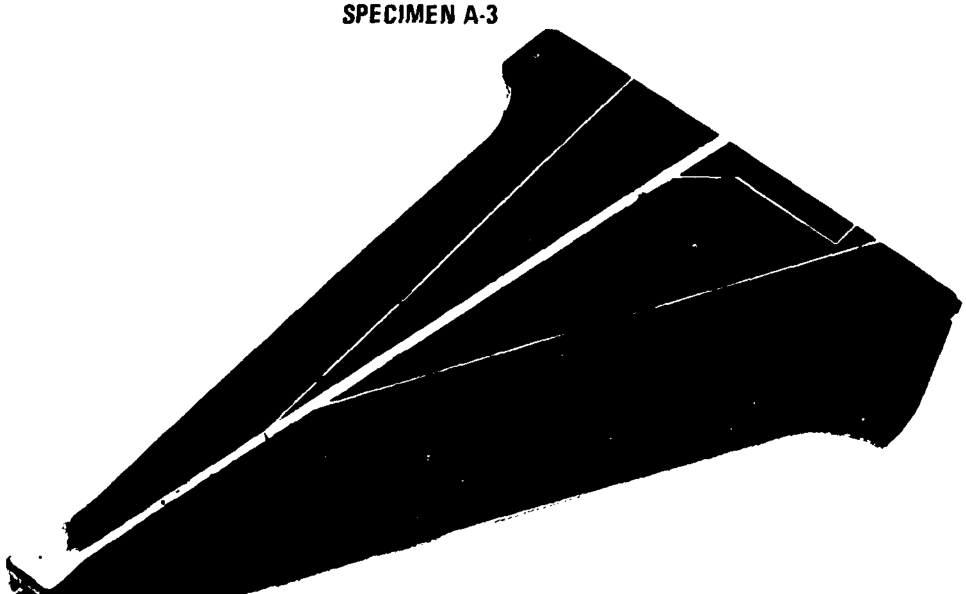


Figure 2 Photograph of Existing Specimens A-1, A-2, and A-3

2-ply dropoff per 2.54 cm (1 in). The skin on the other surface had a uniform thickness of 6 plies. Two FBHs with a diameter of 1.52 cm (0.6 in.) were drilled at each ply dropoff locating at a distance of 2.03 cm (0.8 in.) from the centerline. The FBHs were drilled from the side of the specimen with a uniform thickness through the Al HC to the bottom of the tapered skin. Specimen A-2 simulated disbonds at the interfaces between the G/E skin and the Al HC.

Specimen A-3 was a reference specimen representative of the F-16 horizontal stabilizer spar region. The substructure of this specimen was machined from an actual Ti spar of the F-16 horizontal stabilizer. 22 FBHs with 1.58 cm (0.62 in.) diameter were drilled at different locations through the Ti flange. A tapered G/E skin was bonded to the spar on one side with 2 layers of fiberglass between the spar and skin. The taper was from 52 to 40 plies. On the other side of the structure, a uniform layer of 10-ply G/E skin was bonded. On one side of the web of the Ti spar, the space between the flanges was filled with Al HC similar to the horizontal stabilizer structure. The FBHs on this side of the structure were obscured by the Al HC. On the other side of the web, the FBHs were visible.

Three additional specimens (B-1, B-2, and B-3) were fabricated to supplement the existing Type A specimens with FBHs. The configurations of the Type B specimens provided variations in flaw type, materials, and specimen surfaces commonly found in composite structures on Air Force production aircraft. A sketch showing the specimen configuration for specimen B-1 and B-2 is shown in Figure 3. Specimen B-1 was constructed of two tapered (0/$\pm$45) composite skins (one B/E and one hybrid of B/E and G/E) bonded on two ends to two Ti channels. The space between the two skins not occupied by the channels was filled with Al HC. The skins had 52 plies at the thick end and 4 plies at the thin end with a 2-ply dropoff at every 2.54 cm (1 in.) interval. Both skins contained implanted flaws. The B/E skin has a 15.24-cm (6 in.) wide, 0.05-cm (0.020 in.) thick Ti shim bonded below 4 plies of the B/E tape on one edge of the specimen perpendicular to the Ti channels. A stepped Ti bar with a cross section and dimensions shown in Figure 4 is bonded parallel to the Ti shim on the other edge of the specimen. The hybrid skin on Specimen B-1 had no reinforcement. Surfaces on both skins in Specimen B-1 were painted with 2 coats of primers and 2 coats of polyurethane as per F-16 specifications.

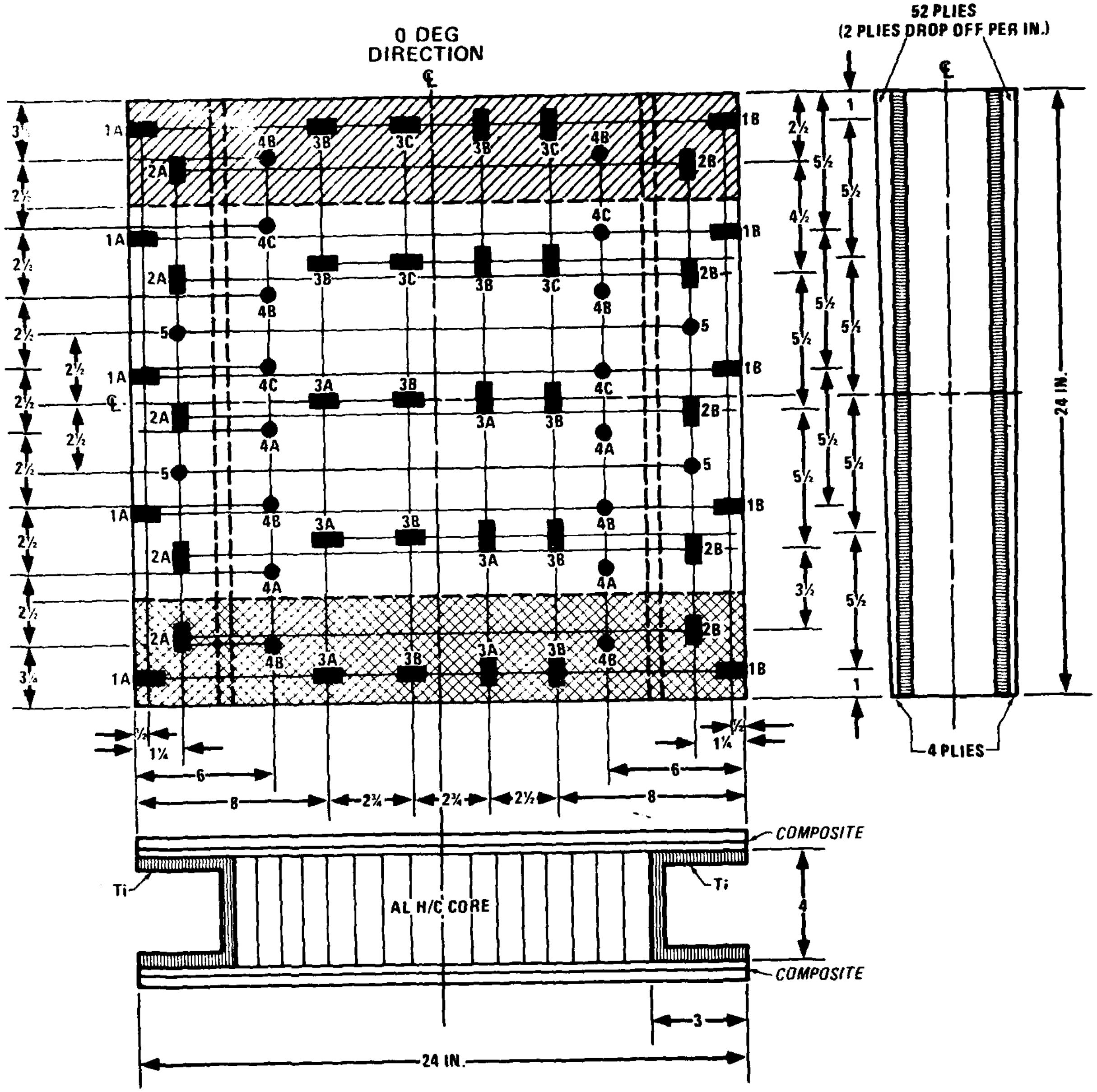


Figure 3 Specimen Configuration for Specimens B-1 and B-2

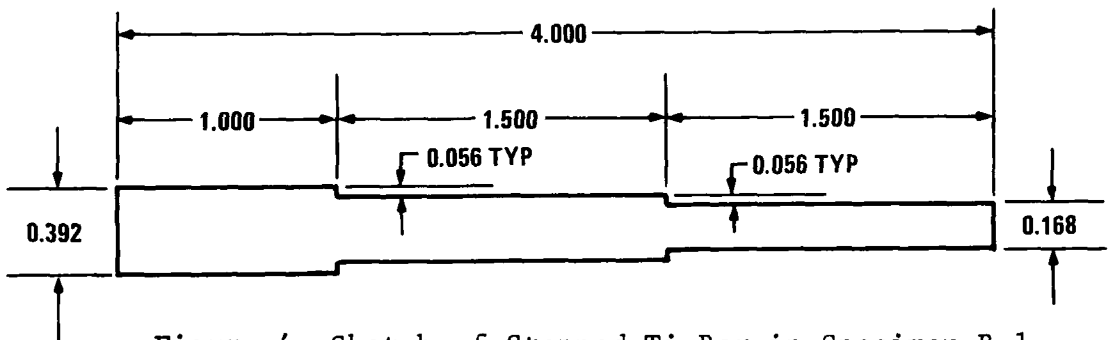


Figure 4 Sketch of Stepped Ti Bar in Specimen B-1
(Dimensions inches)

Specimen B-2 had a configuration similar to that of specimen B-1 except for the skins. One side of B-2 had a G/E skin (0/±45) tapered from 52 to 4 plies with a 2-ply dropoff at every 2.54 cm (1-in.) interval. This skin contained implanted flaws. The surface of this skin was covered with a Al flame-sprayed coating with an approximate thickness of 0.025 cm (0.010 in.). The other skin of specimen B-2 was machined from a rejected F-16 horizontal stabilizer skin known to contain excessive amounts of porosities and delaminations. The surface of the rejected G/E skin was painted per F-16 paint specification.

Specimen B-3 had a G/E skin of a F-16 vertical stabilizer root section bolted to an Al substructure with a bolt pattern similar to that of the vertical stabilizer substructure. After the surface of the skin was coated with a 0.025 cm (0.010 in.) thick Al flame-spray, impact damages were inflicted on the skin by dropping a 4.55 Kg (10-lb) weight from various heights in a drop-test fixture. The dimensions of the Al substructure, the bolt pattern and the impact damage sites are shown in Figure 5. For the purposes of ultrasonic technique development and demonstration of the applicability of the position sensing unit on a contour surface, the root section of a vertical stabilizer of the YF-16 was also used as a test specimen. A photograph of the root section is shown in Figure 6.

2.2 Materials

The materials in type A and B specimens are identified in Table 1. The paint chosen for specimens B-1 and B-2 was standard F-16 polyurethane paint (MIL-C-83286) with an average thickness of 0.005 cm (0.002 in.) and a 0.013 cm (0.0005 in.) thick primer. This type of paint is representative of organic surfaces commonly found on Air Force production aircraft. Flame-sprayed aluminum coatings, used as lightning protection coatings, were usually applied in strips. For the purpose of ultrasonic inspection technique development and system demonstration, it was decided to coat the entire surface of the specimens for manufacturing ease.

2.3 Specimen Size

The dimensions of specimens B-1 and B-2 were 60.96 x 60.96 cm (24 x 24 in.) with an approximate thickness of 12.7 cm (5 in.). These specimen dimensions were selected for two reasons. First it was more economical to fabricate a large specimen compared to several small specimens containing an equal number of flaws. Using the proven technique of flaw implantation described in a later paragraph,

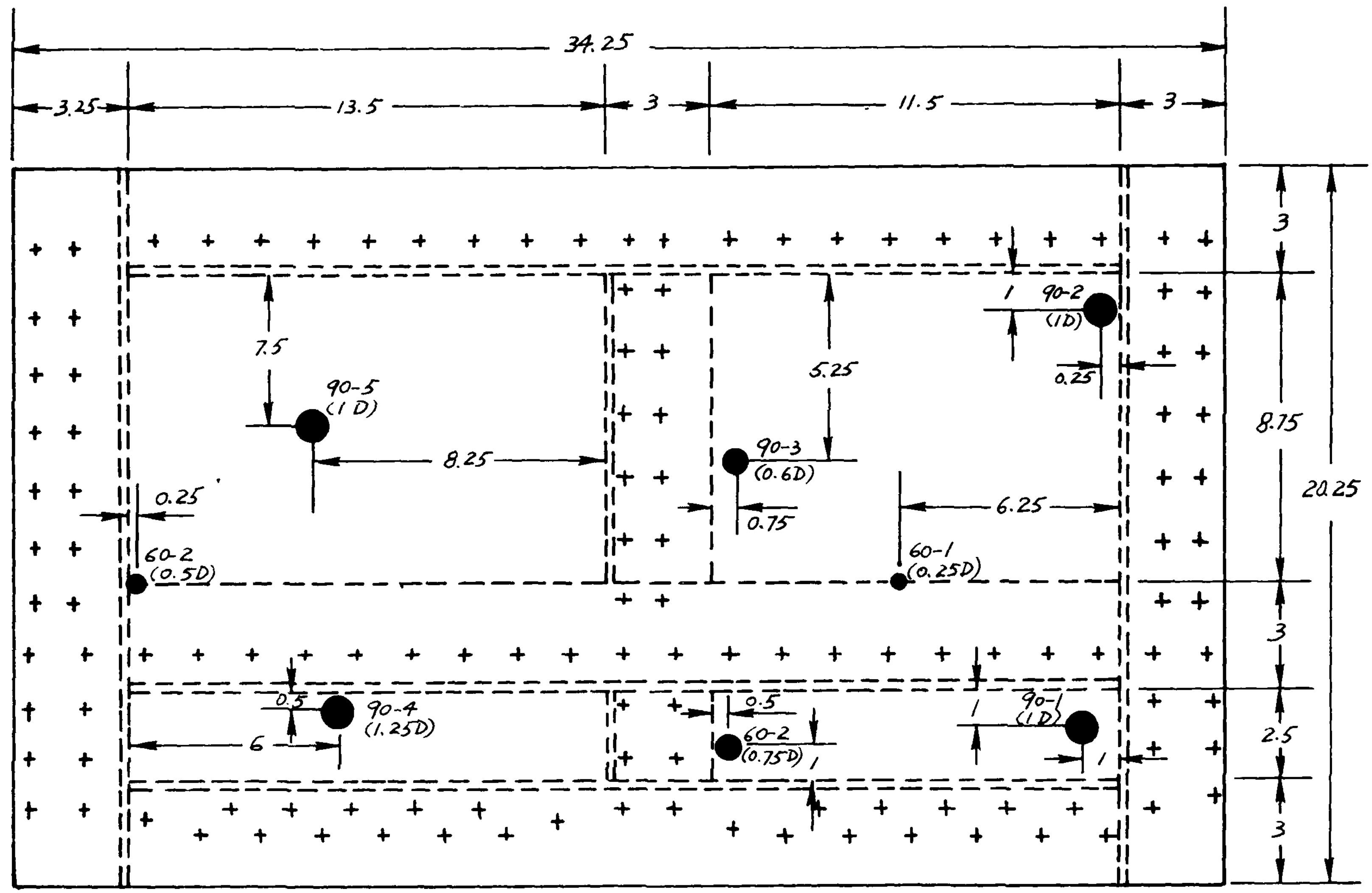


Figure 5 Sketch of Specimen B-3 (Dimensions in Inches)

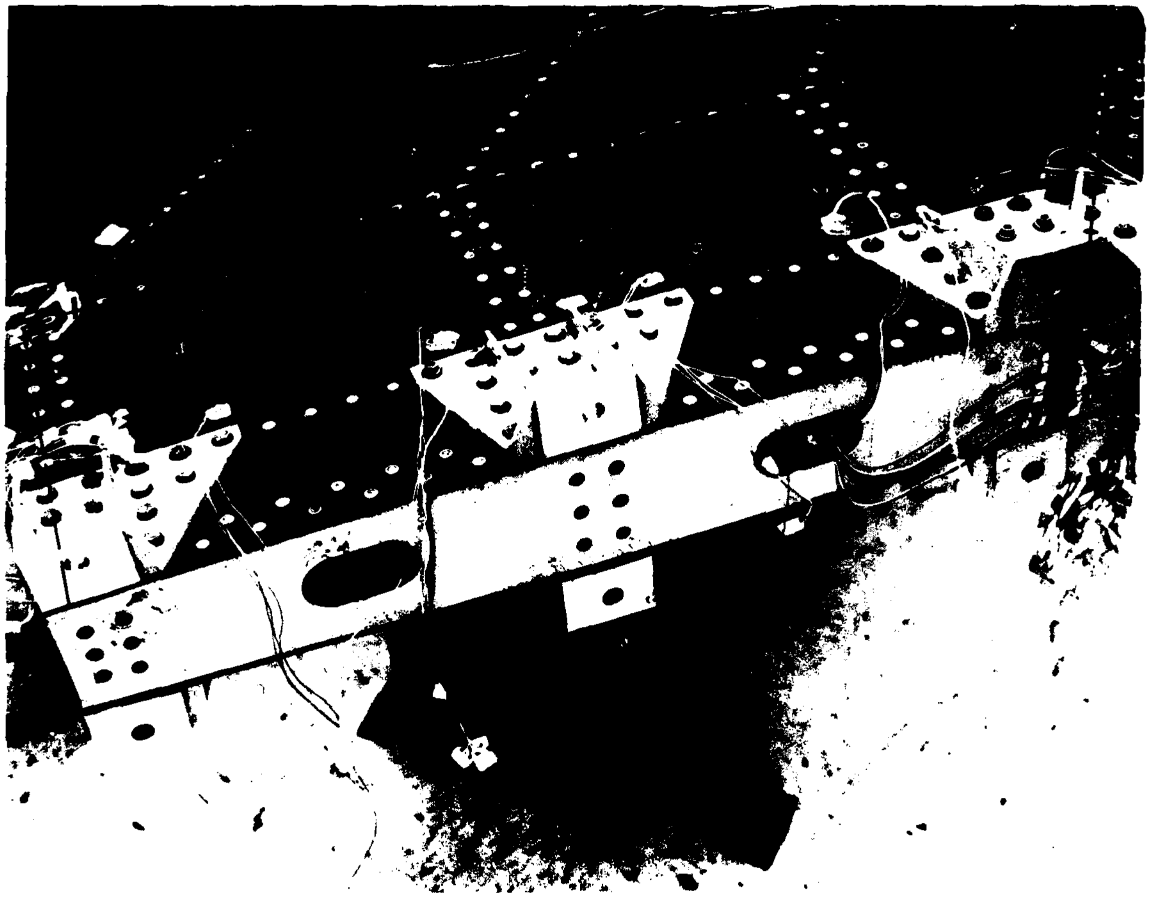


Figure 6 Photograph of the Root Section of a Vertical Stabilizer Skin On a YF-16

TABLE 1. MATERIAL LIST FOR TEST SPECIMENS

COMPONENT	MATERIALS
Laminate B-1 A Side	Narmco-Rigidite 5505 (0/±45) B/E
Laminate B-1 B Side	Narmco-Rigidite 5505 B/E & T300/5208 G/E (OG/±45G/OB)
Laminate B-2	T300/5208 Graphite/Epoxy (0/±45)
Shims	6-4 Ti
Adhesive	RB-398
Fiberglass	American Cyanamide BP 927 with 7581 glass fiber reinforcement
Honeycomb Core	Hexcel CRIII-1/16-5052-0007N- 6.0
Paint	MIL-C-83286 polyurethane with primer
Flame-Sprayed Al	MIL-B-5087B 0.0005 in.
Channel	6-4 Ti

all the flaws in the large specimen were produced simultaneously during the curing process. Trimming and cutting cost will be reduced for a specimen with large dimensions. Secondly, large sizes for the specimens were selected to simulate as closely as possible the degree of difficulty for in-service inspection. One of the major difficulties for in-service inspection of composite structures is to find a small flaw in a large inspection area. The dimensions selected for the specimens simulated a large area while still keeping the cost of materials at a reasonable level.

Specimens B-1, B-2, and B-3 had essentially flat surfaces. The specification for the data recording system is to follow a contour surface 0.61 x 0.61m (2 x 2 ft) with a minimum radius of curvature of 1.22 m (4 ft). An existing data recording system already developed by General Dynamics can easily follow this type of contour which is equivalent to an apex distance of 3.87 cm (1.524 in.) over a plane of the 0.61 x 0.61 m (2 x 2 ft.) surface. A F-16 vertical stabilizer was used to test and demonstrate the ability of the data recording system to track the position of the ultrasonic transducer over a contour surface. The contour of the vertical stabilizer surface was such that the height differential in a 0.61 x 0.61m (2x2 ft) area was greater than 5.08 cm (2 in.). The requirement for the contour-following capability specified in this proposed program was fulfilled and exceeded after it was demonstrated on the vertical stabilizer surface.

2.4 Flaw Location

Flaw locations in specimens B-1 and B-2 may be classified into two categories: (1) flaws in the laminate and (2) flaws in the bondline between the laminate and the substructure. Each of these two categories may be further subdivided into two subcategories when the flaw is over the honeycomb core or over the Ti substructure. The orientation of the rectangular flaws is such that the long dimension is either parallel or perpendicular to the 0-degree fiber direction. Since the 0-degree fibers in a composite laminate are usually the main load-carrying elements, the dimension of the flaws in the anisotropic composite structure and their degrees of inspection difficulty should be addressed.

The different flaw classifications in specimens B-1 and B-2 are identified in Figure 7 and summarized in Table 2. The flaws in specimens A-1 and A-2 were all located in the bondline between fiberglass-Ti or G/E-Ti. In specimen A-3, the flaws were located in areas with different metallic flange thicknesses.

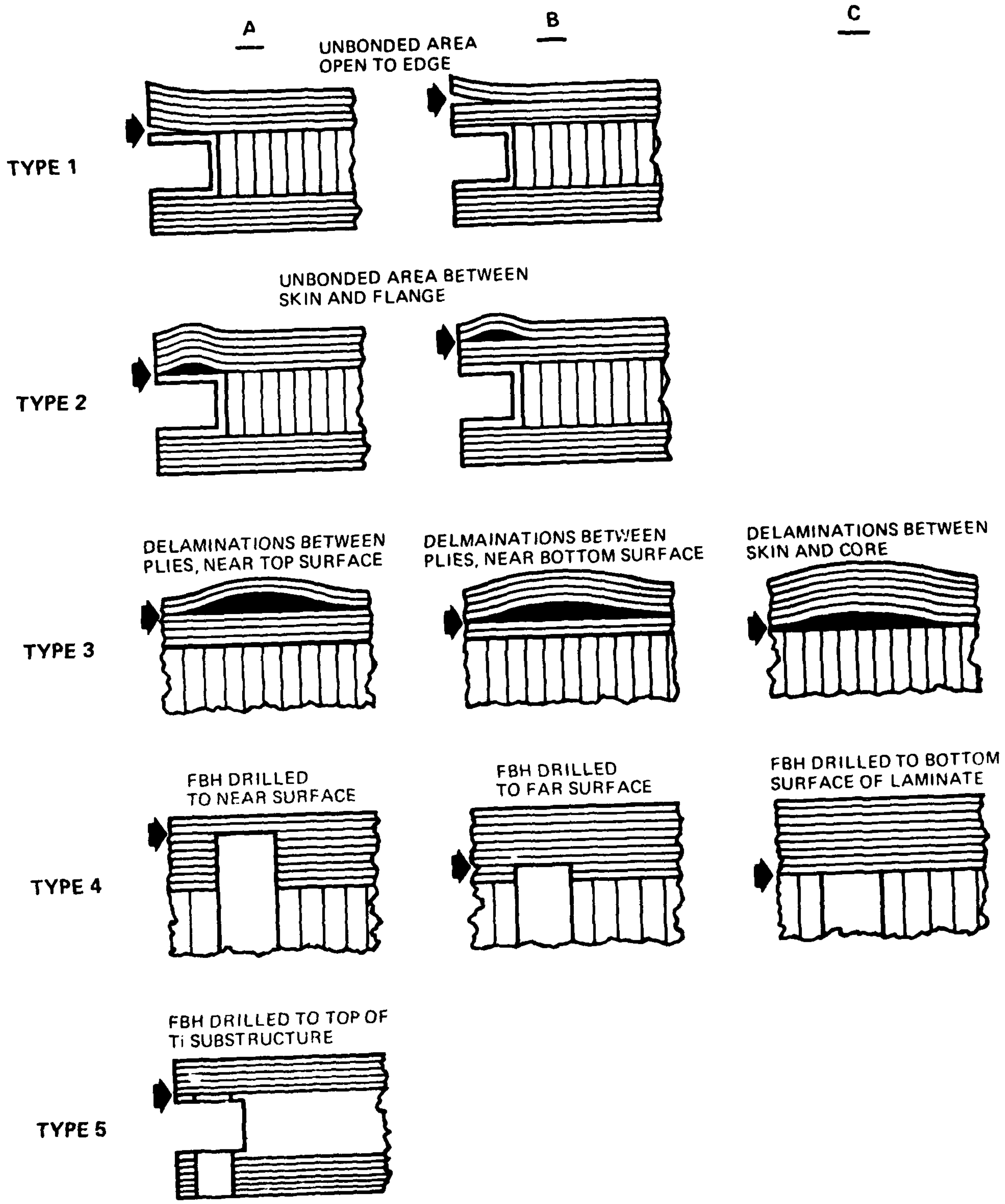


Figure 7 Flaw Type Classification for Type B Specimens

Table 2. Flaw Location Classification
For Type B Specimens

FLAW TYPE	LAMINATE	BONDLINE	OVER METAL	OVER H/C	REMARKS
1A		X	X		Open to edge
1B	X		X		Open to edge
2A		X	X		Not open to edge
2B	X		X		Not open to edge
3A	X			X	Near top surface
3B	X			X	Near bottom surface
3C		X		X	
4A	X			X	Near top surface
4B	X			X	Near bottom surface
4C		X		X	
5		X	X		FBH

Several difficulties were encountered during the fabrication of specimens B-1 and B-2. The 3-D flaw map showing the lateral location and flaw depths in terms of pre-preg ply thicknesses was not detailed enough for the tape lay-up personnel. Confusion in the flaw location led to several misplacements of the implanted flaws. In addition, some of the implanted flaws apparently shifted slightly laterally after they were placed in their designated positions between the pre-pregs. Consequently, some of the C-scan flaw maps showed a slightly different flaw pattern from the designed drawing shown in Figure 3.

2.5 Flaw Type

A unique Kapton film technique developed under a General Dynamics Independent Research and Development (IRAD) program (Reference 2) was used to simulate delaminations in laminates and bondline interfaces at the desired locations. Conventional techniques generally insert a single 0.025 cm (0.010 in.) or 0.013 cm (0.005 in.) thick Teflon (or Mylar) disc cut to the desired shape at the flaw location. This type of flaw actually represents inclusions rather than a void or delamination. They offer a target to the probing ultrasonic beam like foreign inclusions and reflect the sound waves from the acoustical impedance mismatch between the composite and the inclusion materials. The Kapton film technique used two extremely thin layers of Kapton film 0.0013 cm (0.0005 in.) laid one on top of the other. In the first attempt to cure the G/E skins on specimen B-2, the films were cut into 0.64 x 2.54 cm (1/4 x 1 in.) rectangular patches. Two layers of these patches were laid between the pre-preg plies without any adhesive on the edges. During the curing process, it was found that the fluidic epoxy had penetrated into the spacing between the two film layers. The delaminations to be simulated were not achieved. Subsequently, patches with a dimension of 1.27 x 3.18 cm (1/2 x 1 1/4 in.) were cut and a 3M adhesive (EC1403) was used to seal a width of 0.32 cm (1/8 in.) around the edges of the patch. This measure was successful in preventing the epoxy to flow and in producing good simulation of delaminations.

In addition to simulating flaws by implanting Kapton films, flaws were also simulated by drilling FBHs to various depths in the composite structures. This type of flaw was included in the specimens since FBHs have been widely adopted in the NDT community as an accepted reference flaw in metallic and homogeneous materials (Reference 3). Production facilities of advanced AF aircraft use FBHs in reference specimens in production inspection. A cross-reference may be achieved between production and in-service inspections by including specimens containing FBHs as flaws in the technique development and system assembly for in-service ultrasonic inspection.

Impact damages were imparted to specimen B-3 utilizing a drop test fixture shown in Figure 8. An Endevco Model 2252 accelerometer, a Model 2104-5000 force gage, and a Model 2730 GQ charge amplifier were used in conjunction with a Tektronix 2633 storage oscilloscope. The accelerometer and force gage were attached to the hammer assembly with a combined weight of 5.68 kg (12.5 lb.). Eight (8) damage sites were generated on the specimen. Five (5) sites were generated with the hammer dropping from a height of 2.29 m (90 in.) (designated as 90-1 to 90-5). Three (3) sites were generated with the hammer dropping from a height of 1.52 m (60 in.) (designated as 60-1 to 60-3). Figure 5 shows the locations of the damage sites, approximate sizes of the damages, and the relative position of each site relative to the fastener holes.

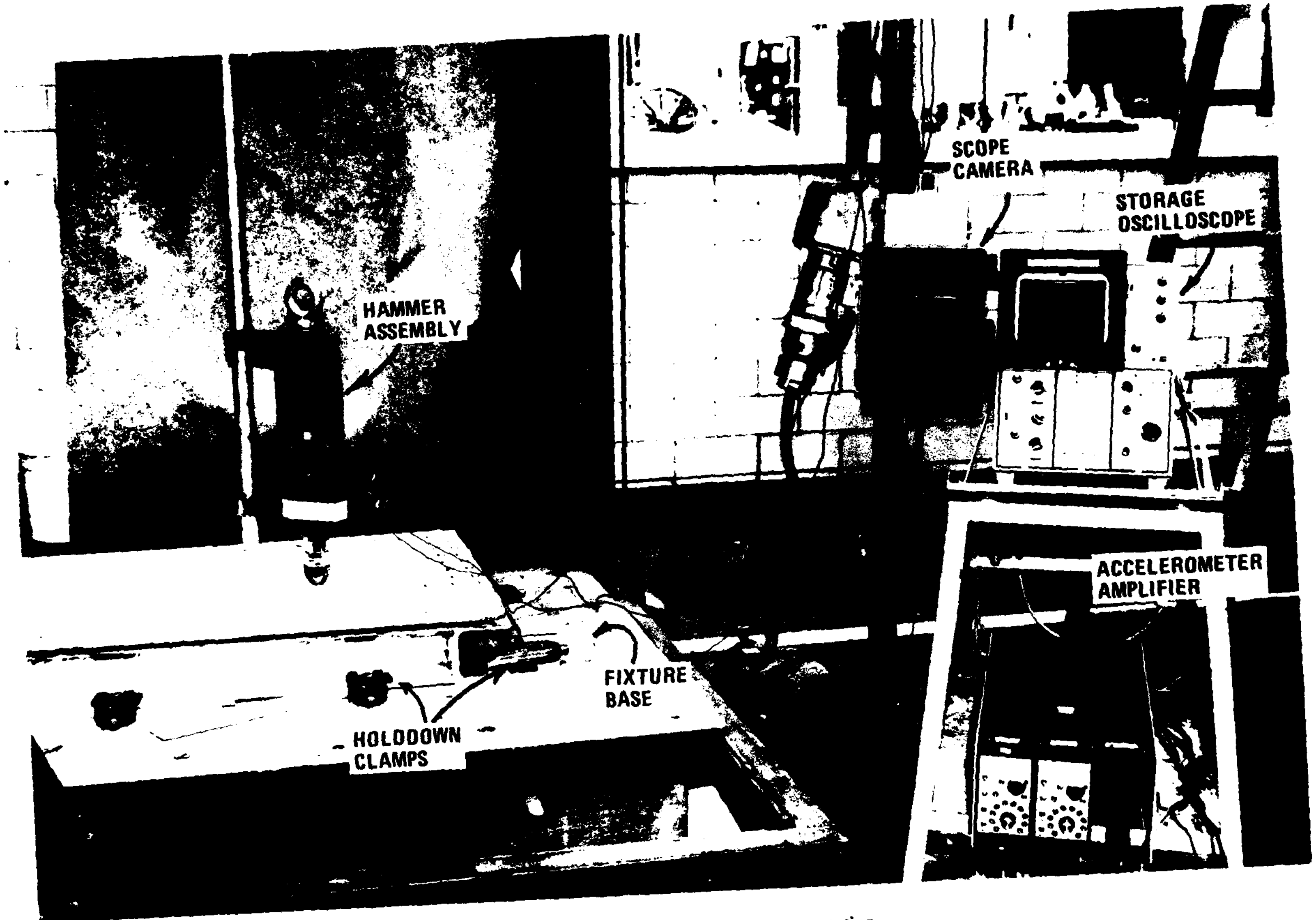


Figure 8 Drop Test Fixture and Instrumentation

III. ULTRASONIC TECHNIQUE DEVELOPMENT

The objective of this task was to develop an ultrasonic technique capable of distinguishing the simulated flaws in the flawed specimens from the various geometrical changes in the specimen configurations representing complex composite aircraft structures. The development of the ultrasonic technique was based on a high-resolution technique developed at General Dynamics for composite-laminate and bonded-joint inspection. The ground rules for the technique development were that access was limited to one side of the specimens and inspection would be limited to near-side flaws only.

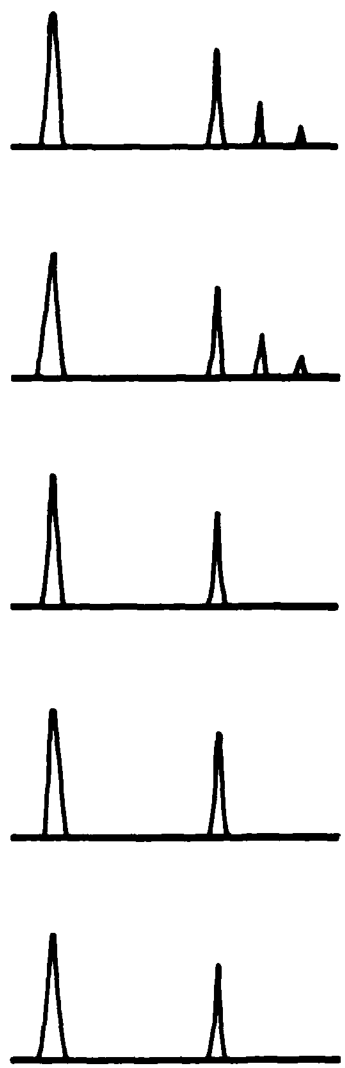
3.1 High-Resolution Ultrasonic Inspection Technique

A high-resolution ultrasonic technique in the contact mode with interface gating has been used by General Dynamics in the composite-structure inspection in the YF-16 prototype and F-16 full-scale-development programs since 1971. This technique uses wide-band pulsers capable of generating high-intensity and short duration pulses to excite high-frequency and highly damped piezoelectric transducers. The combination of this type of pulser and transducer achieved the simultaneous requirement of near-surface resolution (2-3 plies) and penetration power (52 plies plus a bondline between the skin and the substructure). A delay line in the form of a polyethylene spacer with the appropriate thickness is attached to the transducer face plate to allow a better separation of the front surface reflection from signals to be monitored. A Sonic Mark III ultrasonic unit with a PR-25D pulser/receiver, a DTB-250 sweep module, and a Panametric 5 MHz highly damped transducer were used in the high-resolution technique.

3.2 Signal Recognition

One of the most important tasks in the ultrasonic inspection of composite A/C components is the ability to identify the signals reflected from various geometrical interfaces in the composite structures. During the ultrasonic technique development phase of this program, signal recognition work has been conducted on the different types of specimens. Specifically, the prominent flaw signal characteristics of each type of flaw in the test specimens is classified in Figure 9. An example of the loss of multiple Ti reflections characteristic of type 1A, 1B, 2A and 5 flaws is shown in Figure 10. In this figure, the video RF

FLAW TYPE	FLAW DESCRIPTION	NORMAL SIGNAL CHARACTERISTICS	FLAW SIGNAL CHARACTERISTICS	FLAW SIGNAL DESCRIPTION
1A 1B 2A 5	Far Surface Disbond Open to Edge Near Surface Disbond Open to Edge Disbond Skin/Ti FBH Skin/Ti			Loss of Multiple BSR from Ti
2B	Far Surface Disbond Skin/Ti			Signal Between FSR & BSR, Near BSR
3A 4A	Near Surface Delaminations Near Surface FBH			Signal Between FSR & BSR, Near FSR
3B 4B	Far Surface Delamination Far Surface FBH			Signal Between FSR & BSR, Near BSR
3C 4C	Delamination Skin/Core FBH at Skin/Core			Strong Multiple from Delamination



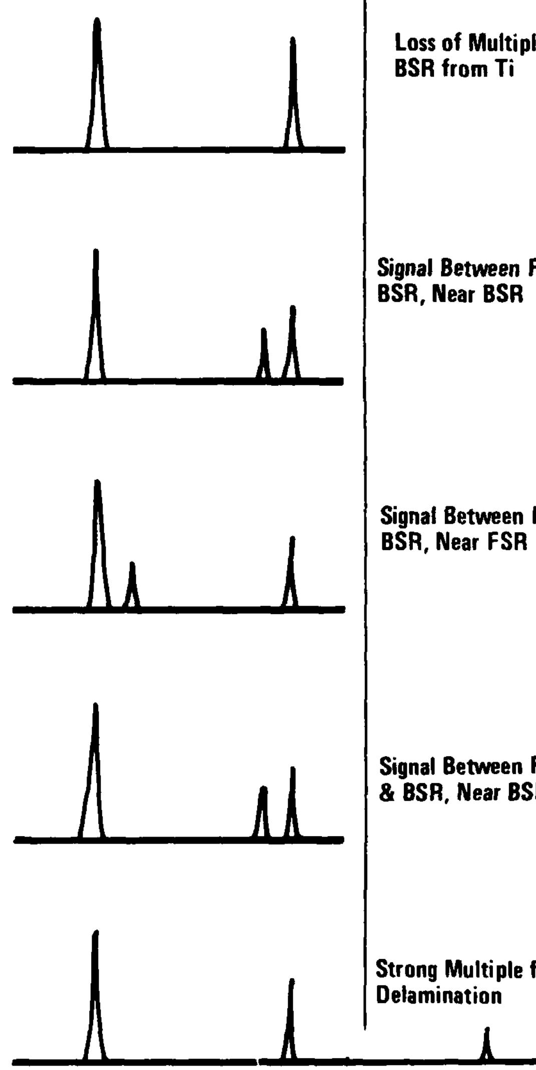


Figure 9 Flaw Signal Characteristics in Type B Specimens

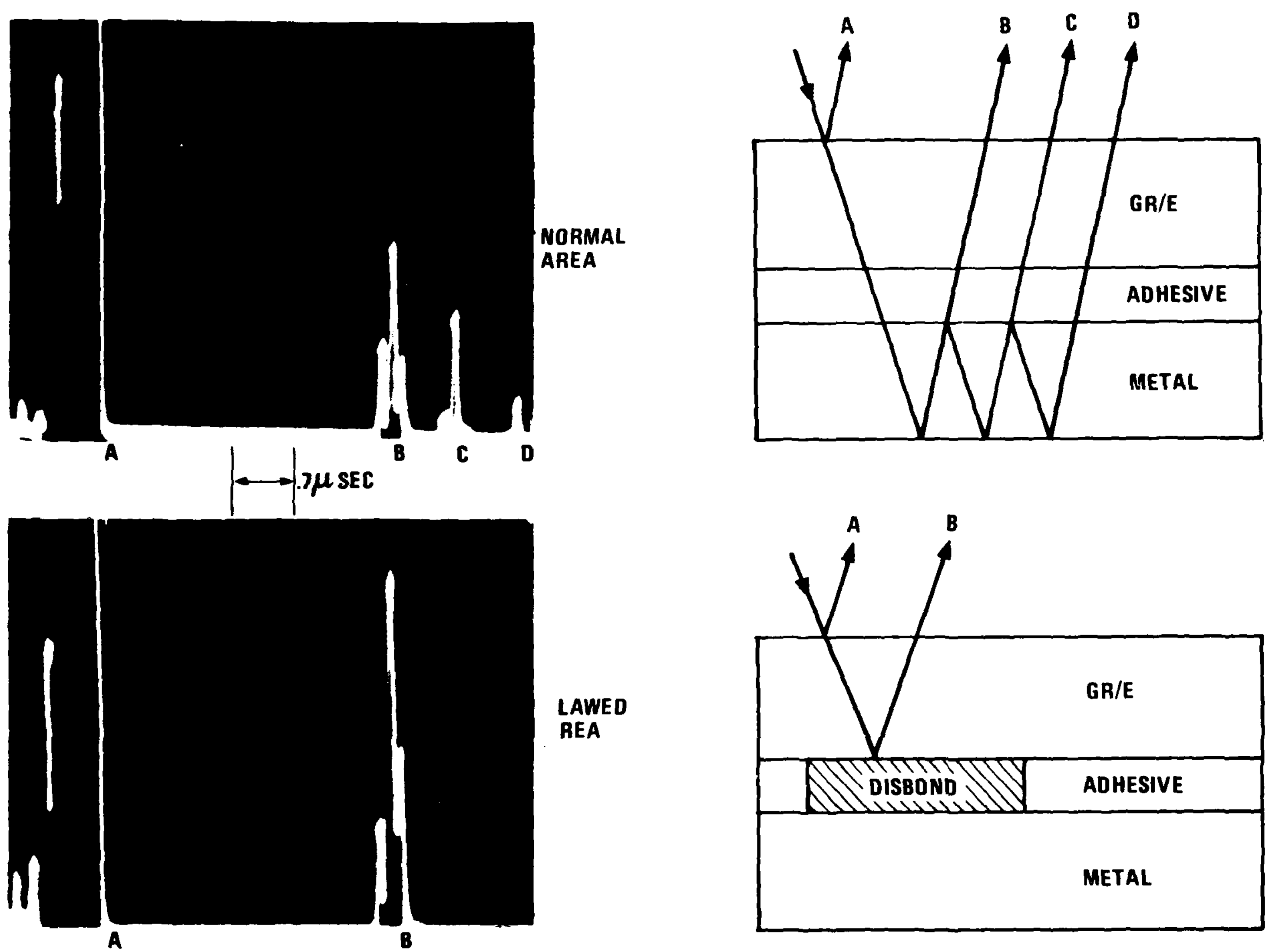


Figure 10 Loss of Multiple Ti Reflections Characteristic of Type 1A, 1B, 2A & 5 Flaws

waveforms for a normal area and a flaw area are shown at the left. A schematic of the sound wave propagation path corresponding to each of the RF waveform is shown at the right. For the sake of distinguishing the sound propagation paths, the beams were slanted in the diagram at a slight angle from the normal to the surfaces. All the actual sound beams should be normal to the specimen surface. Figure 11 shows an example of the video waveforms characteristic of type 3A and 4A flaws. The flaw signal in this figure corresponds to a flaw at a depth of 4 plies. It is separated by a time period of approximately 0.56 microsecond from the interface (IF) signal. It is estimated that a near-surface resolution of 3 plies or less can be achieved using a 5-MHz highly damped transducer.

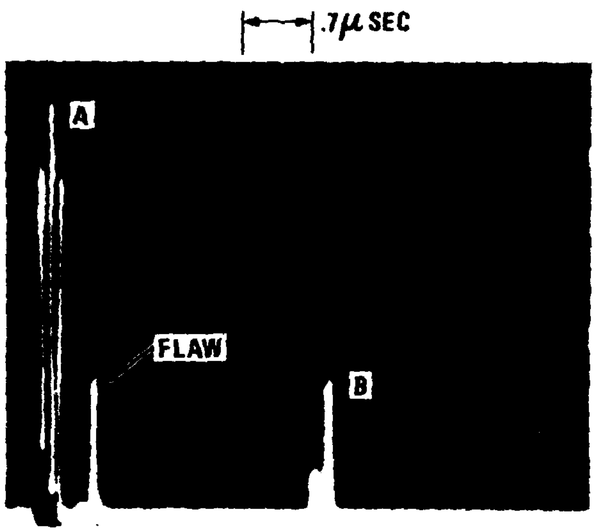
Figure 12 shows an example of the video waveforms characteristic of type 2B, 3B and 4B flaws. The near-surface resolution is obviously less stringent compared to the near-surface resolution without the pulse-width limitation of the IF signal. It should be noted that the back surface reflection (BSR) signal (B) in the waveform shown in Figure 12 may not be present when the flaw area is larger than the transducer size. Figure 13 shows an example of such a case. The flaw signal characteristic of type 2B flaws is similar to that shown in Figure 12. The normal signal characteristics, however, are quite different, as shown in Figure 9.

Flaw signals characteristic of delamination or FBHs at the skin/core interface were difficult to identify. Due to the thinness of the adhesive layer bonding the skin to the honeycomb core, the absence of the layer would not change the amplitude of the BSR signal appreciably. Any signal amplitude change would be shadowed by the normal BSR signal amplitude variation during hand scanning. For the thinner portion of the laminate skin, the criterion of multiple reflection from the G/E skin over areas of skin/core debond was used successfully in distinguishing this type of defect.

The flaw signal characteristics shown in Figure 9 were used in the system tryout phase of the program to map out the flaws implanted in the test specimens. The gating method of monitoring the flaw signal amplitude is discussed in the next subsection.

3.3 Dual Gate Concept

A dual gate technique has been developed to simultaneously monitor possible flaw signals in different sections of the test specimens. A severe difficulty to be overcome in the development of an automatic flaw monitoring system is that the system must transform the operator's visual observation of the entire CRT screen into a small area focussed on the flaw signal(s) on the ultrasonic unit. In lieu of the "automatic gate" of the inspector's visual perceptional senses,



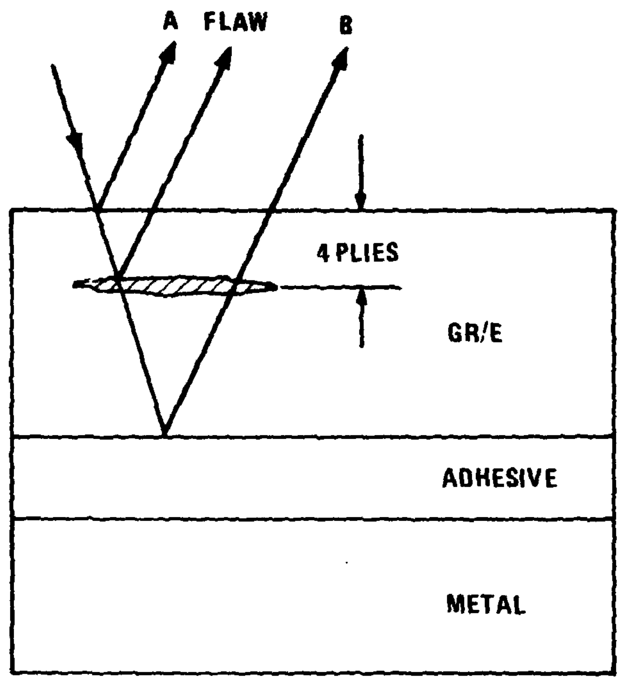
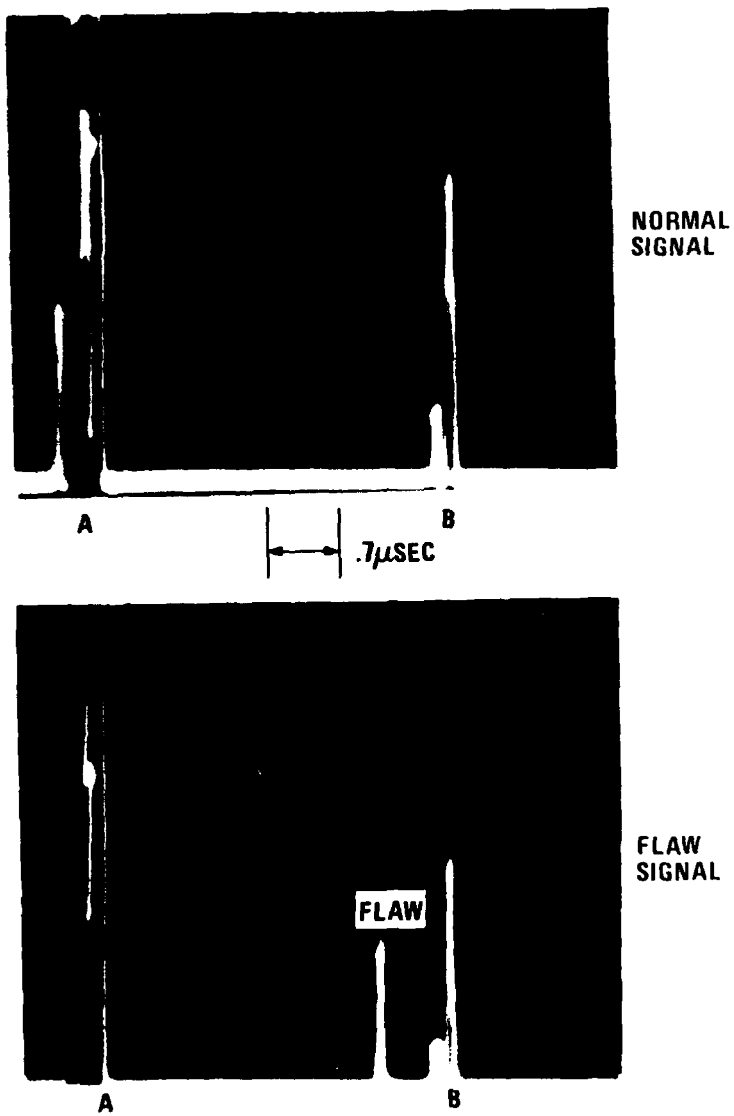


Figure 11 Waveform Characteristic of Near Surface Flaws (Type 3A & 4A)



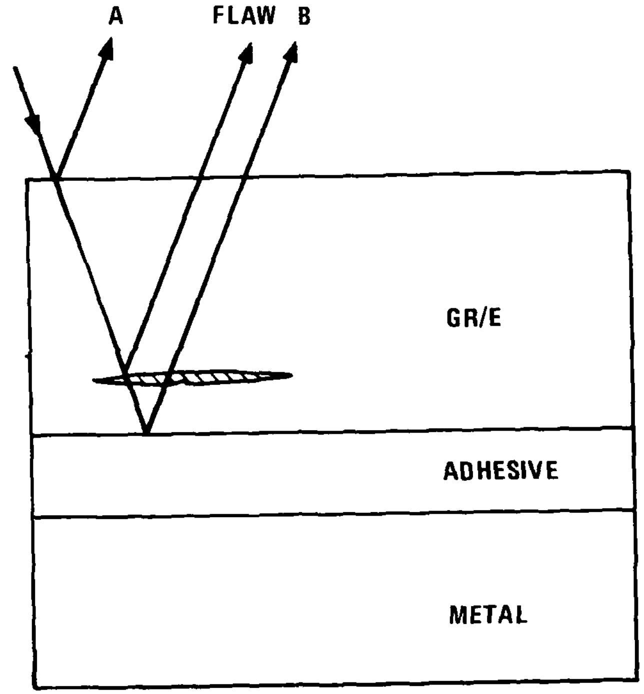


Figure 12 Waveform Characteristic of Far Surface Flaws (Type 2B, 3B & 4B)

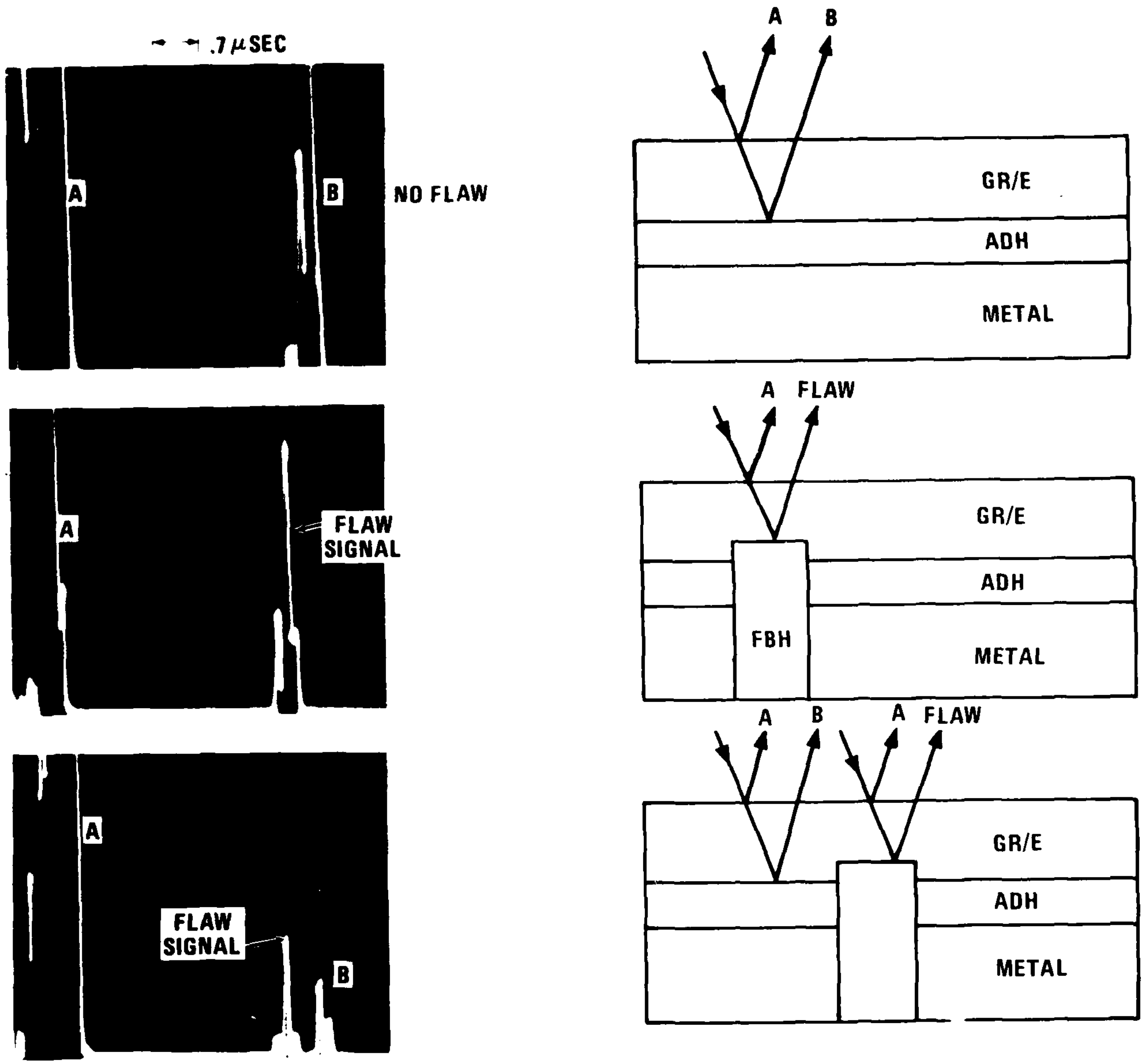


Figure 13 Loss of BSR Signal (B) May Occur for Far Surface Flaws

the system must position a gate over a portion of the time axis of the RF signal so that a peak detector may detect any signal appearing in the gate and sense the amplitude of that signal. If the amplitude of that signal appearing in the gate exceeds a pre-set trigger level, a flaw indication will be flagged either in the hardware of the ultrasonic unit or in the software of the computer. In the ultrasonic inspection of homogeneous materials, the gate can be triggered by the trailing edge of the front surface reflection (FSR) signal and terminated by the leading edge of the BSR. Any flaw signal appearing in the gate would signify a flaw in the material. For the inspection of components made of advanced composite materials, the flaw signal characteristics shown in Figure 9 and discussed in the previous subsection are much more complicated compared to the case of the homogeneous materials. The concept of the amplitude of a simple gated signal exceeding a pre-set value signifying a flaw is no longer valid in general. Sometimes a lack of reflected signals should signify the presence of a flaw.

In the dual-gate concept, the first gate remains the same as in conventional inspection for homogeneous materials. It is triggered by the trailing edge of the FSR signal and terminated by the leading edge of the BSR signal. In addition to this gate, a second gate is initiated by the trailing edge of the BSR and terminated by the multiple second reflection from the buffer or delay line. The purpose of the second gate is to monitor the lack of multiple reflections from the metallic substrate. The flaw discrimination software of the computer can be arranged in an and/or logic depending on the structural details of the specimen being inspected. In an area over the honeycomb core, the criteria of strong multiple reflections from the G/E skin appearing after the initial BSR should be used as a flaw discrimination factor. In this case, the second gate may be extended beyond the second reflection from the buffer and the appearance of a signal in the second gate would signify a flaw. In order to distinguish this case from the case of the loss of multiple Ti reflections, the structural details of the regions to be inspected must be known in order to set up separate flaw discrimination logic.

3.4 Metallic Reinforcements in the Laminates

No satisfactory results have been obtained on the ultrasonic technique development for detecting flaws in the regions on one side of Specimen B-1 with Ti shim and stepped bar. For the flaws implanted beneath the metallic reinforcements, the strong reflection at the front surface of the metal and the subsequent multiple reflections totally obscured any signals reflected from interfaces below the metal. These multiple reflections also invalidated the criterion for the loss of multiple reflections from the Ti channel.

On the side of specimen B-1 with the hybrid skin, a strong discontinuity appeared at a depth immediately below the front surface. This discontinuity also caused a strong reflected signal and overshadowed all subsequent signals. It is surmised that this discontinuity was created during manufacturing processes.

IV SYSTEM ASSEMBLY

The laboratory mock-up model of the in-service inspection system for composites was assembled from off-the-shelf commercial equipment. These equipment were purchased by the Quality Assurance Department of General Dynamics' Fort Worth Division. The mock-up system will be transferred to the production line for F-16 production inspection after it has served the purpose of system concept development in this program. Figure 14 shows a block diagram of the laboratory mock-up system identifying each of the individual components. The system can be divided into four parts: (1) computer, (2) X-Y locator, (3) ultrasonic unit, and (4) pulsed transient recorder. Each of these four parts will be discussed in the following sections.

4.1 Computer and Peripherals

The heart of the inspection system is a HP 9825A desktop computer with 15,036 bytes (8 bits each) of read/write memory with 4 bytes per word. It has a 32 character LED display, 16-character thermal strip printer, and a typewriter-like keyboard with upper-and lower-case alphanumerics. To control the HP 9862 digital plotter, a HP 98214A read-only-memory (ROM) is used to provide general input/out (I/O) and extended I/O capabilities. The desktop computer has a two-track tape cartridge drive with a 250,000 bytes of memory. In addition, a HP 9885M floppy disk drive is used to extend the memory capacity by 468,480 bytes with a fast data transfer rate. Programming of the computer is done by an easy-to-learn high-level programming language (HPL). A digital plotter, HP9862A, serves as a data display unit and provides the C-scan of the inspection results. A HP9878A I/O expander is needed to accomodate all the peripherals interfaced with the computer.

4.2 X-Y Locator

The system has a unique position sensing unit consisting of a GP-3 Graf/Pen Sonic Digitizer. The Sonic Digitizer is primarily a graphics device. It consists of a control unit, a set of sensors, and a cursor.

The functions of the control unit are to initiate low frequency (70kHz) energy pulses (which are converted into sonic waves by the cursor) to measure the time required for the sonic energy to reach the sensors, and to convert the time into dis-

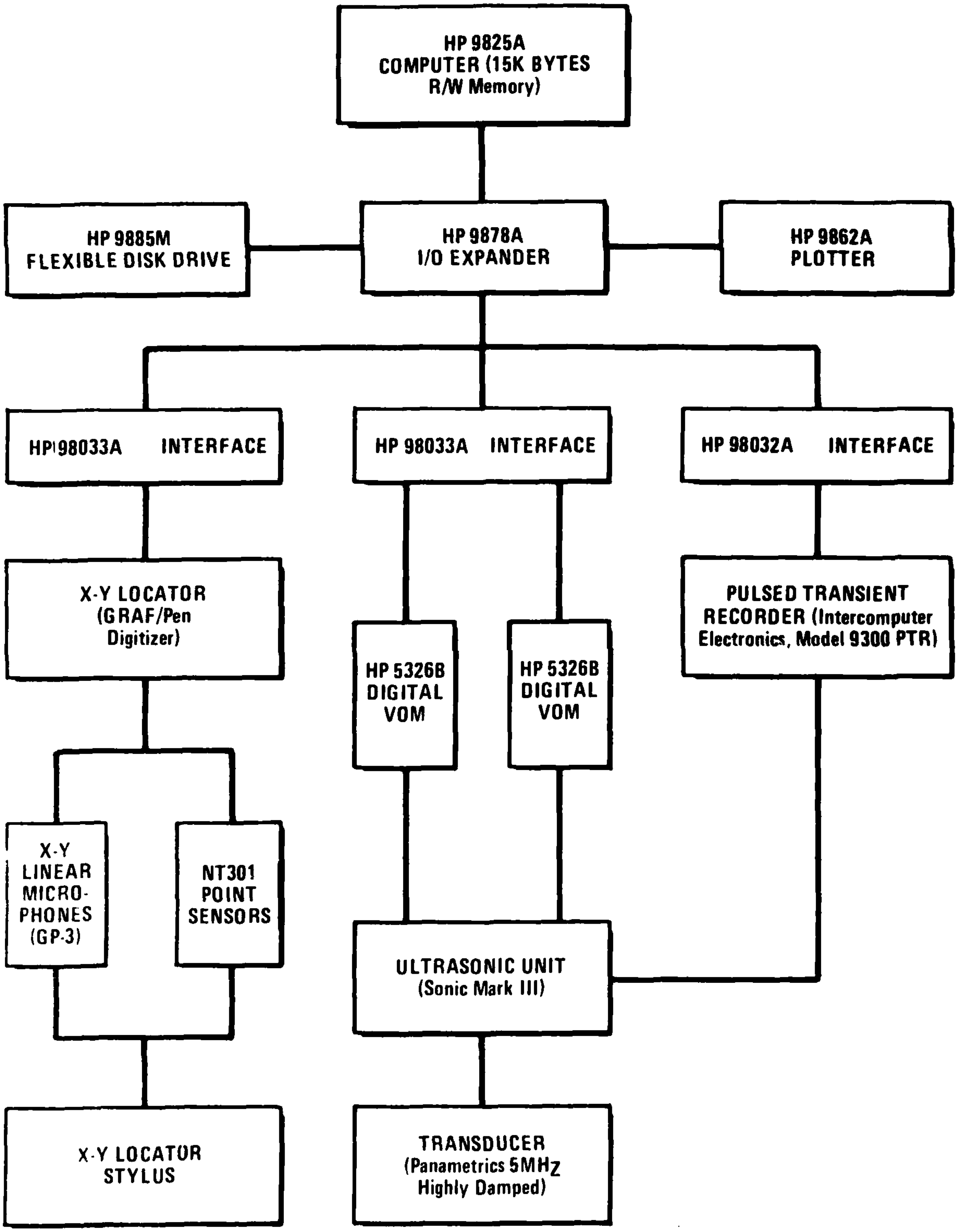


Figure 14 Block Diagram of the Laboratory Mock-Up System

tance measurements in digital form. A discriminator circuit within the control unit prevents ambient noises from interfering with the position sensing operation. Output signals are stored in output registers until both X and Y values are ready at which time an "output ready" signal is generated to inform the computer that another set of coordinate information is available. A numerical display module in the control unit provides visual indication of coordinate readings. The X and Y values in rectangular coordinates or the A and B values in the triangular coordinate in BCD form are taken from the data bus of the GP-3 and transferred to the computer in a serial form.

The position sensors of the Sonic Digitizer can operate in two forms: (1) a set of linear sensor microphones 1.52 x 1.83 m (5 x 6 ft.) providing a pair of rectangular coordinates, and (2) a pair of point sensors providing a set of triangular coordinates. The control unit can be converted from one form of operation to another by inserting a plug-in circuit board. The linear microphones consist of a set of electret elements encased in a protective frame in L-shape. The microphones are connected to the control unit by a 3.05 m (10 ft.) cable. Photographs of the two systems are shown in Figures 15 and 16.

The cursor unit consists of a cylindrically shaped hollow piezoelectric transducer operating in a thickness vibrating mode. The transducer generates 70 kHz sound waves to be received by the sensors for position conversion. A pushbutton on the cursor body permits the operator to operate the position sensing function in a "point" mode. Additional pushbutton switches may be added on the cursor to permit the user to control external circuitries such as the RF waveform digitization. A photograph of the cursor is shown in Figure 17 with an ultrasonic inspection transducer attached to the cursor body. By attaching the inspection transducer to coincide with the cursor transducer, the location of the inspection transducer can be obtained in the form of either a rectangular or triangular coordinate. The coordinate information is transferred to the computer memory and converted to the pen position on the plotter. The precision in both the rectangular and the triangular coordinates is better than 0.076 cm (0.030 in.). In the point sensor operation, however, the sensors must be placed at least 10.16 cm (4 in.) away from the active area on the specimen to be inspected.

4.3 Ultrasonic Unit

The position sensing capability of the system is not dependent on the ultrasonic unit. The only connection of the ultra-

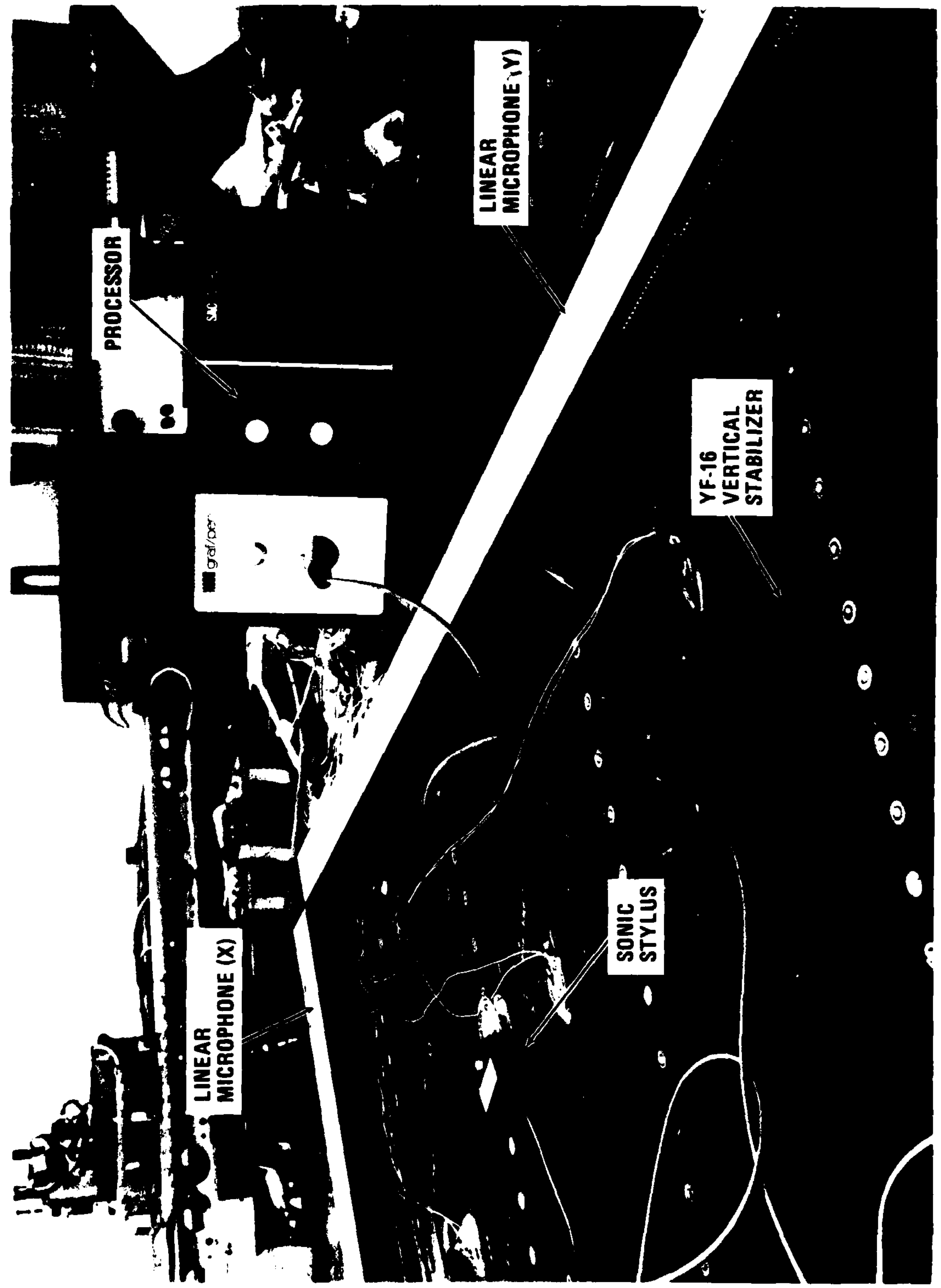


Figure 15 Microphone Sensor X-Y Locator System

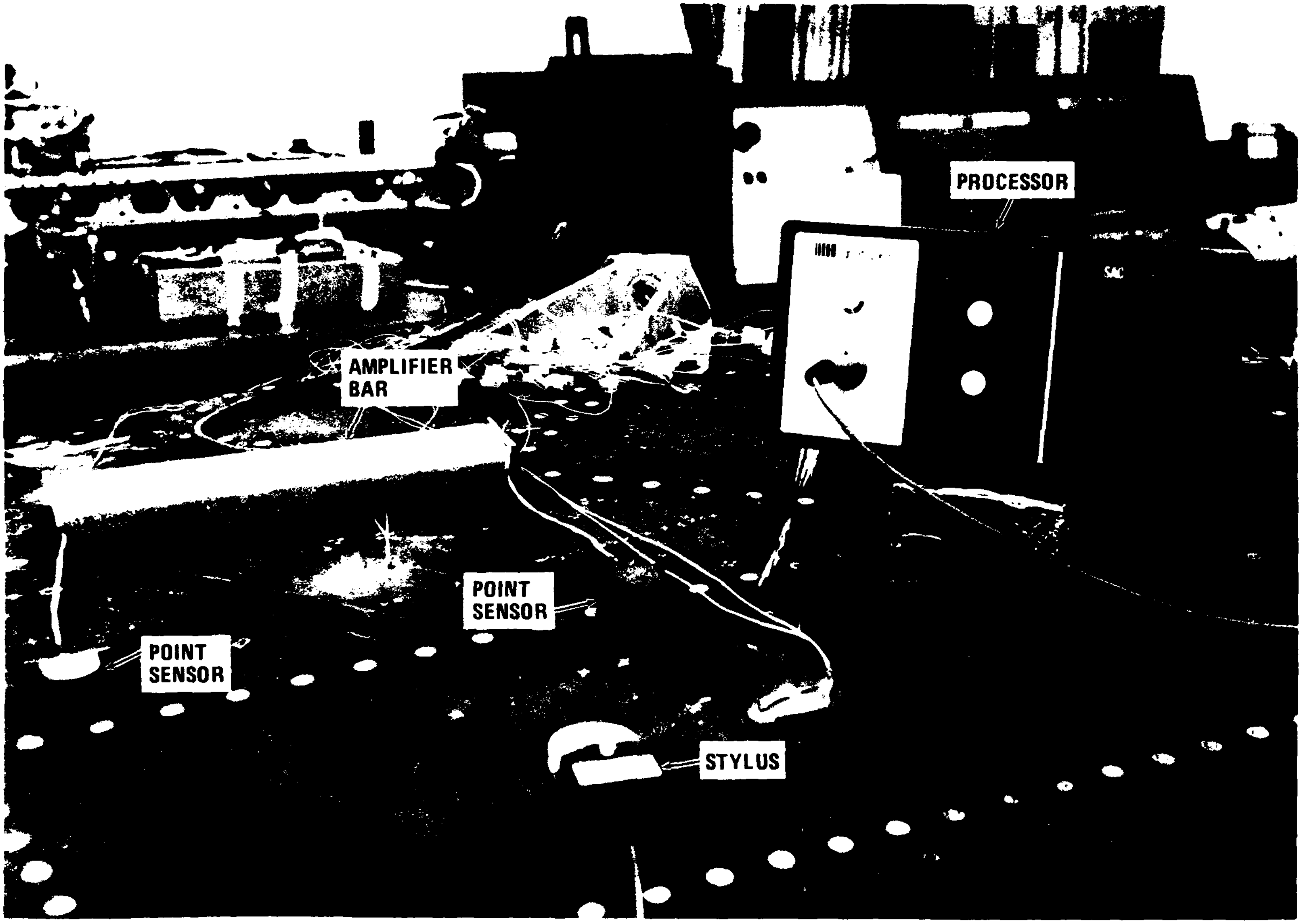


Figure 16 Point Sensor Locator System

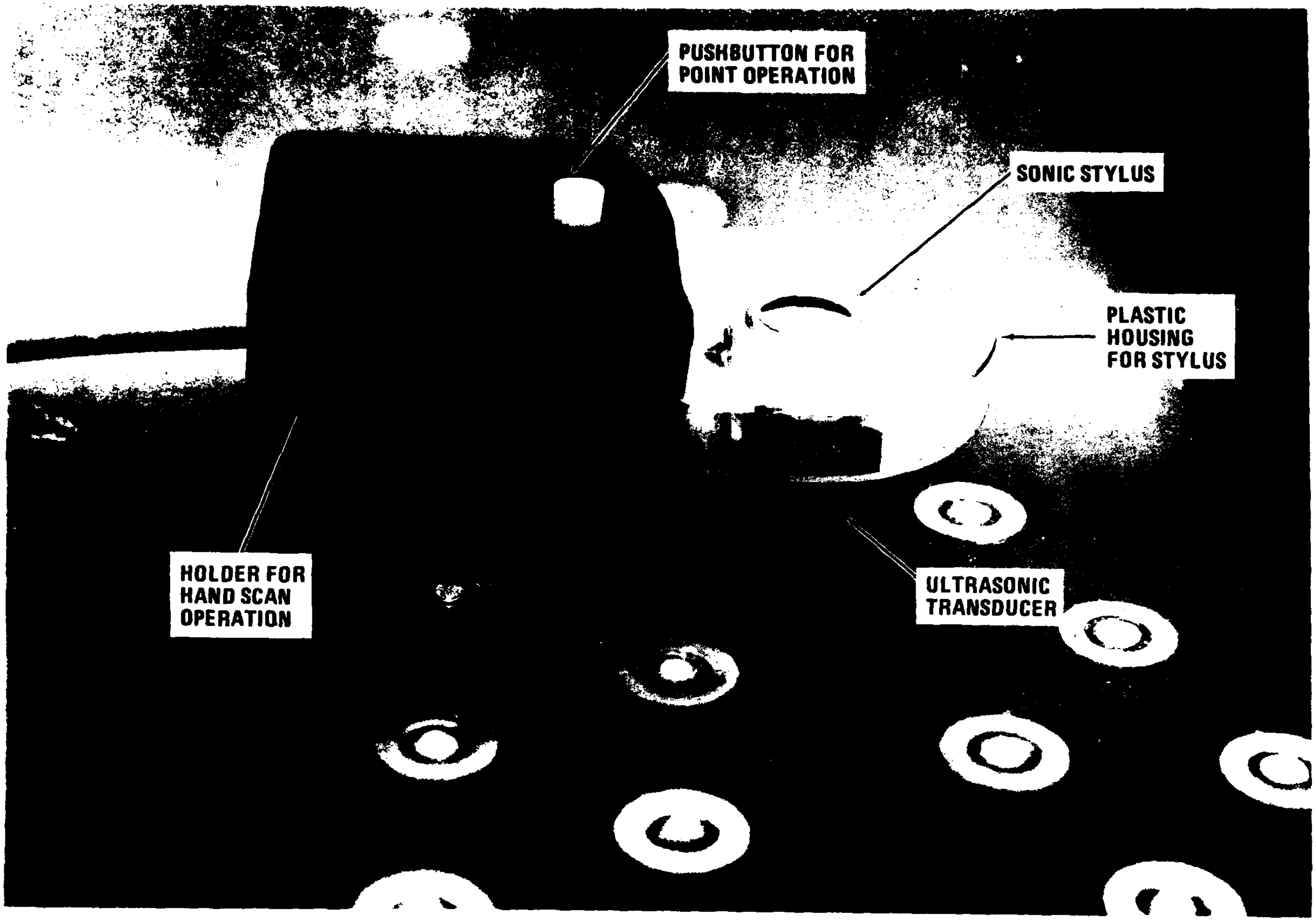


Figure 17 Cursor with a Transducer Attached

sonic unit with the position sensing unit is in the physical attachment of the inspection transducer to the cursor. The primary purposes of the ultrasonic unit are to pulse the inspection transducer sending an ultrasound into the specimen, to receive the reflected ultrasonic signal, and to provide a flaw signal amplitude in the flaw gate to the computer through each of the two analog/digital (A/D) converters. The requirements placed on the ultrasonic unit to be used in the in-service inspection system for composites may be defined along the line of these three purposes.

The first requirement of the ultrasonic unit is to provide electrical pulses with high voltage and short duration. The high pulse voltage enables the transducer to respond with large amplitude stress waves which can propagate through thicker composite laminates and more complex structures with high acoustical attenuation. The short duration pulses decrease the ringtime of the transducer so that it can recover quickly after the interface reflection and react to discontinuities lying near the front surface. The Sonic Mark III with a PR25D pulser/receiver and a DTB250 timebase plug-in module was found to satisfy both of these requirements. The pulse output voltage of 150 v, with a broadband range of 600 kHz to 25 MHz, used in conjunction with highly damped transducers, could easily penetrate 52 plies of G/E or B/E laminates plus a layer of adhesive (approximately 0.015 cm (0.006 in.)) and a Ti substructure of 0.23 cm (0.090 in.) thickness. The near surface resolution achieved with the ultrasonic unit was better than 3 plies of G/E with an Al flame-sprayed coating (worst case).

The second requirement of the ultrasonic unit is to receive and amplify the signal reflected from the different interfaces in the composite structure. The Sonic Mark III has a 100 db range of signal amplitude attenuation plus a manually adjustable distance amplitude compensation (DAC) unit. The effective range of attenuation used in the system tryout was approximately 80 db. The CRT screen display is a rectified video with a grass-root reject adjustment.

The third requirement of the ultrasonic unit is to provide a flaw signal amplitude in the flaw gate to the computer through each of the two A/D converters. Sonic Mark III is a dual gate unit. This feature is especially suitable for the dual-gate concept of flaw detection discussed in the ultrasonic technique development in Section II. The gated video signals in the two gates have a range from -0.4 to 1.6 v. The flaw recognition criteria in the computer software have, therefore, an excursion of 2 v. In this program, two HP digital volt-ohm-meter (VOM) were used to convert the analog voltages of the gated signals to a digital form before they were transferred to the computer. An interface card (HP 98033A) provided the connection between the two VOMs to the HP9825A computer. These two VOMs have been replaced by two Hybrid Model ADC 540-8 A/D converters which are miniature modules with a much faster conversion rate.

An additional requirement for the ultrasonic unit in the laboratory mock-up system is to provide a RF signal to the digitizing unit to produce a permanent record of the RF waveform. The RF waveforms for the reflected signals in certain areas on the specimens are more desirable than rectified video signals because phase change informations can be extracted from the RF waveforms for flaw signal recognition. The Sonic Mark III does not provide a convenient output point for the RF waveform. The RF signal was tapped from the last stage of the RF amplifier immediately after the phase-splitter circuit. An emitter follower circuit was built to isolate the loading created by the pulsed transient recorder.

Use of the ultrasonic unit in the inspection system is quite flexible, depending on the specific requirements imposed on the system. If dual gates are not necessary, Sonic Mark IV or other equivalent units could be used, as long as the basic requirements delineated in the previous paragraphs are satisfied.

4.4 Waveform Digitization Unit

The waveform digitization unit consists of a Computer Electronics Inc., Model 9300 pulsed transient recorder (PTR) connected to the computer through a HP98032A interface card. Waveform digitization permits flaw depth determination and more accurate analysis of the waveforms by both spatial and temporal methods of signal averaging. The PTR has several different rates of digitization. The fastest rate of 10 nsec between points was found to be quite adequate for the 5MHz RF signals. The PTR provides 2816 points for each digitized waveform to the computer. Software programs were prepared for the computer to read the 2816 points from the PTR, store the information on the floppy disk, and output the RF waveform on the plotter. The digitized waveforms stored in the disk can also be retrieved and plotted out by playing back data recorded on the disk.

4.5 System Integration

The different units of the inspection system were assembled and mounted in a standard laboratory rack. Figure 18 shows the front panel of this instrument rack. Figure 19 shows the entire inspection system using a microphone system with Specimen B-3 in the active position sensing area.

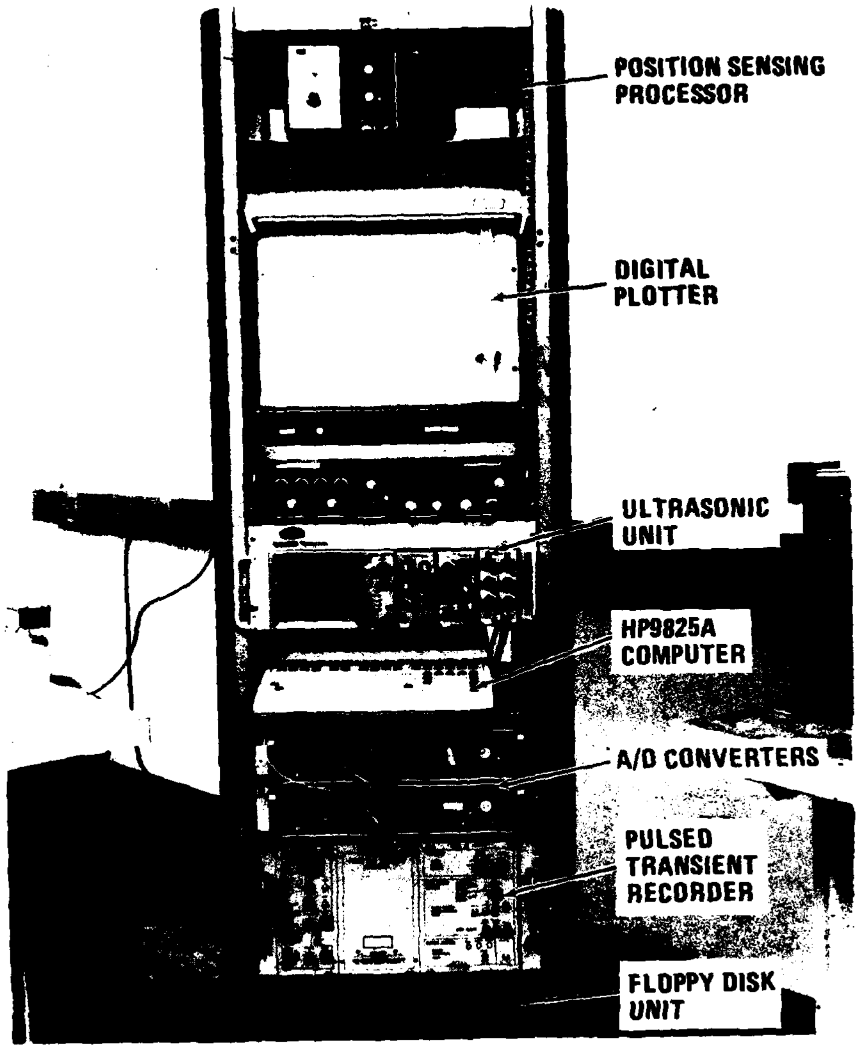


Figure 18 **Front Panel of Mock-Up Laboratory System Instrument Rack**

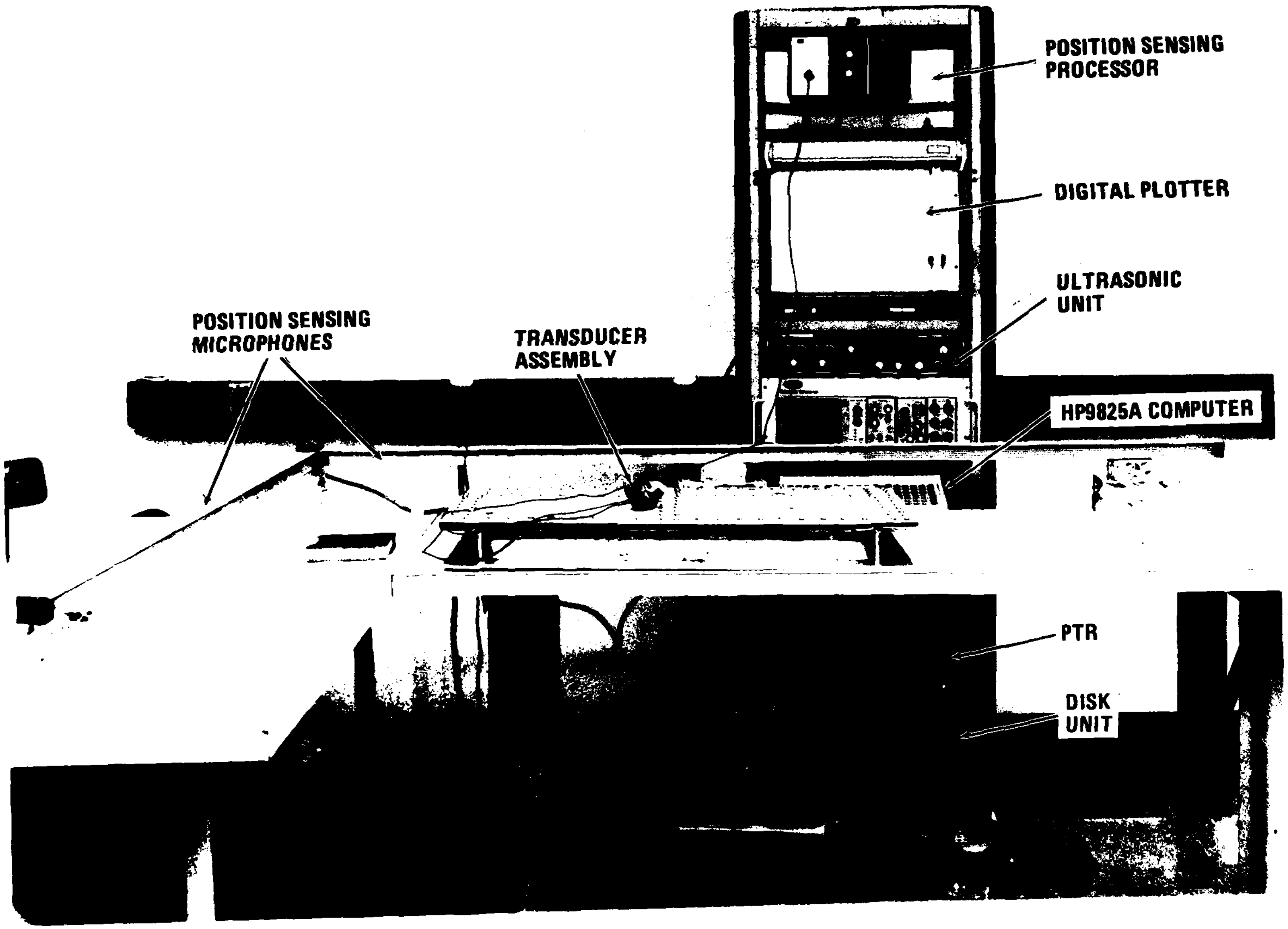


Figure 19 In-Service Inspection System Mock-Up Laboratory Model

V. SYSTEM TRYOUT

The laboratory mock-up system was used on Type A and B specimens to assess its flaw detection and indication capabilities. Results of the system tryout were highly successful. The flaw indicating scheme used by the computer to integrate the ultrasonic unit and the plotter will be described in Section 5.1 immediately following the introductory remarks. Results of the C-scan and flaw plots are presented in Section 5.2 Limitations of the system capabilities and modifications needed in the design of the In-Service Inspection System (ISIS) prototype will be discussed in Section 5.3.

5.1 Flaw Indication Scheme

Flaw areas should appear on the C-scan indications obtained by the system in a shaded background indicating areas that have been scanned by the operator. If an area has been neglected by the inspector during the manual scanning, it should also appear as blank just as a flaw indication. This requirement created some difficulties in the laboratory mock-up system using a HP9825A desktop calculator and digital plotter. The main difficulty was the limitation imposed by the memory capacity and processing speed of the computer-plotter combinations. In order to produce a C-scan with blank flaw indications in a shaded background, data points in the normal areas must be recorded and stored on the floppy disk. The large number of data points that had to be recorded slowed down the processing and overloaded the recording capacity of the floppy disk unit.

Another difficulty encountered in the scheme of blank spaces signifying flaws in a shaded background of normal area arose from the gating schemes used in the ultrasonic technique for the detection of disbonds. When the absence of a signal in a gate was used as a criterion of flaw indication, any inadvertent loss of coupling between the transducer and the specimen surface during scanning would produce an erroneous flaw indication, This created problems for specimens with tapered skins when the transducer was moved across regions with different thicknesses. To produce a C-scan flaw map of the specimens indicating all the different types of flaws without lifting or tilting the transducer with an ensuing loss of coupling was impossible.

The scheme to overcome these difficulties was to divide the flaw indication into two separate plots: (1) a scanned area plot, and (2) a flaw indication C-scan. The scanned area plot produced shaded indications for the area that the inspector had already scanned. Any blank area in this plot would signify a neglected area. The flaw indication C-scan showed shaded flaws in a blank background of normal area. The scanned area plot and flaw indication C-scan were two separate plots on the same sheet of recorder paper. After the inspector had located the boundary points on the specimen, the plotter pen would outline the boundaries for both plots. As the inspector scanned the specimen, the plotter pen would ink in the scanned area on the first plot. After twenty (20) flaw points were recorded in the floppy disk, the plotter pen could move over to the flaw indication C-scan plot and indicate the flaws by dropping on the blank background. The floppy disk recorded the X and Y locations of each flaw point as well as the flaw signal amplitude in each of the two flaw gates. No duplicate flaw data would be recorded on the disk.

After the entire specimen had been scanned, a post inspection plot of the flaw indication could be retrieved from the data recorded on the disk. The flaw data were first sorted out and arranged in ascending order of the coordinates. They were sorted in ascending order of X coordinate within each Y coordinate increment of $\pm 1/16$ in.. A grid of 0.31 x 0.32 cm (.120 x .125 in.) area was assigned to each flaw point. The X value of each flaw point was assigned a finite length of 0.31 cm (0.12 in.). A plot routine was then used to plot out the flaw indications as blank areas in a shaded background of normal areas. Included in the plot routine was a specimen boundary outline program that would allow for a polygon of n sides to be outlined after all the corners of the polygon were defined. This outline scheme was applicable for a closed area of an arbitrary shape by approximating the geometric shape with a polygon of many sides.

The flaw indication schemes and specimen boundary outline routine were implemented in the computer under different program names. Table 3 shows a listing of the major software programs and their functions. The detailed program codes are presented in Figures A-1 to A-9 in the Appendix.

Table 3. Major Software Programs and Functions

Figure No.*	Program Name	Function
A-1	WORK	Takes data and plots
A-2	PTEND	Generates a data file on the disk containing boundary points
A-2	LIST	Lists Data
A-3	PREPAR	Determines corner points for post inspection plot
A-4	SORT	Rearranges data to speed retrieval
A-5	PTR	Digitizes RF waveform
A-6	PSTGRD	Makes axis transformation, draws part boundary for post inspection plot
A-7	PREGRD	Makes axis transformation, draws part boundary, draws grid and labels
A-8	BLOWUP	Magnifies flaw area
A-9	PSTPLT	Makes post inspection plot

* Appendix

5.2 C-Scan Results

The flaw/scan plots for Type A and B specimens obtained by using the laboratory mock-up system with the ultrasonic techniques and flaw indication schemes developed in the previous tasks are presented in this section. Results obtained from a damaged F-15 composite panel made of B/E composite are also presented. Examples on post-inspection flaw data listing and blow-up of specific areas are given. Use of the flaw amplitude discrimination in post-inspection plots will be discussed to demonstrate the system capabilities.

5.2.1 Results for Type A Specimen

Figures 20, 21, and 22 show the flaw/scan plots for specimens A-1, A-2, and A-3 respectively. In these and subsequent figures of similar type, the actual plots made by the digital plotter were reduced and the axis re-labeled to conform with the report format. The dimensions in the X and Y axes are in inches. Flaws contained in specimens A-1, A-2 and A-3 were FBHs with a diameter of 1.52 cm (0.6 in.). The flaw criterion used in the ultrasonic techniques was the loss of multiple reflections from the metallic substrate or composite skin. The flaw shapes in the flaw/scan plots were not perfectly circular due to two reasons. The main reason was the loss of coupling around the edge of the FBHs. A second reason was that some FBHs did not actually have flat bottoms due to improper machining and uneven reflecting surfaces were partially responsible for the irregular flaw indications.

5.2.2 Results for Specimen B-2

The flaw/scan plots for Specimen B-2 are shown in Figures 23 and 24 for the skins with implanted flaws and with natural defects respectively. A map of the implanted flaws in the specimen is inserted at the upper left hand corner of Figure 23. A comparison of the flaw map with the results of the C-scan in other portions of Figure 23 shows that different types of flaws were detected with excellent size and shape correlation except for a small number of omissions. A small number of Type 3C and 4C flaws were missing in the C-scan plots. Figure 24 shows a photograph and the flaw/scan plots for the skin with natural defects in specimen B-2. A combination of planar delaminations and scattered porosites was detected and indicated in the post-inspection flaw plot and real-time C-scan.

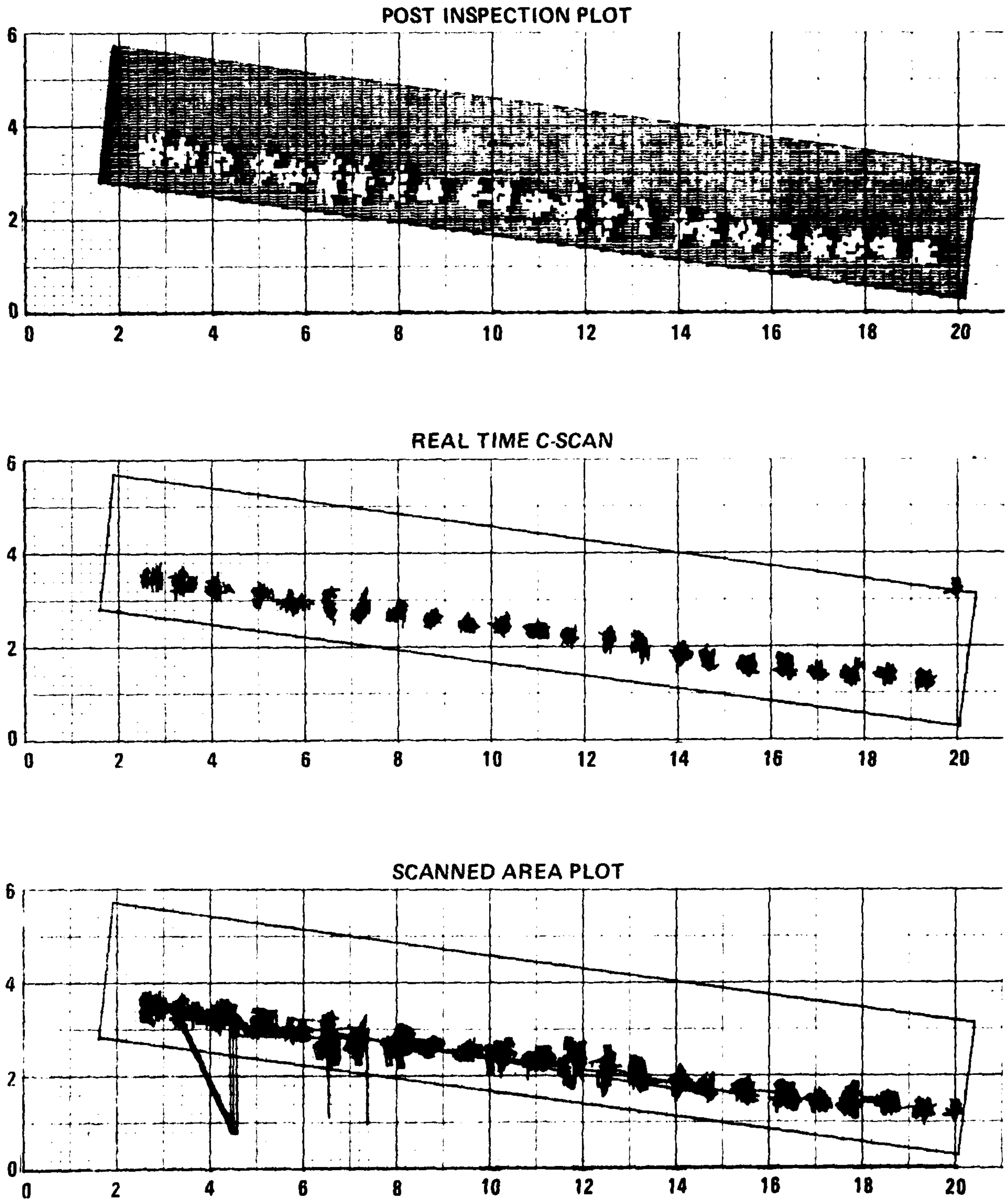


Figure 20 Flaw and Scan Plots for Specimen A-1

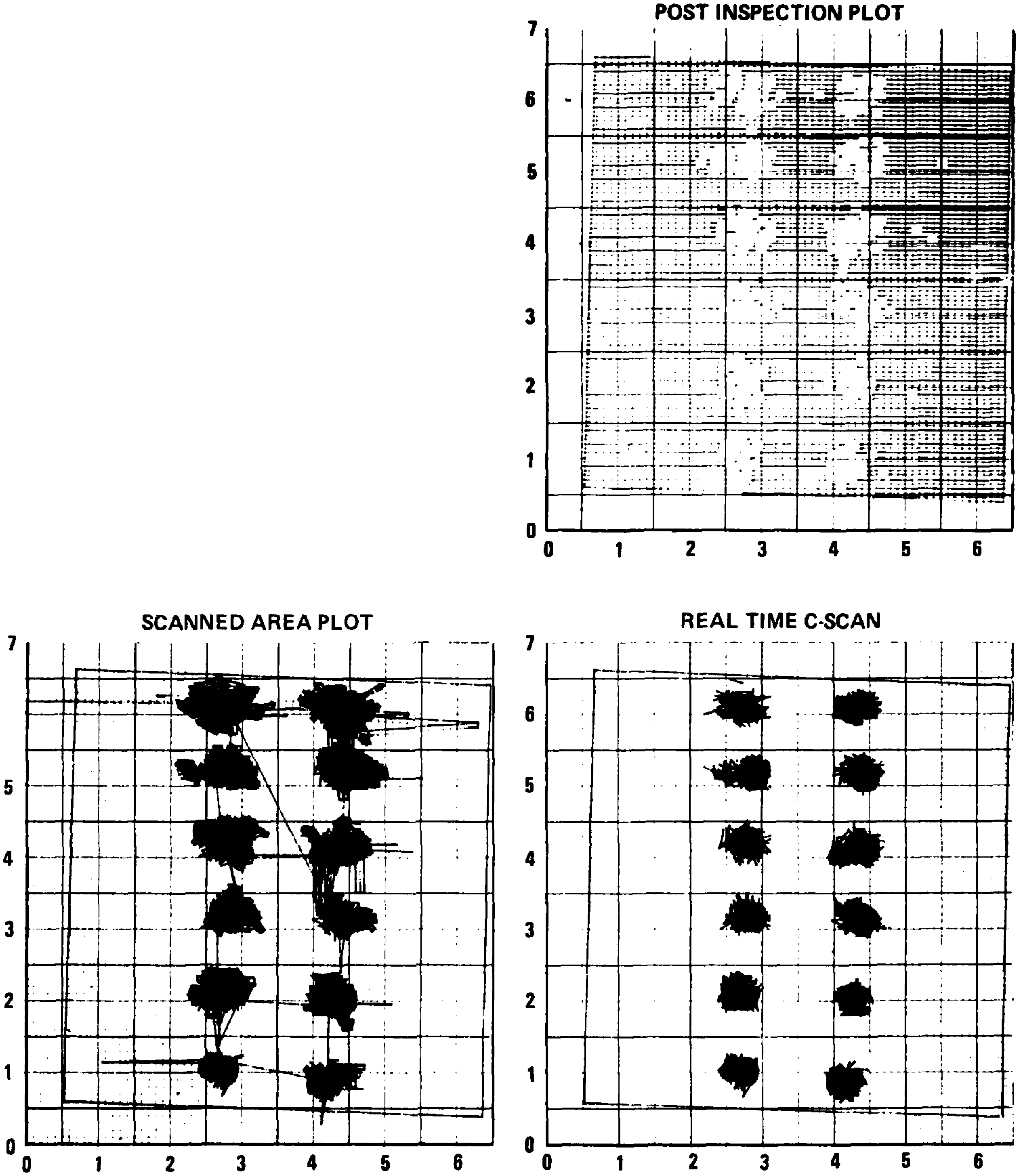


Figure 21 Flaw and Scan Plots for Specimen A-2

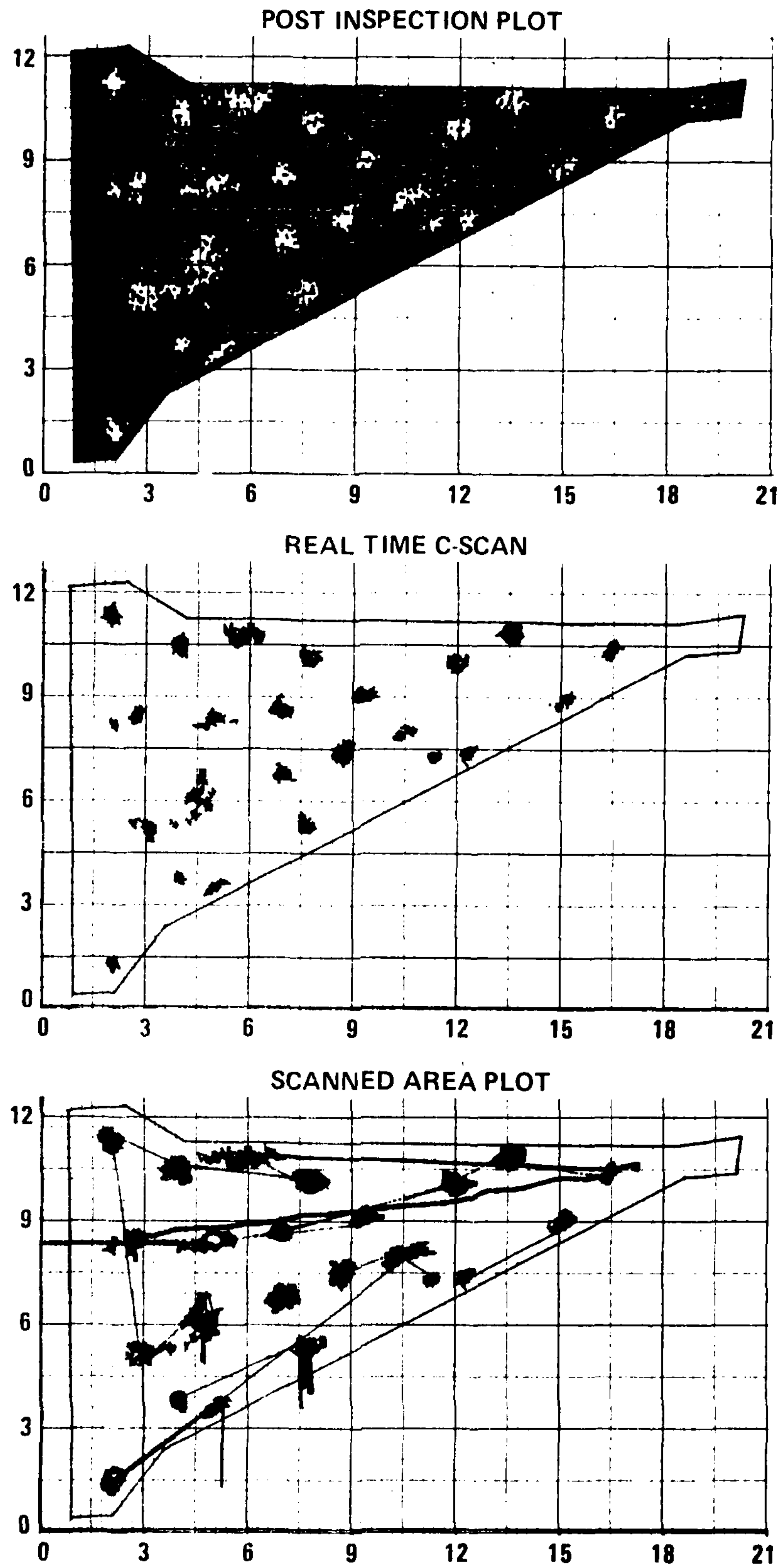


Figure 22 Flaw and Scan Plots for Specimen A-3

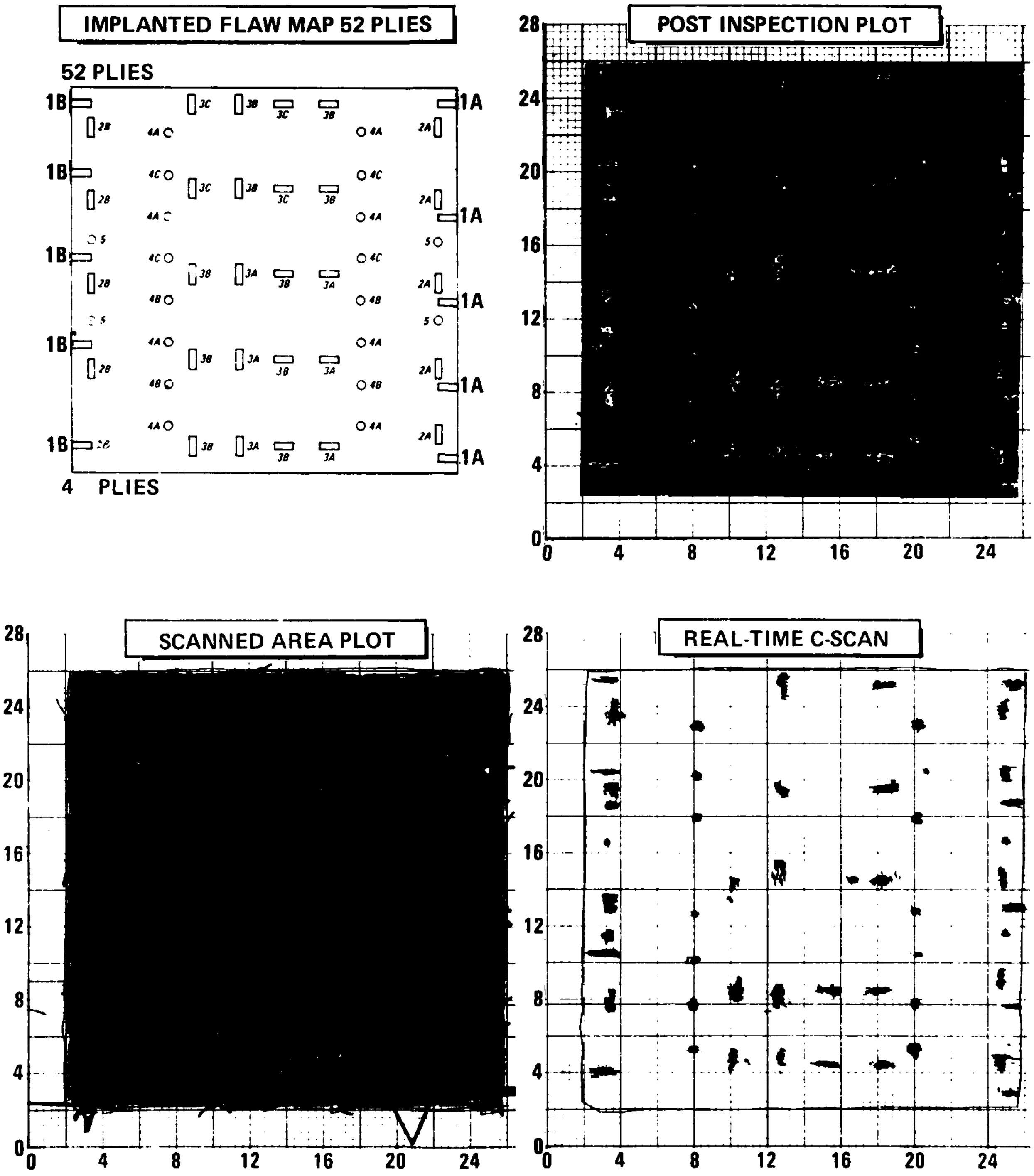


Figure 23 Flaw and Scan Plots for Specimen B-2 (Implanted Flaws)

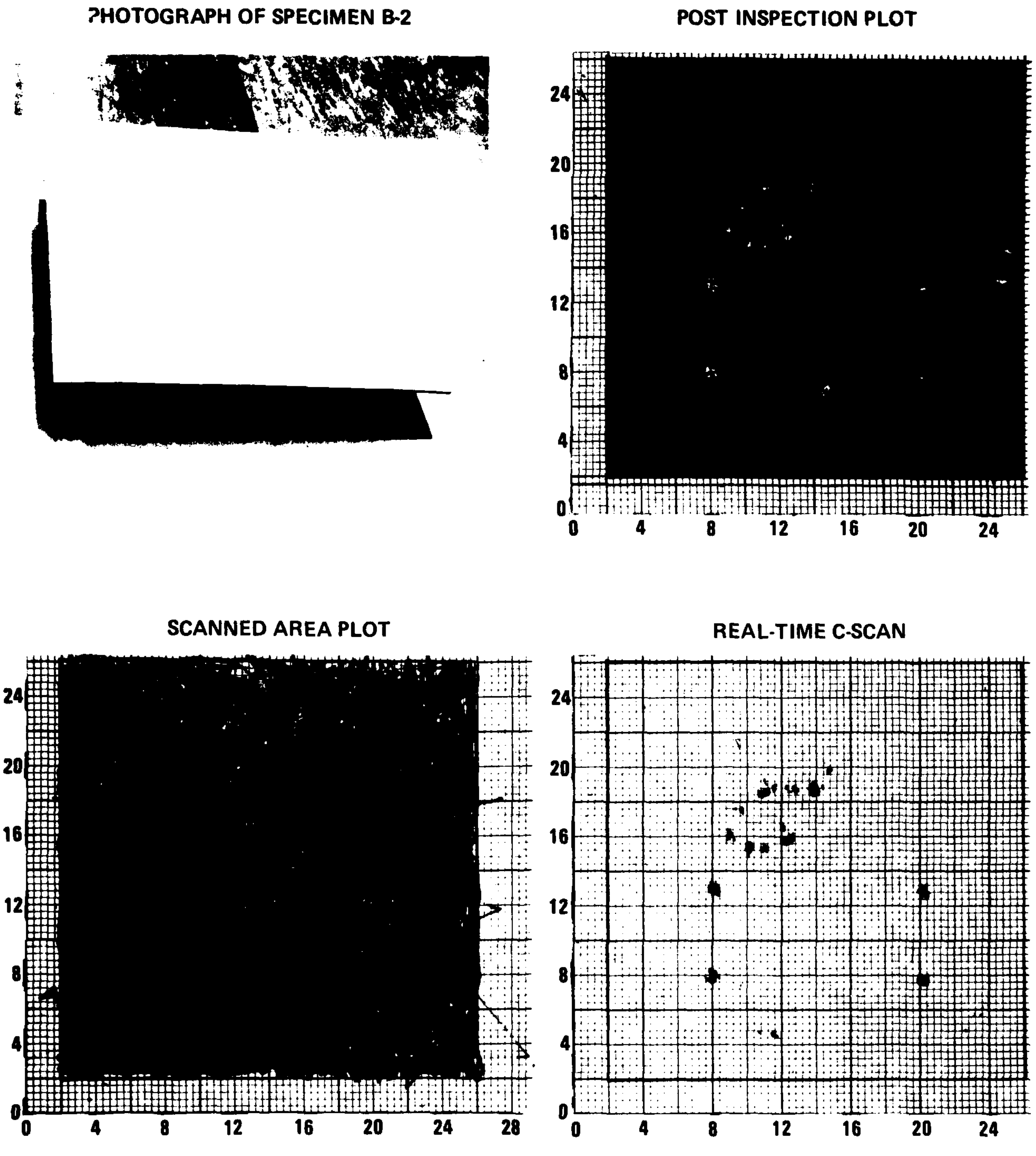


Figure 24 Flaw and Scan Plots for Specimen B-2 (Natural Flaws)

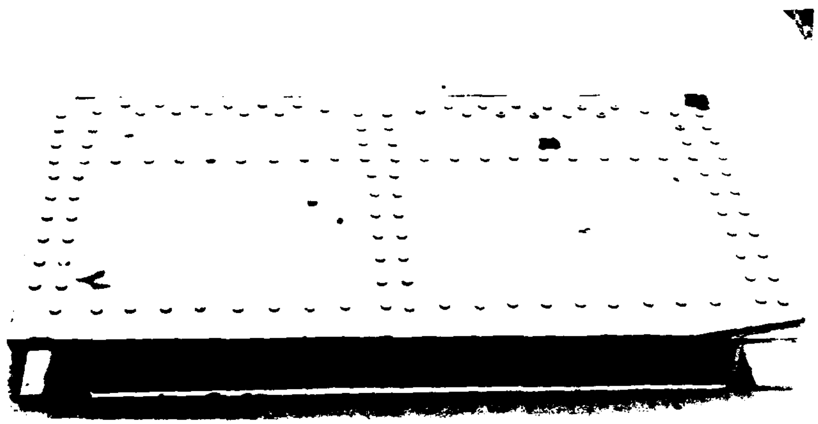
5.2.3 Results for Specimen B-3

Figure 25 shows a photograph and flaw/scan plots of specimen B-3. It will be noted in the scanned area plot that not the entire skin on the specimen was scanned. The omission was based on the apriori knowledge that the skin had no known defects other than impact damages produced after the skin was bolted to the aluminum frame. The post-inspection plot was made by ignoring the unscanned area so that the impact damages would be accentuated in the plot. In the post-inspection plot and real-time C-scan, center areas in many of the damage sites were inaccessible to the transducer due to the surface damages. They were ignored in the flaw plots just like the other unscanned areas. The impact damage indicated by the C-scan in Figure 25 could be compared with the location chart shown earlier in Figure 5. It will be noted that the sketch shown in Figure 5 was a bottom view of the specimen. Therefore, the impact damage sites in the two figures are mirror images of each other. The damages indicated in the post-inspection C-scan plot in Figure 25 were considerably larger than the visible damages on the front surface as noted in parentheses below each site identification in Figure 5. Of particular interest was the damage site 60-1. Only a small circle of an approximate diameter of 0.64 cm (0.25 in.) was visible on the surface. However, the actual damage area below the surface was larger than that of any of the other damage sites. The nature of the damage below the surface was a multi-level delamination. Three bolt patterns inaccessible to the transducer can be discerned in Figure 25 in the vicinity of the damage site. In spite of the difficulty imposed by the Al flame-sprayed surface, results obtained on specimen B-3 were highly satisfactory.

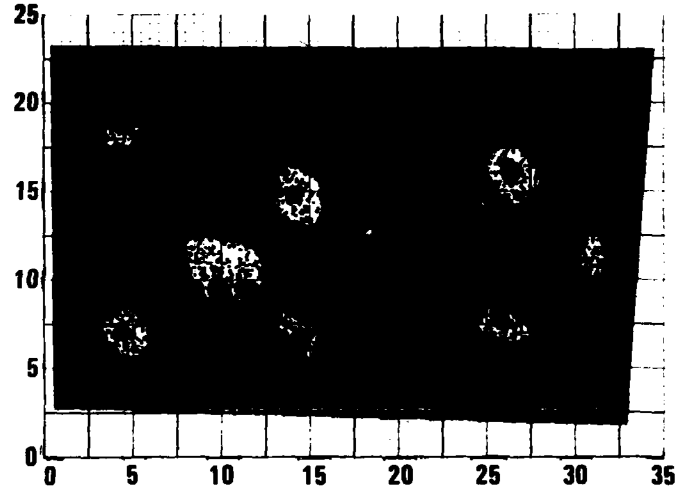
5.2.4 Results for Specimen B-1

Figure 26 shows a photograph and the flaw/scan plots for specimen B-1 with the B/E skin. As discussed earlier in Section 3.4, the Ti stepped bar and Ti shim on portions of the specimen created difficulties in flaw detection. In Figure 26, these areas are shown as unscanned areas. On the other side of the specimen, manufacturing defects immediately below the surface rendered flaw detection impossible.

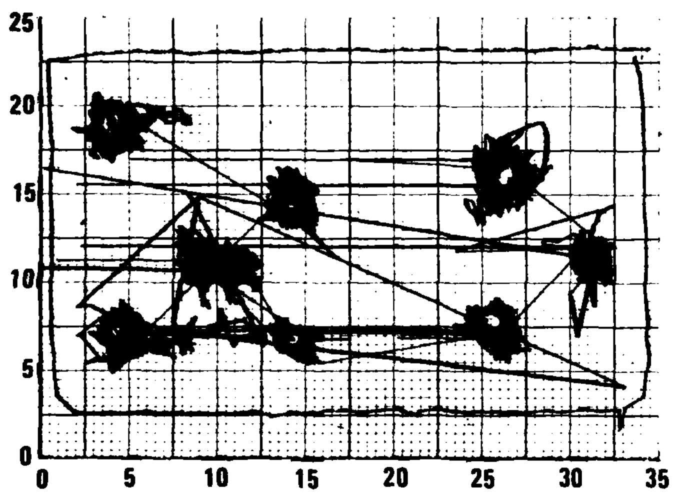
PHOTOGRAPH OF SPECIMEN B-3



POST INSPECTION PLOT



SCANNED AREA PLOT



REAL-TIME C-SCAN

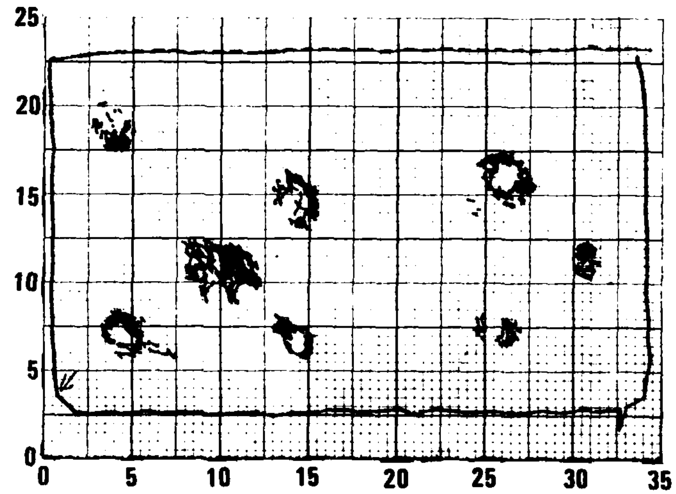


Figure 25 Flaw and Scan Plots for Specimen B-3

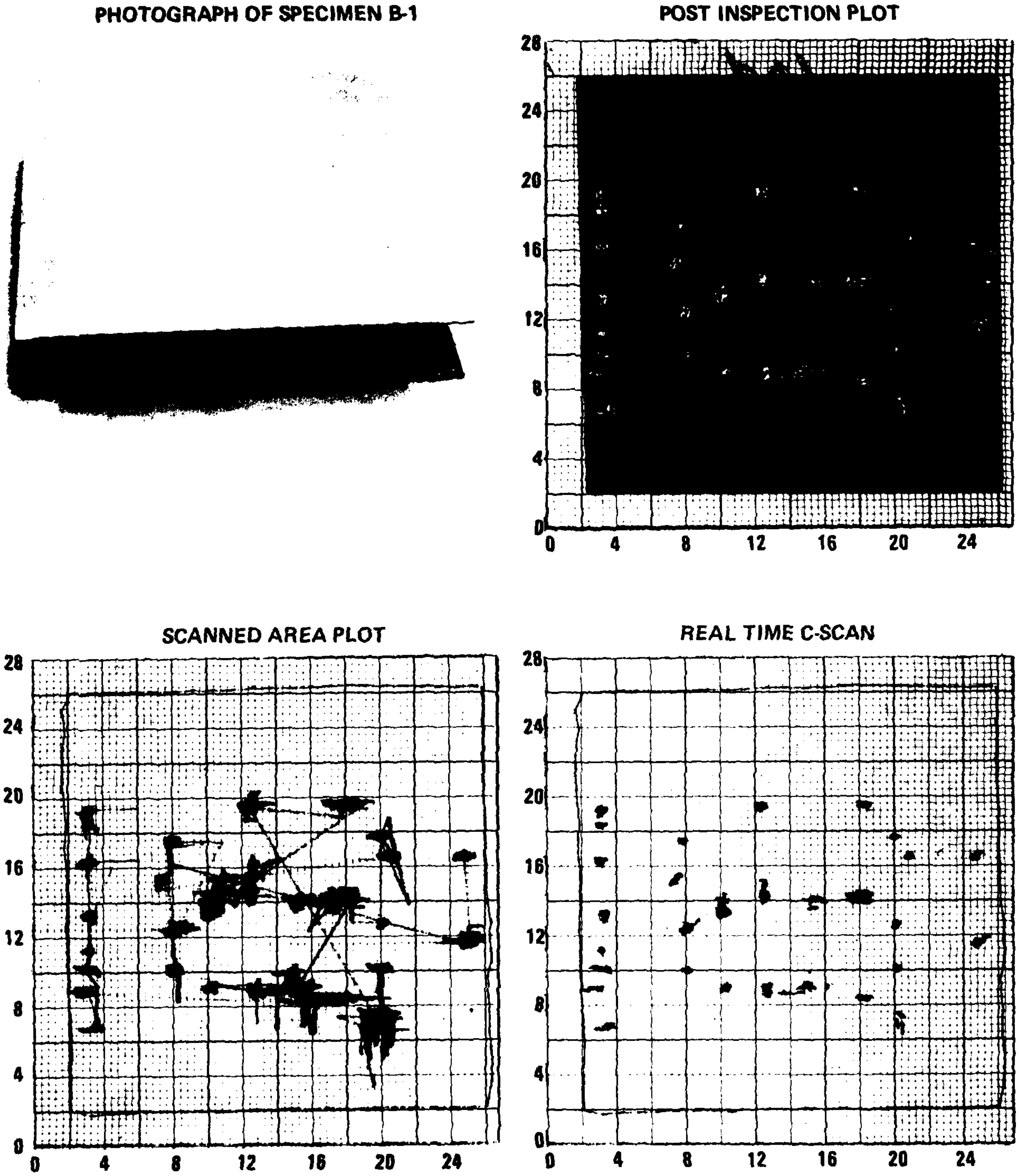


Figure 26 Flaw and Scan Plots for Specimen B-1 (B/E Skin)

5.2.5 Results for F-15 Panel

Figure 27 shows a photograph and the flaw/scan plots of a composite panel from a F-15 vertical stabilizer. This panel was cut from a wrecked F-15 and was brought to General Dynamics by the AFML Project Monitor for demonstration purpose. A photograph of the panel is shown in the insert at the upper left hand corner of Figure 27. Extensive damages in the form of delaminations are evident from the photograph. The outskirt of these damaged area were scanned as well as the interior of the panel. Results of the scan showed some tape joints and isolated flaw areas.

5.2.6 Flaw Amplitude Discrimination Capability

One of the most important advantages of recording the flaw data on a mass storage device is that the flaw signal amplitude can be used as a discriminating level during post-inspection flaw plot. Figure 28 shows an example of this capability. The post-inspection flaw plots at 30% (top) and 10% (bottom) voltage discrimination levels are shown at the left. Portions of the flaw amplitude listings are presented at the right of the corresponding plots. At the lower flaw plot of 10% voltage discrimination level, any signal appearing in the flaw gate with a voltage amplitude exceeding -0.2 volt was considered a flaw by the computer and plotted as such. In the upper flaw plot of 30% voltage discrimination level, signals in the flaw gate were considered as flaws only when they exceeded a voltage level of +0.2 volt. The flaw areas therefore appeared to be smaller. A section of the specimen containing a FBH, two horizontally and one vertically implanted flaws with dimensions of 0.64 x 2.54 cm (0.25 x 1 in.) was selected in Figure 28. The X and Y coordinates of several selected flaw points, along with the flaw signal amplitude in the 1st and 2nd gates are shown at the right. In the example cited, the 2nd gate was not used. The flaw signal amplitude was set at the maximum value of approximately 1.6 volt.

The voltage discrimination capability of the laboratory mock-up system has a significant contribution to the calibration of the sensitivity of the ultrasonic system. In the conventional immersion mode of ultrasonic inspection of composite laminates, 0.64 cm (1/4 in.) diameter circular lead tapes are usually placed on one side of the laminate near the edges to be used as references. The sensitivity of the pulser/receiver is adjusted so that the flaw indications for the lead tapes have a size of 0.64 cm (1/4 in.)

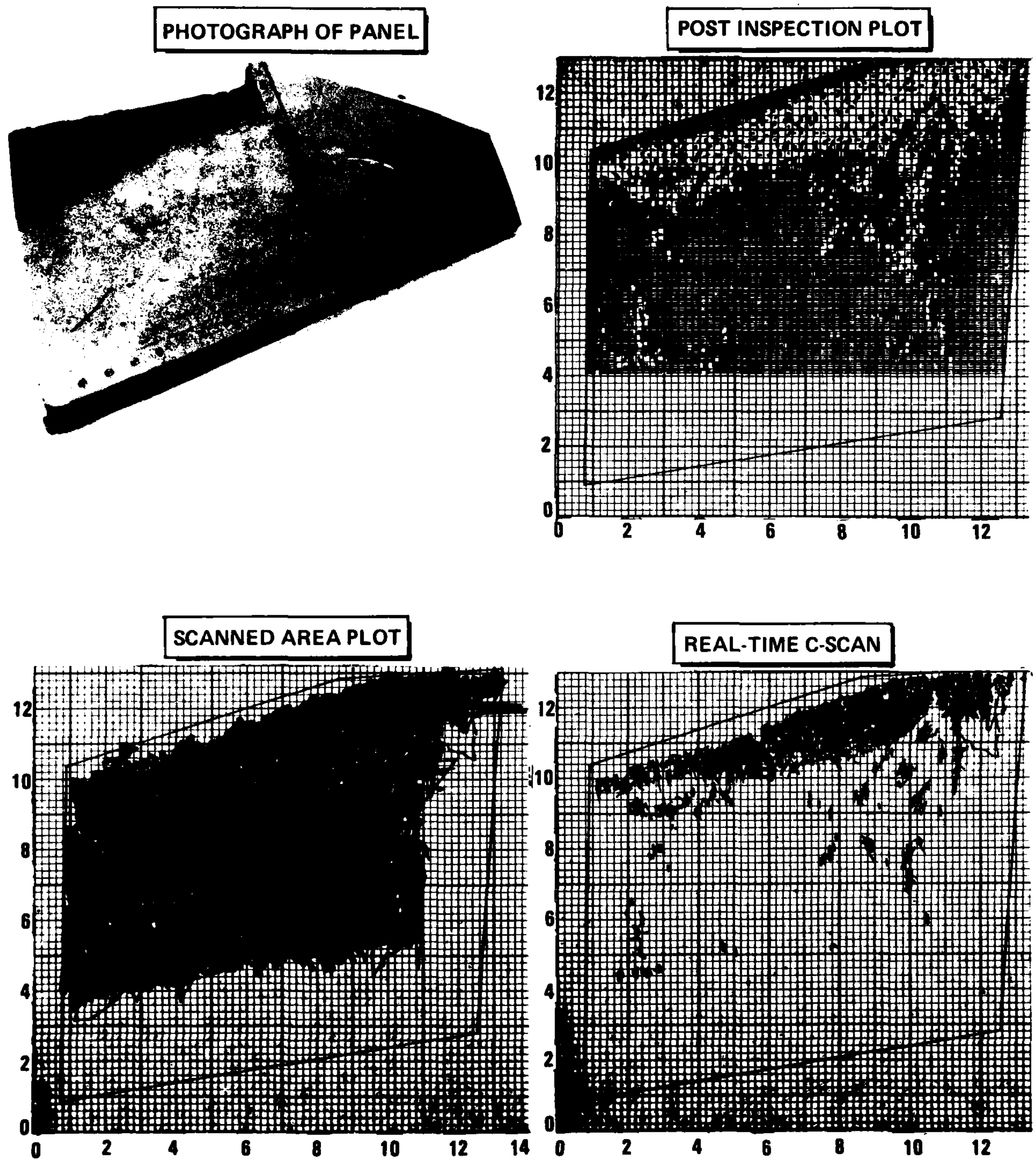


Figure 27 Flaw and Scan Plots for F-15 Panel

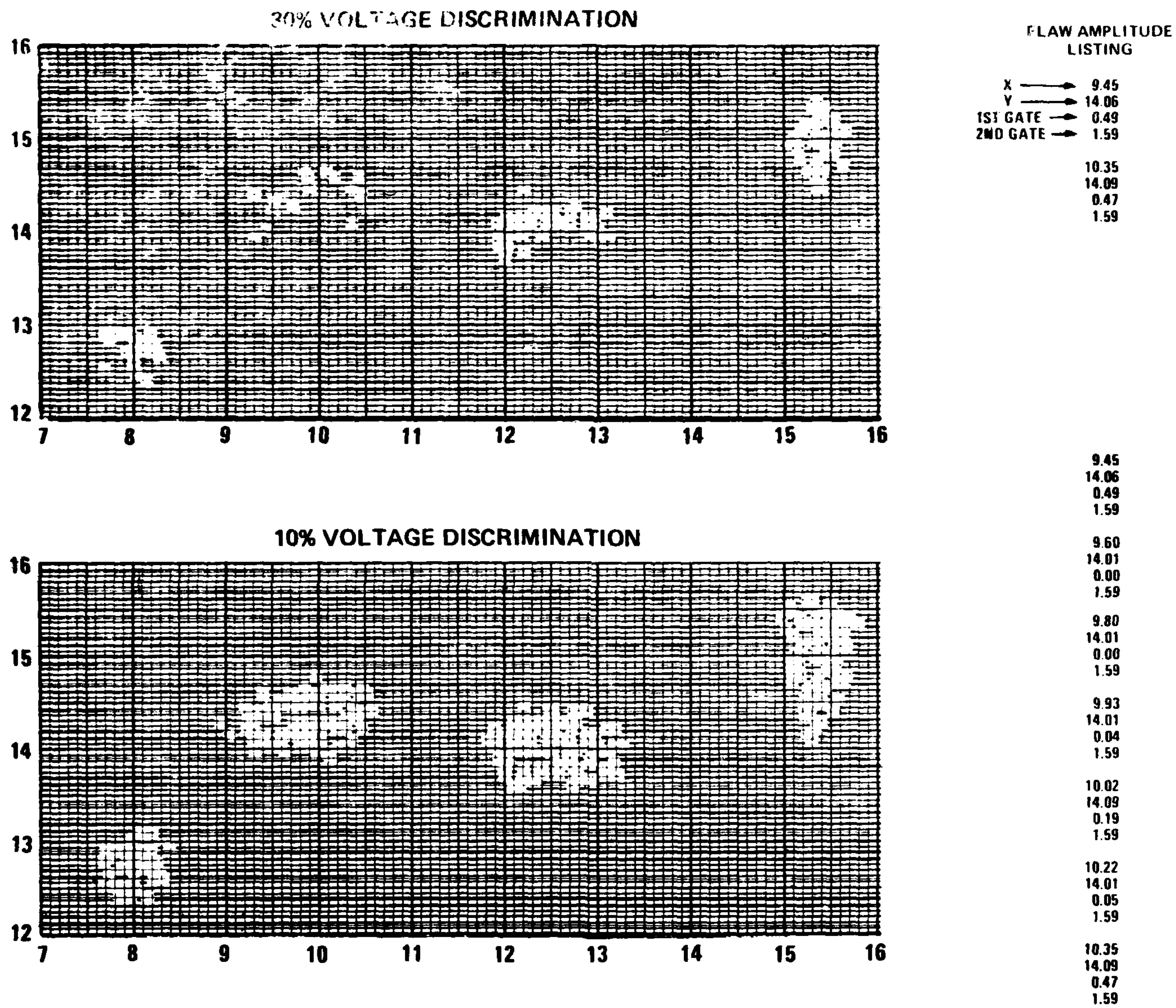


Figure 28 Comparison of Post Inspection Plots from Different Voltage Discrimination Levels

diameter. This method of sensitivity adjustment is not only cumbersome but is subject to variances in laminate thickness and ultrasonic attenuation. In the laboratory mock-up inspection system, the flaw discrimination level can be selected during post-inspection plot to produce a flaw size equal to that of the reference flaw. The need to change the sensitivity level and inspect the reference flaws repeatedly can be eliminated.

Another significant aspect of the voltage discriminating capability of the system is its contribution to distinguish planar delaminations from multi-level porosites in the laminates. Figure 29 shows a comparison of two post-inspection plots with 45% (top) and 10% (bottom) voltage discrimination levels for portions of a natural flaw. Samples of the flaw amplitude listing are shown at the right of the respective plots. In the bottom plot, there are isolated flaw points that appear to be porosites and also larger flaw areas that could be multi-level porosites or planar delaminations. If the larger flaw areas are planar delaminations, the amplitude of the flaw signals at various points in the flaw area would be approximately equal except for the peripheral. Applying a voltage discrimination of a higher level would simply decrease the size of the flaw. If the larger flaw areas are multi-level porosites, the flaw amplitude of the signals would most likely be varying according to their depth in the laminate. Besides, the peripherals of the small porosites would cause the connected flaw areas to be broken into smaller isolated areas or even disappear. By applying successive voltage discriminations, the flaw indications would be more likely to disappear. This was indeed the case in Figure 29.

The capability of the system to produce enlarged plots of the scanned area is a convenient feature for locating flaw areas on the specimen for repair purposes. A 1:1 flaw plot will aid the inspection engineer and repair personnel to locate and determine the extent of areas to be repaired. The examples shown in Figures 28 and 29 are enlarged 1:1 plots of the respective specimens.

5.2.7 Digitization Capability

Another useful feature of the inspection system is the capability to digitize selected RF signal waveforms, store the digitized data on the floppy disk, and display the waveforms on the plotter. Figure 30 shows a comparison of the digitized RF waveforms for a normal area and a FBH on specimen A-2. In this figure, a pair of numbers separated by a dash identifies the spe-

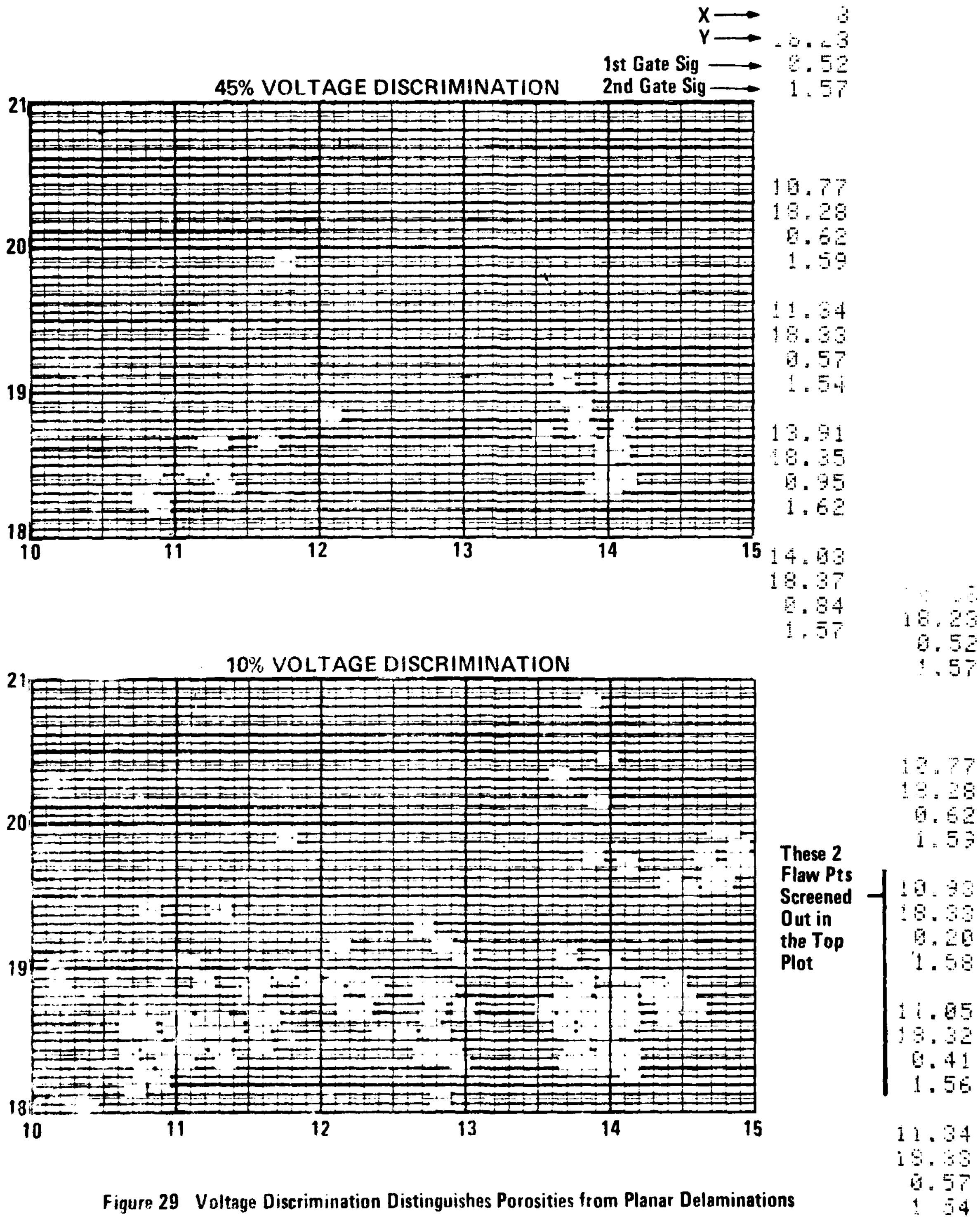


Figure 29 Voltage Discrimination Distinguishes Porosities from Planar Delaminations

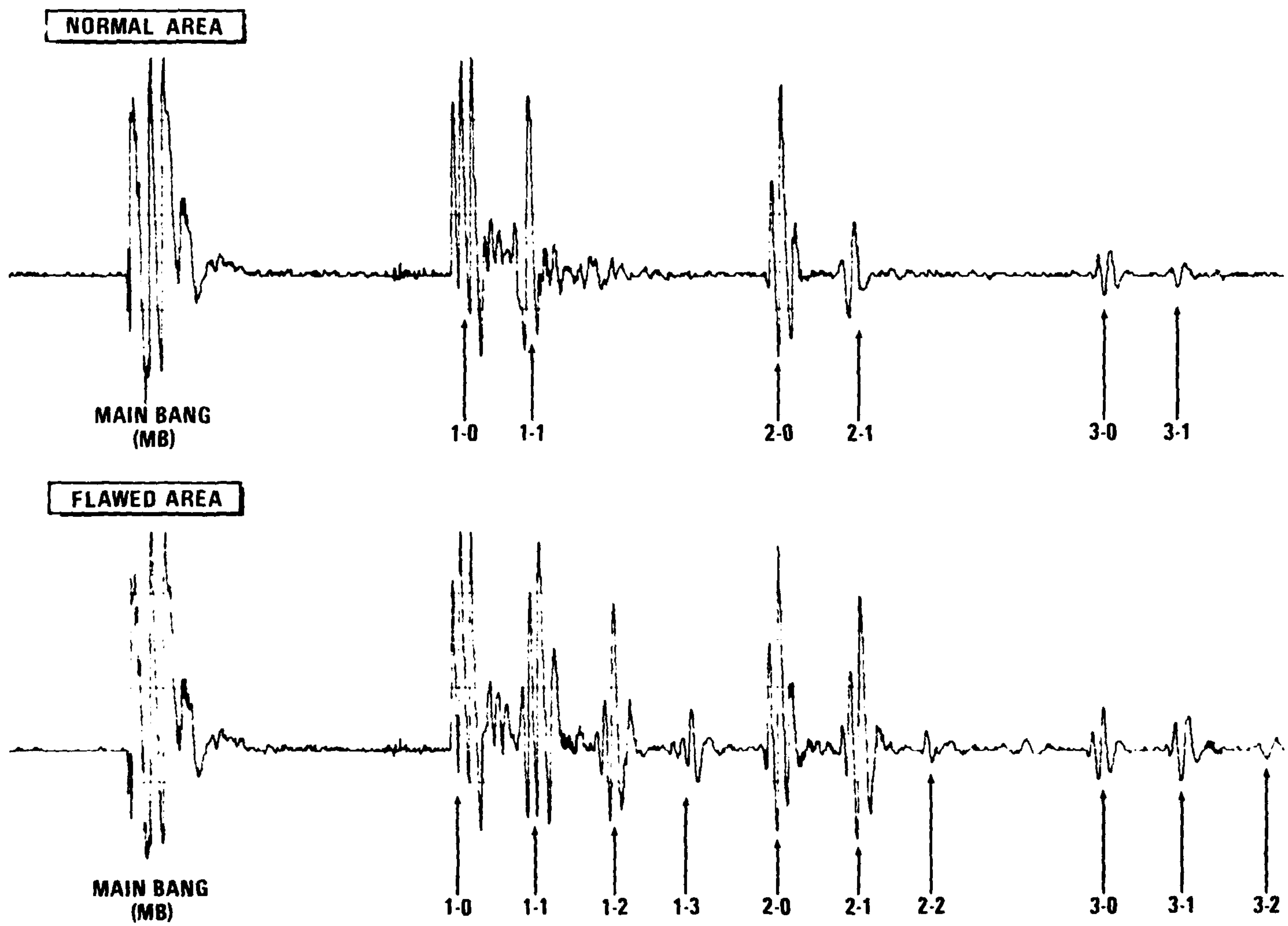


Figure 30 An Example of Digitized RF Signal Waveforms for Specimen A-2

cific signal reflected from a certain interface in a two-layered structure. The first and second numbers denote the number of roundtrips in the first and second layers respectively. For example, the signal identified as 1-2 is the signal that has gone through one roundtrip in the composite laminate and two roundtrips in the Ti structure below the laminate. In Figure 30 the loss of multiple reflections from the Ti structure is evident by comparing the signals corresponding to the normal and flawed areas.

Figure 31 shows another example of the use of digitized waveforms for signal interpretation in a specimen with a multi-layered structure containing a disbond. The RF waveforms corresponding to the different reflected signals are identified by the schematic diagram at the right. A 180° phase reversal of the signal reflected from the laminate/adhesive interface is evident in the figure. The phase reversal is due to the fact that in the top schematic diagram, the sound waves impinged on the G/E and void interface (in the bondline) from an acoustically more dense to a less dense medium. In the bottom schematic diagram there is no void area in the bondline, the sound waves impinged on the G/E and adhesive interface from an acoustically less dense to a more dense medium. The phase of the signals labelled B in the top and bottom diagrams experienced a 180° phase shift because of this difference in sound wave reflection. It will be noted that if the rectified video signal had been monitored on the CRT screen on the ultrasonic unit (as in majority cases) all the negative excursions of the waveforms below the reference zero line would have been rectified and shown above the zero reference line. In this case the phase reversal would not have been observed. The digitization and display of the RF waveforms in selected areas will be useful in resolving anomalies during the process of flaw signal recognition.

5.2 System Modifications and Improvements

Results of the system tryout indicated that a major improvement needed for the system was in increasing the speed of the data processing and display units. The HP9825A computer requires 9 milliseconds to read and store 16 bits of information plus additional time to transfer data to the plotter. The slowness severely limited the scanning speed of the system. As a comparison, it takes a microprocessor 11 microseconds to read and store 16 bits of information. The time required to transform the data information to the electronic graphics display is also greatly reduced. Therefore, the use of a microprocessor plus

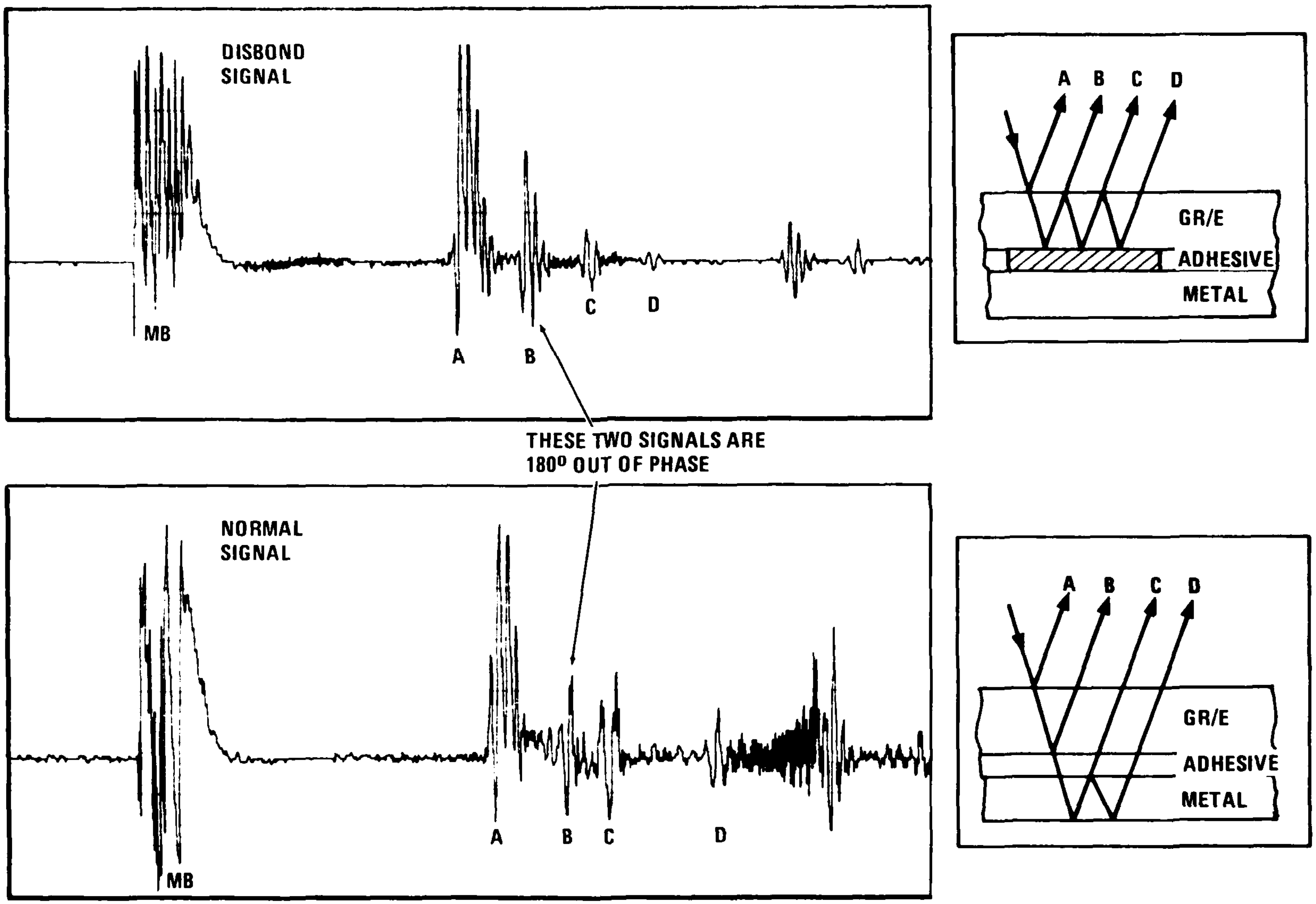


Figure 31 RF Signal Digitization Shows Phase Reversal

a graphics display will improve the speed of the system. The increased speed of the combination will also eliminate the need for a scanned area plot and a separate post-inspection plot. Software programs can be prepared to produce a background on the CRT screen of the graphic display indicating by the inspector. Areas not scanned will remain as blank areas. Flaw areas will be indicated as blinking dots on the display and by dashed lines on the hard copy.

Another limitation of the system encountered in the system tryout was the size of the read/write (R/W) memory. The present 15,036 bytes of R/W memory in the HP9825A computer placed a certain limit on the programming of the different system operations. With the use of a microprocessor, the memory size can be selected to adequately fulfill all the requirements of the system. A larger memory size will also facilitate sorting of data on file in the mass storage device. The system takes data as the specimen is being scanned. X and Y coordinates of the data points would most likely not be arranged in any orderly fashion on the disk. For post-inspection plot or playback, it is imperative that the data points be arranged. A large memory in the data processing unit will speed the data sorting process.

Although it was not set out as an objective of the program, flaw depth determination was found to be a very desirable feature for the system. This capability allows the inspection personnel to differentiate between planar delaminations and multi-level porosities. It also provides repair personnel with the necessary information to perform repair functions. A flaw depth determination module will be designed using a 10 MHz clock which will be initiated by the leading edge of a FSR signal and terminated by the leading edge of a flaw signal in a preset gate. The number of pulses of the 10 MHz clock between the initiation and termination events will be read by the computer and transformed into flaw depth by using the velocity of propagation information. It was estimated that ± 1 ply flaw depth resolution could be obtained by using a 10 MHz clock.

It is also desirable to reduce the weight and size of the system to cater to field and depot usage. The use of a microprocessor and graphics display/hard copy unit in place of the computer/plotter combination will achieve a significant weight saving. Substituting the two digital VOMs by two A/D converters will also contribute to the weight saving. It is highly desirable to reduce the weight of the pulsed transient recorder. This can be achieved if the need to digitize a whole waveform can be relaxed. Generally, the RF waveform as shown on the CRT screen of the ultrasonic unit remains quite stable, Within the time of a fraction of a second, the digitization can be achieved by scanning the time axis and sampling corresponding RF amplitude of successive waveforms, The relaxed requirement would allow a much smaller electronic component to replace the pulsed transient recorder.

VI. PRELIMINARY DESIGN

Based on results of the system tryout discussed in the previous section, a preliminary design of the production in-service inspection system has been completed. A major design improvement has been in the data acquisition/processing and the display/recorder units. A microprocessor dedicated to the data acquisition and processing has been designed to replace the computer. In lieu of the digital plotter, an electronic graphics display will be used. A cassette tape drive replaces the floppy disk unit. These replacements will improve the processing speed and reliability of the system. No major modifications are planned for the transducer unit, position sensing and ultrasonic assembly. A dual position sensing system is planned to provide both rectangular and triangular coordinates. For the rectangular coordinates, the 1.52 x 1.83 m (5 x 6 ft.) microphones will be replaced by a 0.61 x 0.61 m (2 x 2 ft.) microphone system for ease in transportation. Details of the preliminary design of the data acquisition system will be discussed in the following subsections.

6.1 Data Processing System Specifications

The microprocessor-based computer system incorporates the state-of-the art computer technology to perform the data acquisition/processing functions. The data acquisition/processing assembly has sufficient processing power to acquire coordinate data while the inspection transducer is moving at 30.48 cm/sec (12 inch per second (ips)). The microprocessor will rapidly acquire from a digital processing oscilloscope, process and store digitized waveforms on demand. In addition to these input functions, the microprocessor will output a real time C-scan display of the inspection results on a graphics terminal. The specifications of the microprocessor are presented in Table 4.

A block diagram of the data acquisition processing assembly is shown in Figure 32. The Motorola 6800 microprocessor is used as the system's central processing unit (CPU). This type of processor will input and output data faster than a programmable calculator and is less expensive than a minicomputer. The processor is supported by a 1.8432 μs system clock that both provides CPU timing and a clock for the baud rate generator. The microprocessor's memory consists of 48K of random-access-memory (RAM) and 16K of read-only-memory (ROM). The ROM contains the system level software.

Table 4. Specifications of Data Processing System

Characteristics	Specifications
Power Requirements	105-125 VAC 47-63 Hz
Word Size	
Data	8 bits
Address	16 bits
Instructions	8, 16 or 24 bits
Memory Size	
ROM	16 K bytes
RAM	48 K bytes
Clock Cycle Time	1.8432 μs
Interrupt	
$\overline{\text{IRQ}}$	Maskable real time interrupt
NMI	Nonmaskable real time interrupt
Physical Characteristics (Includes mass storage unit)	
Table top	
Length	43.18 cm (17 in.)
Depth	43.18 cm (17 in.)
Height	22.23 cm (8-3/4 in.)
Rack Mountable	
Length	48.26 cm (19 in.)
Depth	43.18 cm (17 in.)
Height	22.23 cm (8-3/4 in.)
Interface	
RS-232C Serial (1)	9600 baud
RS-422 Parallel (16)	8 bit parallel with interrupt

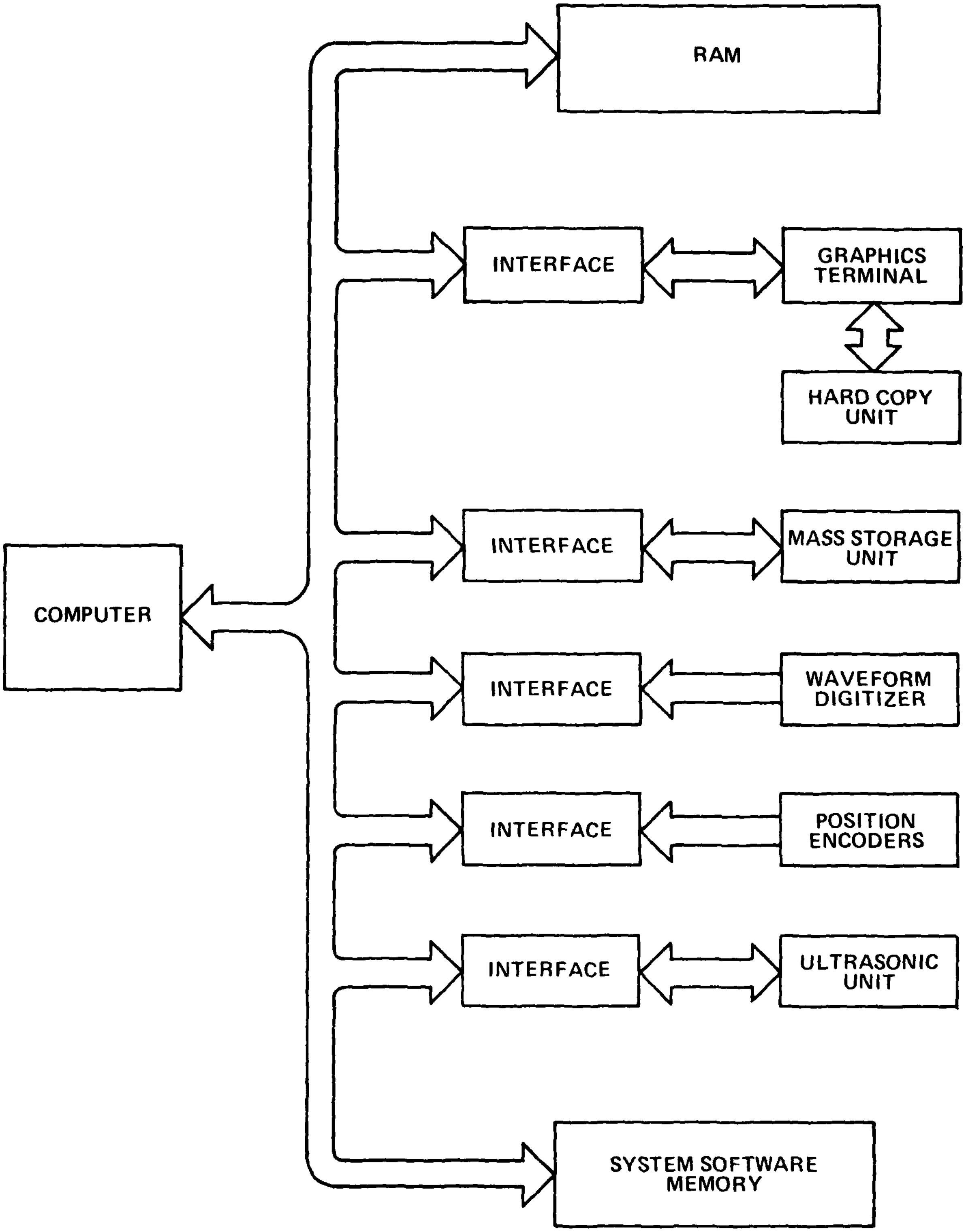


Figure 32 Block Diagram of Preliminary ISIS Design

The ROMs are electrically programmable ROMs (EPROM) which are programmed on a programmable ROM (PROM) programmer. The EPROMs can be erased with ultraviolet light and reprogrammed by a PROM programmer. The EPROMs are covered with black tape to prevent accidental erasure.

6.2 Interface

The interface for the acquisition and output of data is parallel with the exception of a serial interface for the graphics terminal. The extensive use of RS-422 parallel interfaces allows the system to operate at the maximum data rate possible. The use of large scale integration (LSI) components in the fabrication of the interfaces reduces size and cost while maintaining speed and reliability.

6.2.1 Ultrasonic Unit Interface

The ultrasonic unit provides an 8-bit binary presentation for the amplitude of the gated signal. This amplitude varies from 0 to 99.9% screen saturation. The interface between the processor and the ultrasonic unit is a parallel interface providing for 8 bits of binary data. Two levels of interrupt are provided:

1) An interrupt is generated by the flaw alarm unit requesting the processor to obtain and store coordinate and amplitude information and graphically display coordinate information.

2) An interrupt is generated by the early sync (main bang) pulse of the ultrasonic unit requesting the processor to obtain and graphically display coordinate information.

6.2.2 Position Sensor Interface

The position sensors are interfaced to the processor via a parallel interface. There are provisions for 13 binary bits of X information, 13 binary bits of Y information and 16 bits of status/control information. An interrupt is generated by a pushbutton on the transducer assembly requesting the processor to obtain and store the digitized presentation of the RF waveform being processed by the waveform digitizer.

6.2.3 Graphics Terminal/Hard Copy Unit Interface

The hard copy unit provides C-scan recordings, digitized RF waveforms and coordinate/amplitude listings. The graphics terminal presents real time C-scan presentation to monitor the hand-scan inspection and a presentation of digitized RF waveforms. The graphics terminal is raster scanned which presents a bright display visible in a field environment. The traditional storage tube graphics terminal is not acceptable for field operations because its presentation is not visible in a field environment. The graphics terminal has an RS-232C serial interface which will operate at 9600 baud. This allows the terminal to be physically removed to a maximum distance of 30 feet from the system and will still be visible to the operator. The graphics terminal sits on top of the system (see Figure 33) when the operator does not want it removed from the system.

6.2.4 Waveform Digitizer Interface

The waveform digitizer interfaces with the processor through a parallel interface. When a request is made by pushing a button on the transducer assembly, the computer obtains the digitized data from the waveform digitizer. This information is plotted on the graphics display and stored on the 3M tape cartridge.

6.2.5 Line Drivers/Line Receivers

The overall interface utilizes differential line drivers and line receivers in each assembly to maximize noise immunity. Twisted pairs of shielded wires are used to interconnect line drivers and line receivers to further increase the noise immunity.

6.3 Mass Storage Device

The assembly uses a 3M tape drive for mass storage to make permanent records of the inspections. A 3M drive provides over twenty times the storage space of a single density floppy disk system. 3M cartridges are more rugged than disks and produce superior performance in a field environment. The 3M tape drive has a 4 track head providing over 4.3 million bytes of storage per digital cartridge. This is the most trouble-free, reliable and practical approach to mass storage that can be implemented in a field environment. The start time of the drives is 30 millisecond or better and the data transfer rate is 4800 bits per second (bps). The preliminary design of the inspection system is compatible with a Nondestructive Evaluation Terminal (NET) to be installed in a production inspection environment for the F-16 composite components (Reference 4). NET allows the evaluation potential of inspection systems to be realized in an off-station setting where a computer is used to statistically and graphically analyze the inspection data. X-Y coordinate data can be analyzed to reveal patterns of recurring anomalies. The frequency of anomaly occurring in different areas of the production parts is plotted. The capability is provided to enlarge selected areas of the graphics plot for further evaluation. The terminal has the capability to read digital records of inspections and produce their corresponding C-scan recordings on an electrostatic plotter. These functions permit rapid evaluation of inspection results from which quality assurance reports can be generated. The use of 3M cartridges in the system allows the data gathered in the field to be read and evaluated by a NET.

6.4 Programming

The software for the system is modular in format for easy understanding and updating. The software resides in ROM and is written in a Higher Level Language linked to assembly language subroutines which handle input/output operations. The power of the Higher Level Language is used for waveform pattern recognition and the speed of assembly language is used to quickly and efficiently acquire and process data.

6.4.1 Executive Program

The executive program is the portion of the system software that monitors and controls the overall process. The executive program passes control as necessary to the appropriate driver to obtain, display and store data. The executive program also contains modules to process and display digitized waveforms. The executive program makes the decision when to acquire data and what to acquire, store and display. A real time C-scan presentation is displayed on the graphics terminal during the inspection process.

6.4.2. Peripheral Drivers

The graphics software driver is a software package that formats data and controls the input and output of data to the graphics terminal. The blinking of anomalies on the graphics terminal is controlled by this driver. The hard copy unit does not need a software driver. It operates as a function of the graphics terminal. On demand it presents a hard copy of the information being displayed on the graphics terminal.

The waveform digitizer software driver obtains the time versus amplitude information of the signal being analyzed when the appropriate button on the transducer assembly is depressed. This data will be stored in the mass storage device and displayed on the graphics terminal.

The position sensor software driver obtains the X and Y coordinate, status/control informations from the position sensors at a frequency that is a function of the repetition rate of the ultrasonic unit. The early sync (main bang) signal is used to derive the interrupt request to obtain this information.

The ultrasonic unit software driver obtains the amplitude of the gated signal when it receives an interrupt request generated by the alarm signal from the ultrasonic unit. The amplitude and coordinate informations are displayed on the graphics display.

The mass storage software driver is a software package that formats data for the mass storage device and controls the input and output of data to and from the device.

An integrated sketch of the preliminary design of the inspection system is shown in Figure 33.

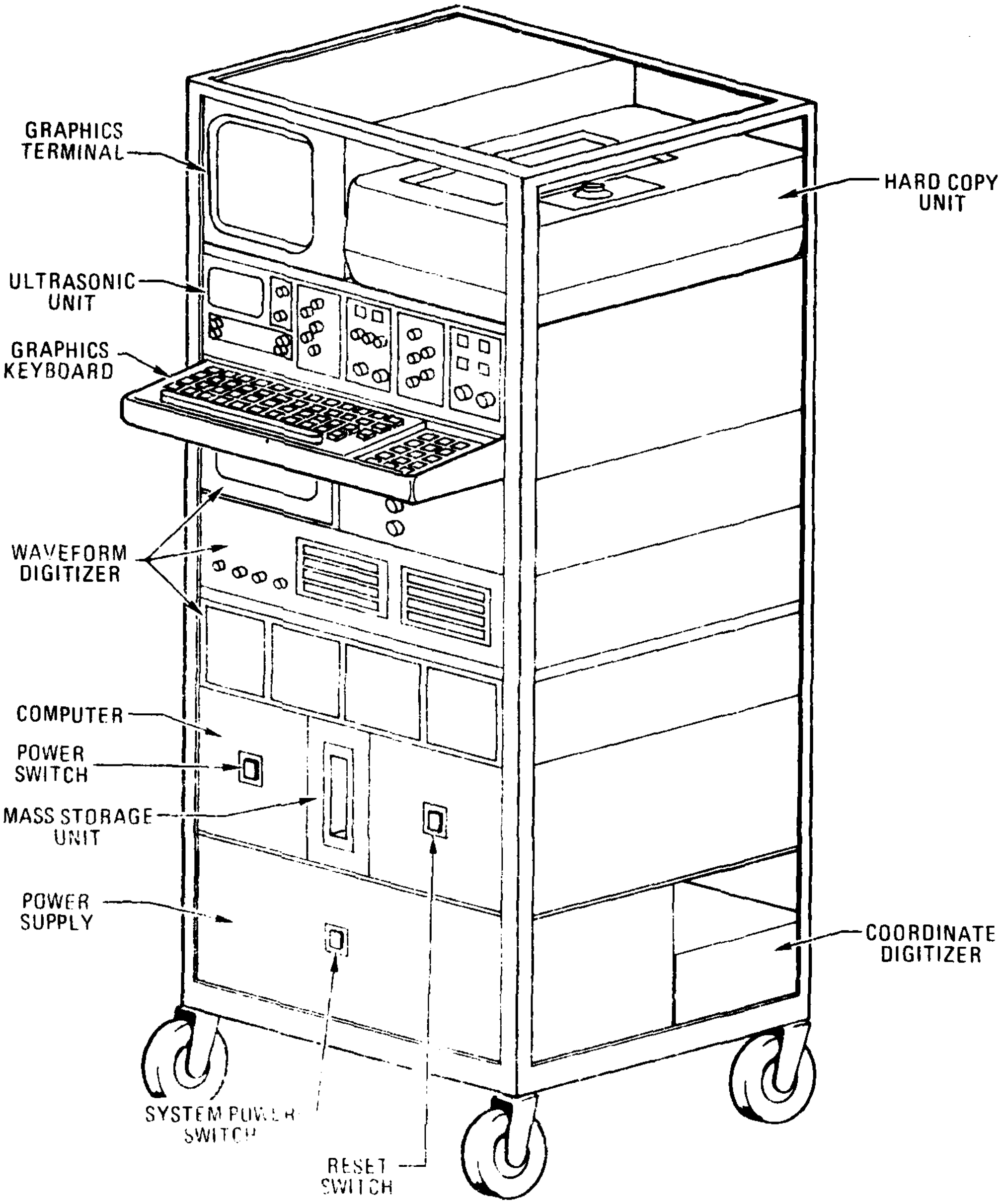


Figure 33 Sketch of Preliminary ISIS Design

VII. SYSTEM COST ANALYSIS

The system cost analysis will provide a detailed accounting of the costs associated with the fabrication of an In-Service Inspection System (ISIS). Of primary consideration in the development of ISIS were ruggedness, reliability and environmental insensitivity. The performance, simplicity, maintainability and portability were also prime considerations. The cost analysis in this section is divided into: (1) the fabrication cost of the individual components comprising the system, (2) system assembly cost, (3) software development cost, (4) system checkout cost, (5) documentation cost, (6) system delivery cost, (7) system operation training cost, and (8) system maintenance cost.

7.1 Component Fabrication Cost

The fabrication cost of the individual assemblies comprising the ISIS is presented in the following subsections. The prices quoted in this cost analysis were provided by vendors or obtained from supplier catalogs and are subject to the normal price fluctuations.

7.1.1 Ultrasonic Unit

The ultrasonic unit selected for integration into ISIS is the Sonic Mark IV. The Mark IV was chosen for several reasons. It is a small portable ultrasonic unit with the option of a rechargeable battery pack as an alternate power source. The unit was designed for military use and is the most rugged ultrasonic unit available. After a market study on other available units it was determined that the Mark IV is the only unit which will hold up in a field environment. A Tek-Tran Immerscope, Sonic Mark II and III, an Automation Industries S-80 and a Krautkrammer Branson Industries KB-6000 were among the units that have been evaluated. All these instruments were either too large, too heavy, or not designed for a field environment. Some of them have plug-in modules which may present problems associated with mechanical ruggedness and electrical connector when it is desired to transport the units in a field environment. These units are all designed to be placed in an ultrasonic system and left in one location. The Sonic Mark I was also evaluated but the superior ruggedness and additional features available in the later model Sonic Mark IV eliminated its adoption in the ISIS.

The total cost of the ultrasonic unit, including the flaw depth circuitry and an additional gate, was estimated to be $5,500.

7.1.2 Transducer Assembly

The main frame for the transducer assembly will be fabricated by General Dynamics and will support the cursor for the position sensors. An illustration of the transducer assembly is shown in Figure 34. The transducers that will be provided with the transducer assembly are detailed in Table 5. They are interchangeable in the assembly by a simple procedure.

Table 5. Transducers Cost in ISIS

FREQUENCY	SIZE (in.)	CONNECTOR	QUANTITY	COST EACH
5 MHz	1/4	UHF	4	$250.00
15 MHz	1/4	Microdot	2	$250.00

A system will be incorporated into the transducer assembly to provide for automatically feeding couplant onto the surface of the part being inspected when the appropriate push button switch on the transducer assembly is depressed. Table 6 shows the cost of the entire transducer assembly.

Table 6. ISIS Transducer Assembly Fabrication Cost

QUANTITY	DESCRIPTION	COST
6	Transducers	$1500.00
1	Transducer Assembly	80 Tooling hours
4	Pushbutton Switches (wire, connectors, misc. parts)	$ 75.00
		Total $1575.00 + 80 Manhours

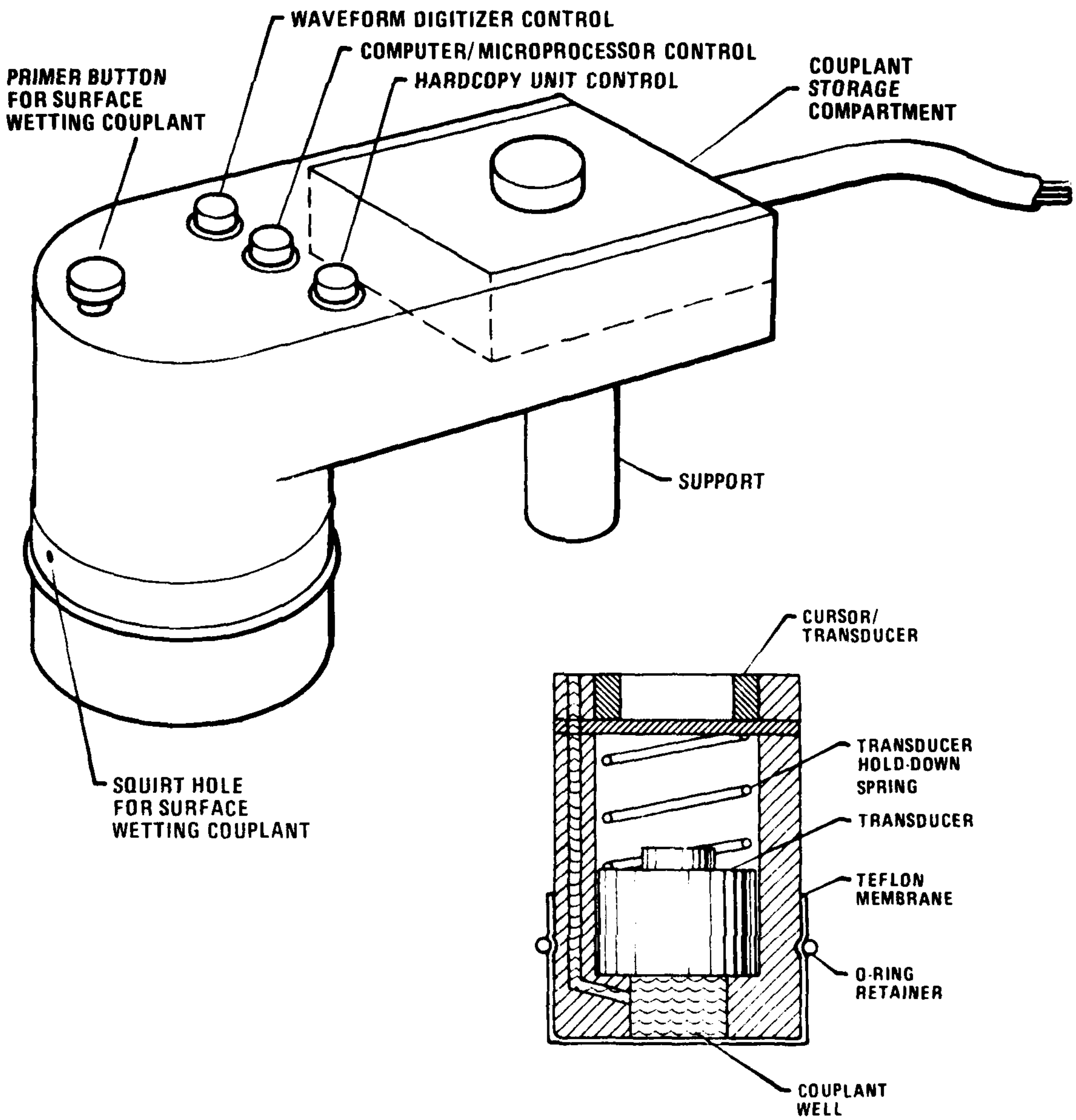


Figure 34 Transducer Assembly

7.1.3 Waveform Digitizer

Currently no available waveform digitizing instrument exists that can fulfill the portability requirement of ISIS. Several excellent transient analyzers and digital processing oscilloscopes were evaluated, but they were found to be either too heavy or too large to meet ISIS requirements. The concept of recording the video signals from the ultrasonic unit with a video recorder was evaluated and rejected because the bandpass of video recorders is too small. Several small and portable waveform digitizing modules are available, but they lack the resolution necessary to operate at ultrasonic frequencies.

Because of the lack of a suitable off-the-shelf waveform digitizer, General Dynamics will build a small portable waveform digitizer to be integrated into ISIS. Tables 7 and 8 contain a breakdown of the costs associated with the development and fabrication of the waveform digitizer. The design and layout costs of the printed circuit board (PCB) are one-time costs associated with the ISIS prototype. The documentation cost for the waveform digitizer is included in the documentation section of this cost analysis.

Table 7. Waveform Digitizer Fabrication Cost

TASK	HOURS
Design	40
PCB Layout	140
Total:	180 Manhours

Table 8. Waveform Digitizer Parts Cost

PART	COST
Resistors, Capacitors, Transistors, IC's	$ 75.00
PCB fabrication	75.00
A/D Converter Circuitry	850.00
Switches, plugs, sockets, wire	50.00
Total:	$1050.00

7.1.4 Position Sensors

A Graf/Pen digitizer will be used for transducer position sensing in ISIS. Point sensors will be used because of their portability. The cost of the various components making up the position sensing assembly is contained in Table 9.

Table 9. Position Sensor Cost

COMPONENT	COST
Control Unit (GP-3) with cables, Connectors, & binary TTL interface	$2700.00
Cursor	40.00
Pt. Sensors	NC
Total	$2740.00

7.1.5 Graphics Display/Hard Copy Unit

The Tektronix 4631 graphics terminal and 4295 hard copy unit will be used as the graphics display/hard copy unit. The 4631 graphics terminal will provide a high resolution raster scanned graphics display which will be viewable in outdoor lighting.

An illustration of a graphics terminal is shown in Figure 35. The hard copy unit will provide a high resolution copy of graphics presentations and ASCII characters present on the graphics display. A breakdown of the costs associated with the graphics terminal and hard copy unit is presented in Table 10.

Table 10. Graphics Display/Hard Copy Unit Cost

PART	COST
4025 (Graphics Terminal)	$3595.00
Opt 22 (32K display memory)	1750.00
Opt 26 (32K graphics memory)	2300.00
Opt 35 (ROM Expansion)	100.00
Opt 1 (Computer Interface)	140.00
Opt 40 (Hard Copy Unit Interface)	70.00
4631 (Hard Copy Unit)	4295.00
Opt 31 (4631/4025 Compatibility)	NC
Total:	$12,250.00

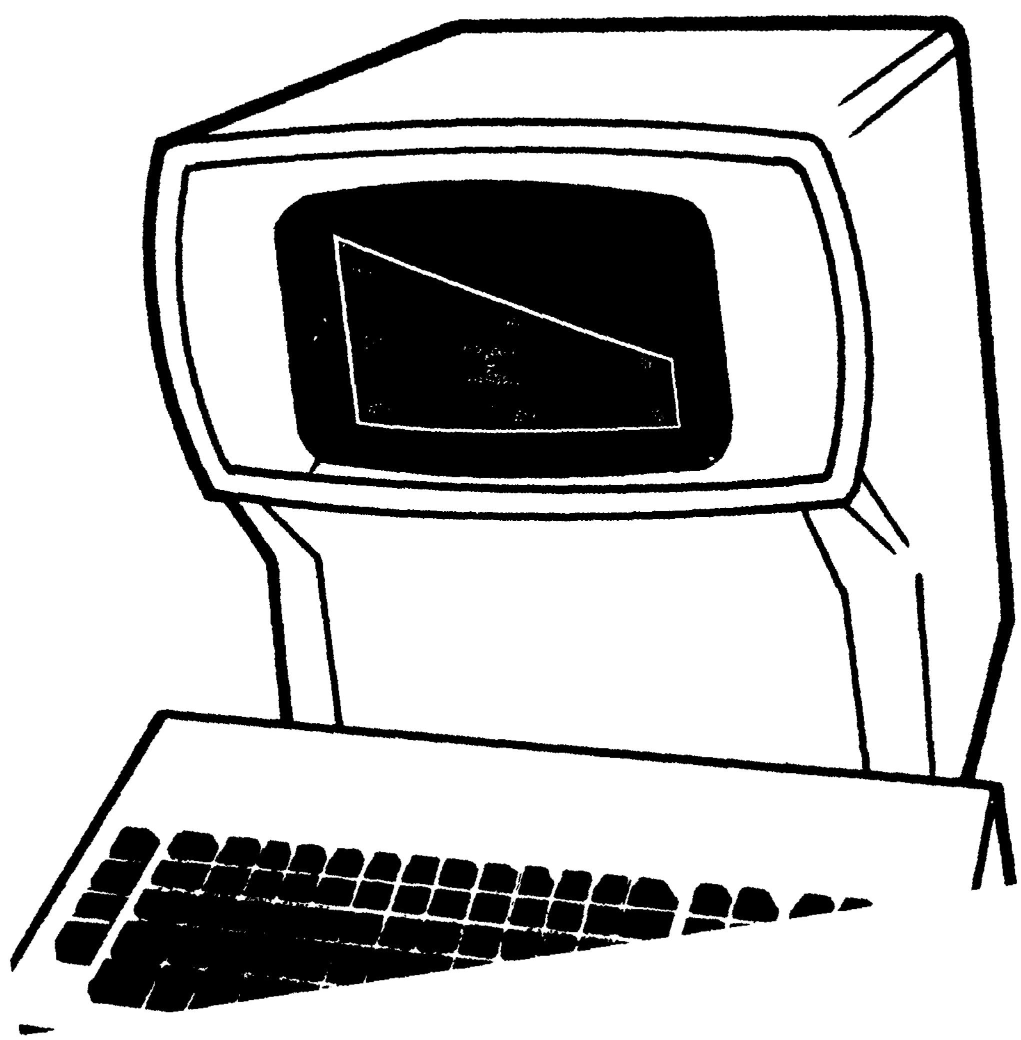


Figure 35 Graphics Terminal Display of C-Scan Presentation

7.1.6 Data Acquisition/Processing Assembly

This assembly incorporates the state-of-the-art computer technology to enhance the data acquisition and processing capabilities of the ISIS Prototype. State-of-the-art technology is demanded by the data acquisition parameters of the system. Actual measurements made during production handscan inspections have shown that the system needs sufficient processing power to acquire coordinate data while the NDE transducer is moving at 12 ips. It is also required to acquire and store both coordinate and amplitude information of the gated signal while the NDE transducer is moving at 1 ips. The assembly will rapidly acquire, process and store digitized waveforms on demand. In addition to these input functions, the system will output a real time C-scan display of the inspection on a graphics terminal.

The computing calculator approach was found to be the slowest approach. This is a result of the calculator being programmable only in the Basic programming language. Calculations showed the HP9825A takes 9 milliseconds to read and store 16 bits of information while a microprocessor takes 11 microseconds to read and store the same information. A minicomputer will offer no advantage over a microprocessor and would cost considerably more. Since the access time for the mass storage device and the display would not change, a minicomputer could not store or display data any faster. Although the initial microprocessor will cost more than a computing calculator on account of the development cost, subsequent units will actually cost less than a computing calculator.

The microprocessor approach will use 64K of memory consisting of 48K of RAM and 16K of ROM. The ROM would contain the system level software to be developed on General Dynamics' Microprocessor Development System (MDS). Subject software will then be programmed by the MDS PROM Programmer. The ROMs would be EPROMs which can be erased with ultraviolet light and reprogrammed. When installed in the assembly, the EPROM would be covered to prevent accidental erasure.

The assembly uses an ANSI X3B5/43 tape drive for mass storage of permanent inspection records. The tape drive provides over 20 times the storage space of a single density floppy disk system.

The power supply for the system operates from 110-120 VAC/60 cps and includes a line filter to protect the processor from transients transmitted through the line voltage. The output of the power supply is regulated and has adequate filtering and fusing. All ISIS assemblies obtain AC power through a common AC bus. There is an on/off switch that allows single switch control of system power. The system is cooled with a muffin fan. The airflow into the fan passes through a filter to minimize dust pollution. This reduces system failure in a field environment due to environmental conditions.

Printed circuit boards are fabricated in accordance with Material Specification PCB0021. The boards are tinned, double-sided boards with plated through holes. A 0.1 mfd capacitor is used with every four integrated circuits to increase the system's noise immunity.

Where available, the discrete components used in the assembly meet military specifications. The state-of-the-art TTL and MOS devices are used to provide optimal speed and performance.

The system will operate satisfactorily in a field environment with a minimal amount of down-time due to environmentally related failures. The use of components covered by military specifications, line filters, cooling fans, line drivers/line receivers, bypass capacitors, shielded and twisted pairs in cable harnesses and tape cartridges results in a system that will deliver the performance required by ISIS.

The cost associated with the development and fabrication of the data acquisition/processing assembly for the prototype ISIS is reflected in Tables 11 and 12.

Table 11. Data Acquisition/Processing Assembly Labor Cost

TASK	TOTAL	
Design	40	(Major portion of design work accomplished in AFML Contract No. F33615-77-C-5026)
PCB Layout	320	
	Total: 360 Manhours	

Table 12. Data Acquisition/Processing Assembly Parts Cost

Quantity	Description	Cost
1	MC6800	$ 28.45
8	MC6821	160.00
1	MC6850	21.00
8	2716-1	650.00
1	6870A	25.00
1	14411	31.68
48	MK4118-4P	1248.00
1	1488L	3.35
1	1489L	3.35
30	AM26LS32DC	87.00
6	AM26LS31DC	17.50
1	54LS13	2.51
1	54LS10	1.28
2	54LS30	2.56
7	DM70L97	17.50
2	54LS00	2.56
2	54LS04	2.82
1	54LS260	.86
4	54L154	22.80
1	54LS155	2.57
1	1KΩ , ¼ watt, 5%	1.25
2	10KΩ , ¼ watt, 5%	2.50
2	3KΩ , ¼ watt, 5%	2.50
1	100 uF mylar	1.80
53	.1 uF	66.25
2	Printed Circuit Boards	200.00
3	Boxer BS2107F-0-1 Fan	93.30
1	LICON 06-71007 1 pole alternating switch	4.55
1	LICON 06-61122 red lens cap	1.30
1	LICON 06-71005 1 pole momentary switch	3.75
1	LICON 06-61133 green lens cap	1.30
1	Cornell-Dubilier NFR101-4 EMI filter	11.25
1	Power Mate PXS-CC-5V @ 16A P/S with overload protection	249.00
10	TRW 37 pin DC-37S socket & DC-37P plug	100.00
2	TRW 25 pin DC-25S socket & DC-25P plug	8.00
127	IC Sockets	145.00
1	Fuseholder	.86
1	Power Cord	1.60
	Total	$3225.00

Data acquisition/processing assemblies in the subsequent ISIS production models do not require development costs. The cost for fabricating the data acquisition/processing assembly for the first ISIS production model is shown in Table 13. The corresponding cost for all subsequent models will be practically zero.

Table 13. Data Acquisition/Processing Assembly Labor Cost in the First ISIS Production Model

TASK		HOURS
Design		40
PCB Layout		240
	Total:	280 Manhours

The tape drive will be mounted in the data acquisition/processing assembly. The cost data for the tape drive follows in Table 14.

Table 14. Tape Drive Cost

QUANTITY	DESCRIPTION	COST
1	Data Electronics, Inc. R3 Ruggedized Tape Drive	$3635.00
2	Power Mate PXS-C-28 28V @ 3.0A P/S with overload protection	358.00
	Total:	$3993.00

7.1.7 ISIS Carrying Cases

ISIS will be packed in two carrying cases for transportation. A third carrying case will be provided to transport the hard copy unit. Normally the hard copy unit will not be carried into the field. The graphics display will be used to monitor the inspection. The permanent digital record made by the tape drive will be used to generate copies on the hard copy unit upon returning from the field. The weight and sizes of the three carrying cases are estimated as follows:

1) Graphics Terminal Carrying Case
   Weight packed - 70 lbs.
   Size - 15" x 23" x 24"

2) Ultrasonic Unit/Computer Carrying Cases
   Weight packed - 70 lbs.
   Size - 20" x 20" x 22"

3) Hard Copy Unit Carrying Case
   Weight Packed - 70 lbs.
   Size - 16" x 18" x 28"

The carrying cases will be custom built by General Dynamics. Table 15 shows the cost of one carrying case.

Table 15. Carrying Case Cost

DESCRIPTION	COST
Materials (metal, wood, hinges, handles, padding, lock, fasteners)	$100.00
Tooling hours	40 hours

Total $100.00 40 Man-Hours/Carrying Case

7.2 System Assembly Cost

Individual components comprising the ISIS will be assembled and integrated into the system. The assembly cost is discussed in the following subsections.

7.2.1 Ultrasonic Unit

Computer interfaces and ultrasonic electronic circuits in the ultrasonic unit not existing in the Sonic Mark IV will be added. Most of the assembly cost had been absorbed by the Quality Assurance Department of General Dynamics.

7.2.2 Transducer Assembly

The transducer and control switches will be mounted on the transducer assembly at a minimal cost.

7.2.3 Waveform Digitizer

The cost associated with the assembly of the waveform digitizer fabricated by General Dynamics is shown in Table 16.

Table 16. Waveform Digitizer Assembly Cost

TASK	HOURS
Assembly	40
Mounting	40
Total:	80 Man Hours

7.2.4 Data Acquisition/Processing Assembly

The assembly and integration costs for the data acquisition processing assembly are shown in Table 17 for the ISIS prototype, ISIS-1 and ISIS-2.

Table 17. Data Acquisition/Processing Unit Assembly and Integration Cost

SYSTEM	ASSEMBLY (Hours)	INTEGRATION (Hours)
ISIS Prototype	160	370
ISIS-1	160	215
ISIS-2	120	212
Total:	400	797 (Manhours)

7.3 Software Development Cost

The software development cost tabulated in Table 18 applies primarily to the development of the ISIS prototype and ISIS-1. Software cost for subsequent systems will only involve programming eight (8) PROMs with one (1) manhour required per PROM. Total cost will be eight (8) manhours.

Table 18. Initial Software Development Cost

TASK	ISIS PROTOTYPE	ISIS-1
Software Design	40 Hrs	20 Hrs
Software Flow Chart	40 Hrs	20 Hrs
Software Preparation	340 Hrs	120 Hrs
Total:	420 Hrs	160 Hrs

7.4 System Checkout Cost

The checkout of the system will occur both at the assembly level when an assembly becomes operational and at the system level when the assemblies are integrated into an ISIS.

The total fabrication, assembly, and debugging cost for the waveform digitizer in the ISIS prototype is 300 man-hours. In subsequent units there will be no development cost resulting in a 220 man-hour reduction.

Table 19 shows a comparison of the checkout hours associated with the data acquisition/processing unit.

Table 19. Data Acquisition/Processing Unit System Checkout Cost

MODEL	ASSEMBLY CHECKOUT	SOFTWARE CHECKOUT	INTEGRATED SYSTEM CHECKOUT
ISIS Prototype	120	280	800
ISIS-1	120	100	320
ISIS-2	60	0	320
Total:	300	380	1440 Manhours

7.5 Documentation Cost

The documentation cost analysis is tabulated in Table 20. The first phase covers the initial documentation for ISIS prototype. The second phase covers the update of ISIS prototype manual to include the redesign effort for ISIS-1. The third phase incorporates field evaluation results into the specifications and operation sections of the manual to prepare a final draft of the manual.

Table 20. ISIS Documentation Cost (Manhours)

TASK	ISIS PROTOTYPE	ISIS-1	ISIS-2
1st Draft	170	-	-
Update	-	90	-
Schematics, Part List, Layouts, Specifications	-	-	140
Final Draft	-	-	400

7.6 System Delivery Cost

The cost of delivering the ISISs to AFML is shown in Table 21.

Table 21. System Delivery Cost

Package	Weight	Motor Freight Transportation Cost	Insurance
Carrying Case #1	70 lbs.	$10.59	NC
Carrying Case #2	70 lbs.	$10.59	NC
Carrying Case #3	70 lbs.	$10.59	NC
	Total	$31.77	

7.7 System Operation Training Cost

A comparison of the training cost for the operation of each system is shown in Table 22. The estimated cost of field training is based on in-house training at General Dynamics' Fort Worth Division.

Table 22. System Operation Training Cost

TASK	ISIS PROTOTYPE	ISIS-1	SUBSEQUENT ISISs
Instructor	40 hrs.	30 hrs.	0
Student	40 hrs.	30 hrs.	0

Total: 140 Man-Hours

7.8 System Maintenance Cost

ISIS maintenance is divided into three areas: (1) Preventtive Maintenance, (2) On-Site Maintenance, and (3) Depot Maintenance. Although AF personnel could be trained to maintain ISIS and certainly will be able to support some of the maintenance, a cost savings will be realized through the use of vendor and General Dynamics' nonleased maintenance because of the small number of ISISs and its relatively trouble free design.

7.8.1 Preventive Maintenance Cost

ISIS has been designed so that preventive maintenance costs can be kept to a minimum. All preventive maintenance can and should be performed by the user. The preventive maintenance schedule and cost estimate are presented in Table 23 by assemblies.

Table 23. ISIS Preventive Maintenance Cost

ASSEMBLY	ACTION	FREQUENCY	MATERIALS COST	LABOR HOURS
Ultrasonic Unit	Clean pots	Once a year	$200	4
	Replace CRT	Once every 5 yrs	200	4

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IN-SERVICE INSPECTION OF ADVANCED COMPOSITE AIRCRAFT STRUCTURE.(U)
FEB 79 F H CHANG, J R BELL, A H GARDNER F33615-77-C-5206
UNCLASSIFIED FZM-6816 AFML -TR-79-4087 NL

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Table 23. ISIS Preventive Maintenance Cost (Cont'd)

ASSEMBLY	ACTION	FREQUENCY	MATERIALS COST	LABOR HOURS
Transducer	None			
Data Acquisition/ Processing Assembly	Replace dust filter	When Dirty (approx once a mo)	$ 1	1
Tape Deck	Replace servo	Every 1000 hrs. (approx once a yr)	300	4
Position Sensors	None			
Waveform Digitizer	None			
Graphics Terminal	Replace CRT	Once every 5 yrs.	200	4
Hard Copy Unit	Clean	Once a month		1
	Lubricate	Once a month	2	1

7.8.2 On-Site Maintenance Cost

On-site maintenance will be performed by the appropriate vendor for vendor supplied assemblies/circuitry. It is entirely conceivable that General Dynamics may have to be consulted to determine the nature of the problem and to summon the appropriate vendor. Projected on-site maintenance cost is tabulated by systems in Table 24.

Table 24. ISIS On-Site Maintenance Cost

SYSTEM	NUMBER OF ON-SITE FAILURES ASSUMED PER YEAR	NUMBER OF DAYS OF DOWNTIME PER FAILURE	VENDOR/GD FEES
ISIS Prototype	2	3	8 hrs. plus $220 for transportation per occurrence
ISIS-1	2	3	8 hrs. plus $220 for transportation per occurrence
Subsequent ISISs	1	2	4 hrs. plus $220 for transportation per occurrence

7.8.3 Depot Maintenance Cost

Depot maintenance will be performed by the appropriate vendor for vendor supplied assemblies and by General Dynamics for General Dynamics supplied assemblies/circuitry. It is conceivable that General Dynamics may have to be consulted to determine the nature of the problem and to summon the appropriate vendor. Projected depot maintenance cost is presented by systems in Table 25.

Table 25. ISIS Depot Maintenance Cost

SYSTEM	NUMBER OF ON-SITE FAILURES ASSUMED PER YEAR	NUMBER OF DAYS OF DOWNTIME PER FAILURE	VENDOR/GD FEES
ISIS Prototype	2	3	8 hrs plus $220 for transportation per occurrence
ISIS-1	2	3	8 hrs plus $220 for transportation per occurrence
Subsequent ISISs	1	2	4 hrs plus $220 for transportation per occurrence

General Dynamics will provide a 90 day warranty on the system after delivery to AFML. General Dynamics will be responsible for all maintenance of ISISs for the duration of the program. The warranty will include all charges such as parts, labor, and transportation.

The projected on-site and depot maintenances anticipated are the "worst cases." Any system with the degree of sophistication and equipment that ISIS possesses will most certainly incur some problems that require maintenance. However, the use of components meeting military specifications coupled with line filters, cooling fans, differential line drivers/line receivers, bypass capacitors, shielded and twisted pairs of wires in cable harnesses and a mass storage tape drive that meets military specifications will result in a reliable system that operates satisfactorily in a field environment with a minimal amount of down-time. An optimal compromise between sophistication and maintainability is one of ISIS's strong points.

The yearly maintenance cost is projected to run about 3 percent of the purchase cost. The graph in Figure 36 shows the projected maintenance costs for ISIS-2 and subsequent ISISs. It combines the costs of preventive, on-site, and depot maintenance. The gradual increase in cost is based on a present day inflation rate of approximately 10 percent a year.

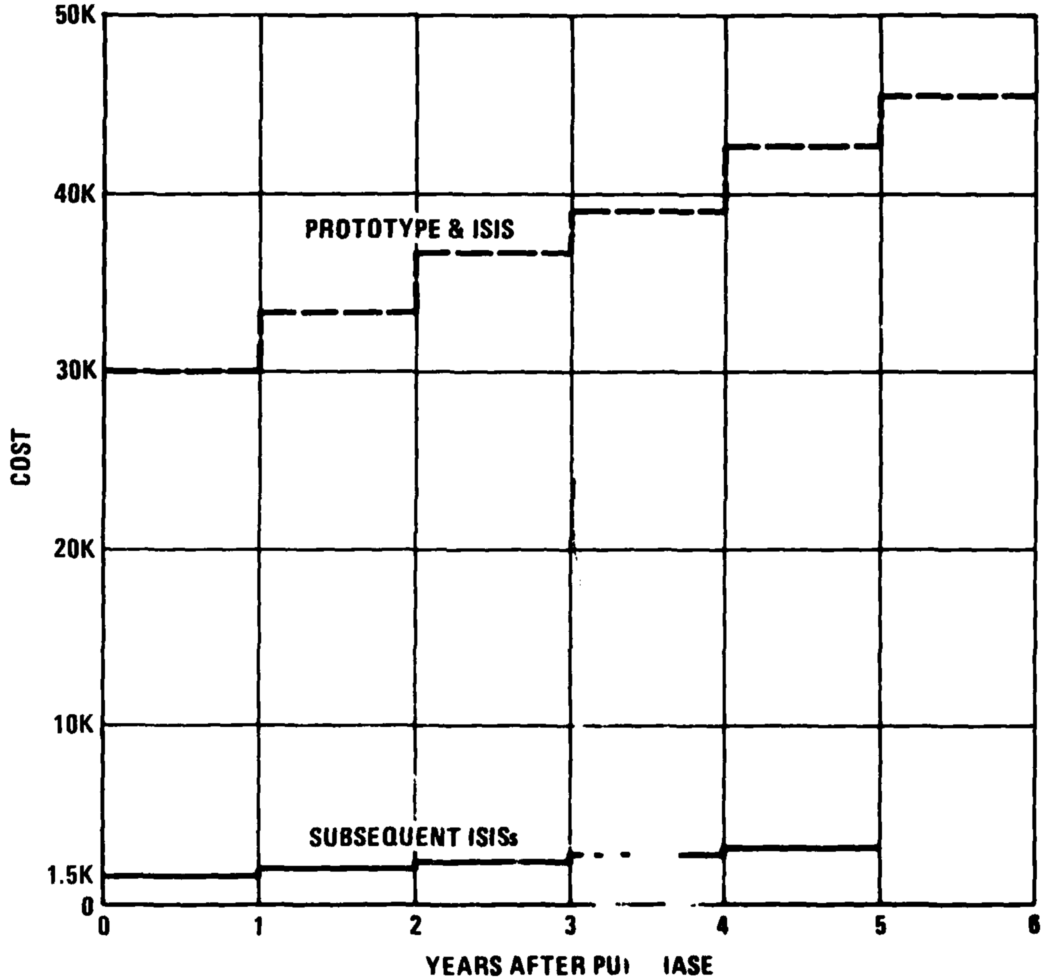

Figure 36 Projected Yearly Maintenance Cost

7.9 Cost Summary

A comparison of the overall cost of the ISIS prototype, ISIS-1, and subsequent ISISs is summarized in Table 26.

Table 26. Cost Comparison of ISIS Prototype, ISIS-1, Subsequent ISISs

TASK	ISIS PROTOTYPE Cost ($)	ISIS PROTOTYPE Labor (Hrs)	ISIS-1 Cost ($)	ISIS-1 Labor (Hrs)	SUBSEQUENT ISISs Cost ($)	SUBSEQUENT ISISs Labor (Hrs)
Fabrication Cost						
Ultrasonic Unit	5550.00		5550.00		5550.00	
Transducer Assembly	1575.00	80	1575.00	80	1575.00	80
Waveform Digitizer	1050.00	180	1050.00		1050.00	
Position Sensor	2740.00		2740.00		2740.00	
Graphics Display/ Hard Copy Unit	12250.00		12250.00		12250.00	
Data Acquisition/ Processing Assy	3225.00	360	3225.00	280	3225.00	
Tape Drive	3993.00		3993.00		3993.00	
Carrying Cases	100.00	40	100.00	40	100.00	40
Assembly Cost						
Ultrasonic Unit						
Transducer Assy						
Waveform Digitizer		80		80		80
Position Sensor						
Data Acquisition/ Processing Assy		160		160		160
Tape Drive						
Carrying Cases						
System Integration		370		215		212
Software Development		420		160		8
Checkout Cost						
Ultrasonic Unit						
Transducer Assy						
Waveform Digitizer		40				
Position Sensor						
Data Acquisition/ Processing Assy		120		120		60
Tape Drive						
Carrying Cases						
Software		280		100		
ISIS System Checkout		800		320		320*
Documentation		170		90	50.00	540*
Delivery	31.77		31.77		31.77	
Training		40		30		
TOTAL	30514.77	3140	30514.77	1675	30564.77	920

*ISIS-2 ONLY.

VIII. REFERENCES

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3. Sushinsky, G. F., Eitzen, D. G., Chwirut, D. J., Bechtoldt, C. J., Ruff, A. W., "Improved Ultrasonic Standard Reference Blocks," AFML-TR-77-40, April 1977.

4. Anon., "Engineered Computer Automated Ultrasonic Inspection System (CAUIS) Production Demonstration for the F-16," General Dynamics Proposal FZP-1904-1, March 10, 1978.

APPENDIX

WORK

```
0: files Bndbnd,
 Phtpht
1: 1→Q
2: rread 1,1
3: on end 1,16
4: sread 1,X,Y
5: if R=1;gto 10
6: X→A
7: X→B
8: Y→C
9: Y→D
10: if X>B;X→B
11: if X<A;X→A
12: if Y>D;Y→D
13: if Y<C;Y→C
14: 1→R
15: gto 3
16: prt "","END
 OF FILE"
17: fxd 2
18: prt A,B,C,D
19: ent "X-INC?"
 ,K
20: ent "Y-INC",
 J
21: ent "PLY
 DROPOFF",r12
22: .055*2*r12/
 .12→r12
22: ent "X Offse
 t",r17
24: ent "Y offse
 t",r18
25: ent "Xmax",
 r19
26: ent "Ymax",
 r20
27: ent "X grid
 separ.",r21
28: scl 0,2r17+
 2r19+r21,0,2r18
 +r20
29: dim S[300],
 I[20],L[20],
 G[20]
30: rread 2,1
31: red 12,r2,
 r10
32: if r2>90;
 1→r14;0→r11;
 jmp -1
33: if r11=0;
 r2→r11;gto 40
34: abs(r2-r11)→
 r13
35: if r13<=2+
 r12;r2→r11;gto
 40
36: if r2>r11;
 r2→r11;gto 40
37: rdb(9)→E
38: (frc(E/256)+
 256-70)/100→r1
39: gto 43
40: 0→r1
41: r11-18→r13;
 if r13<=0;1→r13
42: wtb 9,r13*
 10.936
43: r2*.12/20/
 .0055-1.5→r2
44: red 3,X,Y
45: X/100→X
46: Y/100→Y;fxd
 2;dsp Q,r1,r2
47: X*24.125/
 14.36→X
48: Y*24.125/
 14.36→Y
49: X-A→X
50: Y-C→Y
51: X+r17+(r19-
 (B-A))/2→X
52: Y+r18+(r20-
 (D-C))/2→Y
53: if abs(W-
 X)<.01;gto 31
54: if abs(W-X)+
 abs(Z-Y)<.1;
 gto 31
55: if r1>.25
 and r1<.4;0→r11
 ;gto 31
56: if r1>.2;
 1→r5
57: if r6=0;gto
 121
58: if r14=1;
 plt W,Z,1;plt
 X,Y,1;0→r14;
 X→W;Y→Z;gto 31
59: if r5+r3>=1;
 gto 84
60: if r9=0;plt
 X,Y,1
61: plt X,Y
62: atn((Y-Z)/
 (X-W))→T
63: sin(T)/16→U
64: cos(T)/16→V
65: X-U→M
66: Y+V→N
67: plt M,N
68: W-U→M
69: Z+V→N
70: plt M,N
71: W+U→M
72: Z+V→N
73: plt M,N
74: X+U→M
75: Y+V→N
76: plt M,N
77: plt X,Y
78: X→W
79: Y→Z
80: r1→r7
81: r2→r8
82: 1→r9;0→r14
83: gto 31
84: if r1<=.2;
 0→r3;gto 60
85: plt X,Y
86: X→W
87: Y→Z
88: r1→r7
89: r2→r8
90: r5+r3→G[Q]
91: r5→r3
92: 0→r5
93: X*8→M
94: Y*8→N
95: int(M)+1→M
96: int(N)+1→N
97: N/1000→N
98: M+N→M
99: if R=1;gto
 106
100: 1→T
101: if S[T]=M;
 gto 110
102: if S[T]=0;
 gto 106
103: 1+T→T
104: if T>300;
 gto 106
105: gto 101
106: M→S[R]
107: sprt 2,W,Z,
 r7,r8,"end"
108: 1+R→R
109: if R>300;
 2→R
110: if Q=20;
 plt X,Y,1
111: if G[Q]=2;
 gto 113
112: if G[Q]=1;
 gto 114
113: if abs(X-
 r15)+abs(Y-r16)
 >.5;G[Q]-1→G[Q]
114: X→r15;Y→r16
 ;X+r19+r21→X
115: X→I[Q]
```

Figure A-1 Program "WORK"-1

```
116: Y→L[Q]
117: Q+1→Q;1→r9
118: if Q>20;
 gto 129
119: if Q=20;
 prt Q
120: beep;gto 31
121: plt X,Y,1
122: X→W
123: Y→Z
124: 1→r6
125: gto 31
126: X→W
127: Y→Z
128: gto 31
129: 1→Q
130: plt I[Q],
 L[Q],1
131: plt I[Q],
 L[Q],G[Q]
132: Q+1→Q
133: if Q<=20;
 gto 131
134: plt I[Q-1],
 L[Q-1],1
135: 1→Q
136: 0→r9
137: gto 31
138: end
+14466
```

Figure A-1 Program "WORK"-2

LIST

```
0: dim X[50],
 Y[50],U[50],
 V[50]
1: 1→N;1→M;1→J
2: ent "Min Y",A
3: ent "Max Y",B
4: ent "Min X",C
5: ent "Max X",D
6: ent "Fst GT
 Amp Bias",r13
7: ent "Min Dept
 h",r14
8: ent "Max Dept
 h",r15
9: files Srt639,
 Compor
10: rread 2,1
11: on end 2,14
12: sread 2,X,Y
13: gto 11
14: A+Y→A;B+Y→B;
 C+X→C;D+X→D
15: X→r11;Y→r12
16: .125→S;A+S→S
17: rread 1,1
18: on end 1,28
19: sread 1,r1,
 r2,r3,r4
20: if r1<C or
 r1>D;gto 18
21: if r2<A;gto
 18
22: if r3<r13;
 gto 18
23: if r4>r15;
 gto 18
24: if r4<r14;
 gto 18
25: if r2>=S;
 gto 28
26: r1→X[N];r2→Y
 [N];r3→U[N];
 r4→V[N]
27: N+1→N;gto 18
28: N-1→N;N→J
29: if J<2;gto
 43
30: 1→M;1→P
31: X[M]→r1;Y[M]
 →r2;U[M]→r3;
 V[M]→r4
32: M+1→P
33: if P>J;gto
 40
34: X[P]→r5;Y[P]
 →r6;U[P]→r7;
 V[P]→r8
35: if r5>r1;
 gto 39
36: r1→X[P];r2→Y
 [P];r3→U[P];
 r4→V[P]
37: r5→X[M];r6→Y
 [M];r7→U[M];
 r8→V[M]
38: r5→r1;r6→r2;
 r7→r3;r8→r4
39: P+1→P;gto 33
40: M+1→M
41: if M=J;gto
 43
42: gto 31
43: 1→M
44: if J=0;gto
 58
45: spc 2;fxd 2
46: X[M]-r11→X[M
 ];Y[M]-r12→Y[M]
47: M+1→M
48: if M>J;gto
 50
49: gto 46
50: 1→M
51: prt X[M],
 Y[M],U[M]
52: prt V[M]
53: fxd 2
54: M+1→M
55: if M>J;gto
 58
56: spc
57: gto 51
58: S→A;A+.125→S
59: if A>=B;gto
 65
60: 1→N
61: 0→X[N];0→Y[N
 ];0→U[N];0→V[N]
62: N+1→N
63: if N>J;1→N;
 gto 17
64: gto 61
65: end
*23544
```

Figure A-2 Program "LIST"

PREPAR

```
0: 1→N
1: dim P[120],
 Q[120],A[4],
 W[4],K[4],H[4],
 X[4],Y[4]
2: 0→P[N];0→Q[N]
3: N+1→N
4: if N>120;gto
 6
5: gto 3
6: 1→N
7: files Bndbnd,
 Compor
8: rread 1,1
9: on end 1,19
10: sread 1,r1,
 r2
11: if N#1;gto
 13
12: r1→A;r1→B;
 r2→C;r2→D
13: if r1>B;r1→B
14: if r1<A;r1→A
15: if r2>D;r2→D
16: if r2<C;r2→C
17: 2→N
18: gto 9
19: prt "","END
 OF FILE"
20: fxd 2
21: prt A,B,C,D
22: B-A→K
23: D-C→J
24: ent "X Inc",
 K
25: ent "Y Inc",
 J
26: ent "X&Y
 Offset",I
27: ent "Max X",
 r1
28: ent "Max Y",
 r2
29: scl 0,r1+2I,
 0,r2+2I
30: 1→N
31: rread 1,1
32: on end 1,38
33: sread 1,r3,
 r4
34: r3→P[N]
35: r4→Q[N]
36: 1+N→N
37: gto 32
38: N-1→Z;1→N
39: if P[N]=0;
 gto 46
41: P[N]+I+(r1-
 (B-A))/2→P[N]
42: Q[N]-C→Q[N]
43: Q[N]+I+(r2-
 (D-C))/2→Q[N]
44: N+1→N
45: gto 39
46: ent "Search
 for Corners?",S
47: if S=1;gto
 95
48: 1→N
49: P[1]+Q[1]→X
50: P[1]→r1;Q[1]
 →r2
51: 1→N
52: if P[N]=0;
 gto 56
53: if P[N]+Q[N]
 >X;N+1→N;gto 52
54: P[N]+Q[N]→X
55: P[N]→r1;Q[N]
 →r2;N+1→N;gto
 52
56: 1→N
57: P[N]/Q[N]→X
58: P[1]→r3;Q[1]
 →r4
59: N+1→N
60: if P[N]=0;
 gto 64
61: if P[N]/Q[N]
 <X;gto 59
62: P[N]/Q[N]→X
63: P[N]→r3;Q[N]
 →r4;gto 59
64: 1→N
65: P[N]+Q[N]→X
66: P[1]→r5;Q[1]
 →r6
67: N+1→N
68: if P[N]=0;
 gto 72
69: if P[N]+Q[N]
 <X;gto 67
70: P[N]+Q[N]→X
71: P[N]→r5;Q[N]
 →r6;gto 67
72: 1→N
73: Q[N]/P[N]→X
74: P[1]→r7;Q[1]
 →r8
75: N+1→N
76: if P[N]=0;
 gto 81
77: if Q[N]/P[N]
 <X;gto 75
78: Q[N]/P[N]→X
79: P[N]→r7;Q[N
 →r8;gto 75
80: plt r1,r2,1
81: plt r1,r2;
 plt r3,r4
82: plt r5,r6;
 plt r7,r8
83: plt r1,r2;
 plt r1,r2,1
84: files Compor
85: rread 1,1
86: sprt 1,K,J,
 "end";sprt 1,
 r1,r2,"end"
87: sprt 1,r3,
 r4,"end";sprt
 1,r5,r6,"end"
88: sprt 1,r7,
 r8,"end"
89: rread 1,1
90: on end 1,95
91: sread 1,X,Y
92: prt X,Y
93: gto 90
94: gto 164
95: rread 2,1
96: on end 2,99
97: sread 2,X,Y
98: gto 96
99: 0→N;0→r15
100: N+1→N;if N+
 1>Z;gto 103
101: if P[N]-
 P[N+1]#0;jmp -1
102: P[N+1]-.01→
 P[N+1];1→r15;
 gto 100
103: if P[1]-
 P[Z]=0;P[1]-
 .01→P[1];1→r15
104: if r15=1;
 gto 99
105: 0→N;0→r15
106: N+1→N;if N+
 1>Z;gto 109
107: if Q[N]-
 Q[N+1]#0;jmp -1
108: Q[N+1]-.01→
 Q[N+1];1→r15;
 gto 106
109: if Q[1]-
 Q[Z]=0;Q[1]-
 .01→Q[1];1→r15
110: if r15=1;
 gto 105
111: 1→N
112: if N#1;gto
 114
```

Figure A-3 Program "PREPAR"—1

```
113: Q[N]→r8;
 Q[N]→r9
114: if Q[N]<r8;
 gto 119
115: if Q[N]>r9;
 gto 120
116: N+1→N
117: if N>Z;gto
 121
118: gto 112
119: Q[N]→r8;
 gto 116
120: Q[N]→r9;
 gto 116
121: 1→N
122: (Q[N]-Q[N+
 1])/(P[N]-P[N+
 1])→A[N]
123: Q[N]-A[N]*
 P[N]→W[N]
124: P[N]→r5;
 P[N+1]→r6
125: if r5<r6;
 gto 127
126: r6→H[N];
 r5→K[N];gto 128
127: r5→H[N];
 r6→K[N]
128: Q[N]→r5;
 Q[N+1]→r6
129: if r5<r6;
 gto 131
130: r5→X[N];
 r6→Y[N];gto 132
131: r6→X[N];
 r5→Y[N]
132: N+1→N
133: if N=Z;gto
 135
134: gto 122
135: (Q[N]-Q[1])
 /(P[N]-P[1])→A[
 N]
136: Q[N]-A[N]*
 P[N]→W[N]
137: P[N]→r5;
 P[1]→r6
138: if r5<r6;
 gto 140
139: r6→H[N];
 r5→K[N];gto 141
140: r5→H[N];
 r6→K[N]
141: Q[N]→r5;
 Q[1]→r6
142: if r5<r6;
 gto 144
143: r5→X[N];
 r6→Y[N];gto 145
144: r6→X[N];
 r5→Y[N]
145: 1→N
146: rread 2,1
147: sprt 2,P[N]
 ,Q[N],"end"
148: N+1→N
149: if N>Z;gto
 151
150: gto 147
151: 1→N
152: sprt 2,A[N]
 ,W[N],K[N],H[N]
 ,X[N],Y[N],"end
 "
153: N+1→N
154: if N>Z;gto
 156
155: gto 152
156: 1→N
157: sprt 2,r8,
 r9,Z,Z,X,Y,"end
 "
158: plt P[N],
 Q[N],1
159: plt P[N],
 Q[N]
160: N+1→N
161: if N>Z;gto
 163
162: gto 159
163: plt P[1],
 Q[1];plt P[1],
 Q[1],1
164: end
*29364
```

Figure A-3 Program "PREPAR" - 2

SORT

```
0: 0→A
1: dim S[112],
 Z[112],U[112],
 V[112]
2: 112→I
3: 0→G;0→B
4: 1→N
5: files Phtpht,
 Srt639
6: rread 1,1
7: on end 1,18
8: sread 1,X,Y,
 r1,r2
9: if N#1;gto 14
10: Y→r3
11: Y→r4
12: N+1→N
13: gto 7
14: if Y<r3;Y→r3
 ;gto 7
15: if Y>r4;Y→r4
 ;gto 7
16: N+1→N
17: gto 7
18: 1→M
19: fxd 2
20: .2→L
21: r3+L→r5;M→Q;
 dsp r5
22: rread 1,1
23: on end 1,30
24: sread 1,X,Y,
 r1,r2
25: if Y<r3 or
 Y>=r5;gto 23
26: X→S[M];Y→Z[M
 ];r1→U[M];r2→V[
 M]
27: M+1→M
28: if M>I;gto
 36
29: gto 23
30: M→Q;if r5>r4
 ;gto 36
31: if M/I>.6;
 gto 36
32: r5+L→r5;0→B
33: dsp r3,M
34: r3+L→r3
35: gto 22
36: M-1→M
37: if M=I;L/
 2→L;gto 91
38: .2→L;1→J
39: 1→N
40: if S[J]=0;
 gto 60
41: S[J]→X
42: Z[J]→Y;U[J]→
 r8;V[J]→r9
43: J+1→N
44: if N>M;gto
 57
45: if Z[N]=0;
 gto 57
46: if Z[N]>Y;
 gto 55
47: S[N]→r1
48: Z[N]→r2;U[N]
 →r6;V[N]→r7
49: X→S[N]
50: Y→Z[N];r8→U[
 N];r9→V[N]
51: r1→S[J]
52: r2→Z[J];r6→U
 [J];r7→V[J]
53: r1→X
54: r2→Y;r6→r8;
 r7→r9
55: N+1→N
56: gto 44
57: J+1→J
58: if J>M;gto
 60
59: gto 40
60: if r5>r4;
 M→P;gto 69
61: M/8→r6
62: int(r6)→r6
63: 8*r6→r7
64: M-r7→K;K→r7
65: if K=0;M→P;
 gto 67
66: M-r7→P
67: if G=1;gto
 70
68: A+1→A
69: if G=0;1→A
70: 1→N
71: rread 2,A
72: sprt 2,S[N],
 Z[N],U[N],V[N],
 "end"
73: N+1→N
74: if N>P;gto
 76
75: gto 72
76: if r5>r4;
 gto 96
77: A+r6→A;1→G;
 1→B
78: if r7=0;1→M;
 gto 84
79: 1→J
80: S[P+J]→S[J];
 Z[P+J]→Z[J];
 U[P+J]→U[J];
 V[P+J]→V[J]
81: J+1→J
82: if J>r7;r7+
 1→M;gto 84
83: gto 80
84: r5→r3;dsp r3
85: M→J
86: 0→S[J];0→Z[J
 ];0→U[J];0→V[J]
87: J+1→J
88: if J>I;gto
 20
89: gto 86
90: prt "Stp
 size too large"
91: 0→J
92: 0→S[J];0→Z[J
 ];0→U[J];0→V[J]
93: J+1→J
94: if J>I;0→M;
 gto 21
95: gto 92
96: end
*13601
```

Figure A-4 Program "SORT"

PTR

```
0: ent K
1: 1→N
2: files Ptr2dt
3: rread 1,1
4: scl 0,3000,-
 300,300
5: rdb(10)→A
6: A+K→A
7: sprt 1,A,"end
 "
8: if N>1;gto 10
9: plt N,A,1
10: plt N,A
11: N+1→N
12: if N>2600;
 gto 14
13: gto 5
14: end
*86
```

PTEND

```
0: files Bndbnd
1: ent "NO. OF
 BOUNDARY POINTS
 ",K
2: 0→B
3: 0→A
4: rread 1,1
5: red 3,X,Y
6: X*24.125/14.3
 6/100→X
7: Y*24.125/14.3
 6/100→Y
8: if X>10;gto
 10
9: if Y<10;gto
 19
10: if abs(X-
 A)>1;gto 13
11: if abs(Y-
 B)>1;gto 13
12: gto 5
13: sprt 1,X,Y,
 "end"
14: X→A
15: flg 2;prt X,
 Y,"OK"
16: beep
17: Y→B;N+1→N;
 if N=K;gto 20
18: gto 5
19: sprt 1
20: end
*19286
```

Figure A-5 Programs "PTR" and "PTEND"

PSTGRD

```
0: ent "X&Y Offs
 et",A
1: ent "X&Y Inc"
 ,I
2: ent "Max X",C
3: ent "Max Y",D
4: scl 0,C+2A,0,
 D+2A
5: A→X;A→Y
6: plt X,Y,1
7: plt X,Y
8: X+I→X
9: if X>I+C;gto
 15
10: plt X,Y
11: Y-.07I→Z
12: plt X,Z
13: plt X,Y
14: gto 8
15: plt X,Y,1
16: A→X;A→Y
17: plt X,Y,1
18: plt X,Y
19: Y+I→Y
20: if Y>I+D;
 gto 26
21: plt X,Y
22: X-.07I→Z
23: plt Z,Y
24: plt X,Y
25: gto 19
26: plt X,Y,1
27: .8A→X
28: I/2→Y
29: 0→L
30: fxd 0
31: csiz 3,1.7,
 1,0
32: plt X,Y,1
33: lbl L
34: L+I→L
35: X+I→X
36: if L>C;gto
 33
37: gto 32
38: plt X,Y,1
39: A→Y;.9→X
40: 0→L
41: plt X,Y,1
42: lbl L
43: Y+I→Y;I+L→L
44: if L>D;gto
 46
45: gto 41
46: plt X,Y,1
47: csiz 3,1.7,
 1,0
48: D+A→Y;2I→X
49: plt X,Y,1
50: lbl "BONDED
 PANEL"
51: end
*29742
```

Figure A-6 Program "PSTGRD"

PREGRD

```
0: files Bndbnd,
 Compor
1: ent "Offset
 X",r1
2: ent "Offset
 Y",r2
3: ent "Xmax",r3
4: ent "Ymax",r4
5: ent "X inc",K
6: ent "Y inc",J
7: ent "Grid
 Separ.",r5
8: scl 0,2r1+r5+
 2r3,0,2r2+r4
9: dim P[10],
 Q[10]
10: 0→E
11: rread 1,1
12: on end 1,25
13: sread 1,X,Y
14: if E=1;gto
 19
15: X→A
16: X→B
17: Y→C
18: Y→D
19: if X>B;X→B
20: if X<A;X→A
21: if Y>D;Y→D
22: if Y<C;Y→C
23: 1→E
24: gto 12
25: prt "","End
 of File"
26: fxd 2
27: prt A,B,C,D
28: fxd 0
29: K→X
30: J→Y
31: plt r1,r2,1
32: plt r1,r2
33: r1+K→X
34: if X>r3+r1;
 gto 40
35: plt X,Y
36: Y-.07J→Z
37: plt X,Z
38: plt X,Y;X+
 K→X
39: gto 34
40: r1+r3+r5→X
41: plt X,Y,1
42: plt X,Y
43: Y-.07J→Z
44: plt X,Z
45: plt X,Y
46: X+K→X
47: if X>r1+r5+
 2r3;gto 49
48: gto 42
49: r1→X;plt r1,
 r2,1
50: plt r1,r2
51: r2+J→Y
52: if Y>r2+r4;
 gto 58
53: plt X,Y
54: X-.07*K→Z
55: plt Z,Y
56: plt X,Y
57: Y+J→Y;gto 52
58: plt X,Y,1;
 1→S
59: rread 1,1
60: on end 1,70
61: sread 1,X,Y
62: X-A→X
63: Y-C→Y
64: X+r1+(r3-(B-
 A))/2→X
65: Y+r2+(r4-(D-
 C))/2→Y
66: if S#1;gto
 68
67: X→U;Y→V;2→S
68: plt X,Y
69: gto 60
70: prt "","End
 of File"
71: plt U,V;plt
 U,V,1;1→S
72: rread 1,1
73: on end 1,83
74: sread 1,X,Y
75: X-A→X
76: Y-C→Y
77: X+r1+r3+r5+
 (r3-(B-A))/2→X
78: Y+r2+(r4-(D-
 C))/2→Y
79: if S#1;gto
 81
80: X→U;Y→V;2→S
81: plt X,Y
82: gto 73
83: prt "","End
 of File"
84: plt U,V;plt
 U,V,1
85: .4*J→Y
86: .8*K→X
87: 0→Z
88: plt X,Y,1
89: csiz 2,1.7,
 2/3,0
90: fxd 0
91: lbl Z
92: K+X→X
93: K+Z→Z
94: if Z>r3;gto
 96
95: gto 88
96: plt X,Y,1
97: r1+r3+r5-.3*
 K→X
98: 0→Z
99: plt X,Y,1
100: lbl Z
101: K+X→X
102: K+Z→Z
103: if Z>r3;
 gto 106
104: plt X,Y,1
105: gto 100
106: .8→X
107: r2→Y
108: 0→Q
109: plt X,Y,1
110: csiz 2,1.7,
 2/3,0
111: fxd 0
112: lbl Q
113: J+Y→Y
114: J+Q→Q
115: if Q>r4;
 gto 117
116: gto 109
117: .4*(2r1+r5+
 2r3)→X
118: .95*(2r2+
 r4)→Y
119: plt X,Y,1
120: csiz 2,1.7,
 2/3,0
121: lbl "PRODUC
 TION HORIZONTAL
 TAIL #S340639"
122: rread 2,1
123: sprt 2,r1,
 r2,"end"
124: end
*1586
```

Figure A-7 Program "PREGRD"

BLOWUP

```
0: files Bis639,
 Compor
1: dim P[100],
 Q[100],A[4],
 T[4],W[4],K[4],
 H[4],X[4],Y[4]
2: 1→M;100→I;1→R
3: rread 2,1
4: on end 2,7
5: sread 2,P[M],
 Q[M]
6: M+1→M;gto 4
7: P[M-2]→Z;Z+
 1→J;Z→r16
8: P[M-1]→r7
9: Q[M-1]→r8
10: 1→M;1→N
11: P[M+Z]→A[N];
 Q[M+Z]→W[N]
12: P[M+Z+1]→K[N
 ];Q[M+Z+1]→H[N]
13: P[M+Z+2]→X[N
 ];Q[M+Z+2]→Y[N]
14: M+3→M;N+1→N
15: if M>3*Z;
 gto 17
16: gto 11
17: 1→M;P[4*Z+
 M]→r17;Q[4*Z+
 M]→r18
18: ent "offset
 Y",r1;r1→r22
19: ent "Offset
 Y",r2;r2→r23
20: ent "Min Y",
 r3
21: ent "Max Y",
 r4
22: ent "Min X",
 r5
23: ent "Max X",
 r6
24: scl r5-r1,
 r6-r1,r3-r2,r4+
 r2
25: 0→N;0→J;0→L
26: N+1→N;if
 N>r16;gto 30
27: if P[N]<r5+
 r7 or P[N]>r6+
 r7;jmp -1
28: if Q[N]<r3+
 r8 or Q[N]>r4+
 r8;jmp -2
29: J+1→J;P[N]→P
 [J];Q[N]→Q[J];
 jmp -3
30: if J=r16;
 gto 60
31: 0→N;r3+r8→r2
 7;0→Z
32: N+1→N;if
 N>r16;gto 37
33: (r27-W[N])/
 A[N]→r28
34: if r28>K[N]
 or r28<H[N];
 jmp -2
35: if r28<r5+
 r7 or r28>r6+
 r7;jmp -3
36: J+1→J;r28→P[
 J];r27→Q[J];
 jmp -4
37: if Z=1;jmp 2
38: 0→N;r4+r8→r2
 7;1→Z;gto 32
39: 0→N;r5+r7→r2
 7;0→Z
40: N+1→N;if
 N>r16;gto 45
41: A[N]*r27+
 W[N]→r28
42: if r28>X[N]
 or r28<Y[N];
 jmp -2
43: if r28<r3+
 r8 or r28>r4+
 r8;jmp -3
44: J+1→J;r27→P[
 J];r28→Q[J];
 jmp -4
45: if Z=1;jmp 2
46: 0→N;r6+r7→r2
 7;1→Z;gto 40
47: if J<=1;prt
 "J=",J;gto 64
48: 1→N→M
49: 1+M→M;if
 M=N;1+M→M
50: if M>J;gto
 57
51: (Q[M]-Q[N])/
 (P[M]-P[N])→B
52: 0→C
53: 1+C→C;if
 C>r16;gto 56
54: if abs(B-
 A[C])>.00001;
 jmp -1
55: plt P[M]-r7,
 Q[M]-r8,1;plt
 P[M]-r7,Q[M]-
 r8;plt P[N]-r7,
 Q[N]-r8;jmp -2
56: if M#J;gto
 49
57: N+1→N;N→M
58: if N>J;gto
 64
59: gto 49
60: 1→N;plt P[N]
 -r7,Q[N]-r8,1
61: plt P[N]-r7,
 Q[N]-r8;plt
 P[N+1]-r7,Q[N+
 1]-r8
62: N+1→N;if
 N#r16;jmp -1
63: plt P[N]-r7,
 Q[N]-r8;plt
 P[1]-r7,Q[1]-r8
64: 0→M
65: M+1→M
66: 0→P[M];0→Q[M
 ]
67: if P[M+1]#0;
 gto 65
68: r5→r25;r3→r2
 6;r1→N
69: plt r5,r3,1
70: plt r5,r3
71: r25+N→r25
72: if r25>r6;
 gto 78
73: r26-.05N→Z
74: plt r25,r26
75: plt r25,Z
76: plt r25,r26
77: gto 71
78: plt r25,r26,
 1
79: r5→r25
80: plt r25,r26,
 1
81: plt r25,r26
82: r26+N→r26
83: if r26>r4;
 gto 89
```

Figure A-8 Program "BLOWUP"-1

```
 4: plt r25,r26
:5: r25-.05N→Z
36: plt Z,r26
37: plt r25,r26
88: gto 82
89: plt r25,r26,
 1;r3→r26
90: plt r25,r26,
 1
91: r25-.4N→r25
92: r26-.6N→r26
93: r5→L
94: plt r25,r26,
 1
95: csiz 20/(r4-
 r3+2*r1),2,(r4-
 r3+2r1)/(r6-r5+
 2r1),0
96: fxd 0
97: lbl L
98: L+N→L
99: r25+N→r25
100: if L>r6;
 gto 102
101: gto 94
102: plt r25,
 r26,1
103: r3→r26
104: r5-.8N→r25
105: r3→L
106: plt r25,
 r26,1
107: lbl L
108: L+N→L
109: r26+N→r26
110: if L>r4;
 gto 112
111: gto 106
112: ent "Fst
 GT Amp Bias",
 r12
113: ent "Min
 Depth",r24
114: ent "Max
 Depth",r14
115: gto 257
116: 1→N
117: (Z-W[N])/
 A[N]→T[N]
118: if T[N]<H[N
 ] or T[N]>K[N];
 0→T[N]
119: N+1→N
120: if N>r16;
 gto 122
121: gto 117
122: 1→N;1→J
123: T[N]→r1;1+
 N→J
124: if J>r16;
 gto 129
125: if T[J]<r1;
 gto 128
126: T[J]→r2
127: r1→T[J];
 r2→T[N];r2→r1
128: 1+J→J;gto
 124
129: 1+N→N
130: if N#r16;
 gto 123
131: 1→N
132: if T[N]=0;
 gto 134
133: N+1→N;jmp -
 1
134: N-1→r13
135: 0→N
136: r13→J
137: T[J-N]→r1;
 T[N+1]→r2
138: r2→T[J-N];
 r1→T[N+1]
139: N+1→N
140: if N#r13/2;
 gto 137
141: ret
142: 1→M;1→r15
143: 0→P[M];0→Q[
 M]
144: M+1→M
145: if M>I;1→M;
 gto 147
146: gto 143
147: rread 1,R
148: on end 1,
 163
149: sread 1,
 r25,r26,r1,r2
150: if r26<Z-1/
 16;gto 159
151: if r26>Z+1/
 16;gto 163
152: if r25<U
 or r25>V;gto
 158
153: if r1<r12;
 gto 158
154: if r2>r14;
 gto 158
155: if r2<r24;
 gto 158
156: r25→P[M];
 r26→Q[M]
157: M+1→M
158: if r26>Z;
 gto 161
159: r15+1→r15
160: if r15=9;
 1→r15;R+1→R
161: if M>I;gto
 182
162: gto 148
163: M-1→M;M→L;
 dsp L
164: if M<2;gto
 183
165: M→L
166: 1→M;1→N
167: P[M]→r25;
 Q[M]→r26
168: N+1→N
169: if N>L;gto
 177
170: P[N]→r9;
 Q[N]→r10
171: if r9>r25;
 gto 175
172: r9→P[M];
 r10→Q[M]
173: r25→P[N];
 r26→Q[N]
174: r9→r25;r10→
 r26
175: N+1→N
176: gto 169
177: M+1→M
178: if M>L;gto
 183
179: M→N
180: gto 167
181: gto 183
182: prt "array
 too large";stp
183: ret
184: 1→J;0→B;0→C
185: if L=0;gto
 191
186: P[J]-1/8→D;
 P[J]+1/8→E
187: if U>D and
 U<=E;E→U;gto
 190
```

Figure A-8 Program "BLOWUP"-2

```
188: if U<D and V>E;B+1→B;gto 193
189: if V>=D and V<=E;D→V;gto 191
190: if J#L;J+1→J;gto 186
191: plt U,Z,1;plt U,Z;plt V,Z;plt V,Z,1
192: gto 255
193: P[J+1]-1/8→F;if F>=V;gto 240
194: if P[J+1]+.125>V;J+1→L
195: if J=L-1;gto 208
196: if J=L;gto 241
197: if B#1;gto 203
198: plt U,Z,1;plt U,Z;plt D,Z
199: plt D,Z,1;plt E,Z,1
200: F-E→C
201: if C>0;plt E,Z
202: gto 207
203: if C>0;plt D,Z;plt D,Z,1;plt E,Z,1
204: if C<0;plt D,Z,1;plt E,Z,1
205: F-E→C
206: if C>0;plt E,Z
207: gto 190
208: P[J+1]+1/8→G
209: if G>V;gto 228
210: if B>1;gto 218
211: F-E→C
212: plt U,Z,1;plt U,Z;plt D,Z;plt D,Z,1
213: plt E,Z,1
214: if C>0;gto 217
215: plt F,Z,1;plt G,Z,1;plt G,Z
216: plt V,Z;plt V,Z,1;gto 255
217: plt E,Z;plt F,Z;gto 215
218: if C>0;plt D,Z;plt D,Z,1;plt E,Z,1
219: if C<=0;plt D,Z,1;plt E,Z,1
220: F-E→C
221: if C<=0;gto 225
222: if C>0;plt E,Z;plt F,Z;plt F,Z,1
223: plt G,Z,1;plt G,Z;plt V,Z;plt V,Z,1
224: gto 255
225: plt F,Z,1;plt G,Z,1;plt G,Z
226: plt V,Z;plt V,Z,1
227: gto 255
228: if B>1;gto 235
229: F-E→C
230: plt U,Z,1;plt U,Z;plt D,Z;plt D,Z,1
231: plt E,Z,1
232: if C>0;gto 234
233: plt F,Z,1;plt V,Z,1;gto 255
234: plt E,Z;plt F,Z;gto 233
235: if C>0;plt D,Z;plt D,Z,1;plt E,Z,1
236: if C<0;plt D,Z,1;plt E,Z,1
237: F-E→C
238: if C>0;gto 234
239: if C<=0;gto 233
240: if B#1;gto 244
241: plt U,Z,1;plt U,Z;plt D,Z;plt D,Z,1;plt E,Z,1
242: plt E,Z;plt V,Z;plt V,Z,1
243: gto 255
244: if C<=0;gto 248
245: if C>0;plt D,Z;plt D,Z,1;plt E,Z,1
246: plt E,Z;plt V,Z;plt V,Z,1
247: gto 255
248: plt D,Z,1;plt E,Z,1;plt E,Z
249: plt V,Z;plt V,Z,1;gto 255
250: plt U,Z,1;plt U,Z;plt V,Z;gto 251
251: plt V,Z,1;gto 255
252: if B=0;gto 191
253: if C>0;plt V,Z;plt V,Z,1
254: if C<=0;plt V,Z,1
255: ret
256: 1→N
257: if P[N]=0;jmp 3
258: 0→P[N];0→Q[N]
259: N+1→N;jmp -2
260: 1→N
261: r4+r8→r21
262: 1/16→S;1→R
263: r3+r8→Z
264: r7+r5→r19;r7+r6→r20
```

Figure A-8 Program "BLOWUP"- 3

```
265: Z+S→Z;if
 Z>r21 or Z>r18;
 gto 292
266: if Z<=r17;
 gto 265
267: r7+r5→U;r7+
 r6→V
268: gsb 116
269: 1→W
270: if T[W]>r20
 ;gto 265
271: if r19>T[W+
 1];gto 265
272: if r19<T[W]
  and r20>T[W+
 1];gto 279
273: if r19>=T[W
 ] and r20<=T[W+
 1];jmp 3
274: if r19<T[W]
  and r20<=T[W+
 1];jmp 3
275: if r19>=T[W
 ] and r20>T[W+
 1];jmp 3
276: r19→U;r20→V
 ;gto 280
277: T[W]→U;r20→
 V;gto 280
278: r19→U;T[W+
 1]→V;gto 280
279: T[W]→U;T[W+
 1]→V
280: gsb 142
281: 1→M;if L=0;
 gto 286
282: P[M]-r7→P[M
 ];Q[M]-r8→Q[M]
283: 1+M→M
284: if M>L;gto
 286
285: gto 282
286: U-r7→U;V-
 r7→V
287: Z-r8→Z
288: gsb 184
289: Z+r8→Z
290: W+2→W;if
 T[W]=0;gto 265
291: gto 273
292: (r5+r6)/2-
 1→X;r4+r23-.3→Y
 ;fxd 2
293: plt X,Y,1
294: cplt -.3,-
 .3
295: lbl "Voltag
 e >",r12
296: plt X,Y,1
297: cplt -.3,-
 1.3
298: fxd 0
299: lbl "Plies"
 ,r24,"→",r14
300: end
*27229
```

Figure A-8 Program "BLOWUP"-4

PSTPLT

```
0: files Compor,
 Bis639
1: dim P[86],
 Q[86],A[4],T[4]
 ,W[4],K[4],H[4]
2: 1→M;86→I;1→R
3: rread 1,1
4: on end 1,8
5: sread 1,P[M],
 Q[M]
6: M+1→M
7: gto 4
8: P[M-2]→Z;Z+
 1→J
9: P[M-1]→r1;
 Q[M-1]→r3
10: 1→M;1→N
11: P[M+Z]→A[N]
12: Q[M+Z]→W[N]
13: P[M+Z+1]→K[N
 ];Q[M+Z+1]→H[N]
14: M+3→M;N+1→N
15: if M>3*Z;
 gto 17
16: gto 11
17: 1→M;P[4*Z+
 M]→r8;Q[4*Z+
 M]→r9
18: ent "Max X",
 r2
19: ent "Max Y",
 r4
20: ent "min
 voltage",r15
21: ent "Min
 depth",r16
22: ent "Max
 depth",r17
23: scl 0,2r1+
 r2,0,2r3+r4
24: 1→N
25: Z→r10
26: gto 167
27: 1→N
28: (Z-W[N])/
 A[N]→T[N]
29: if T[N]<H[N]
 or T[N]>K[N];
 0→T[N]
30: N+1→N
31: if N>r10;
 gto 33
32: gto 28
33: 1→N;1→J
34: T[N]→r6
35: 1+N→J
36: if J>r10;
 gto 41
37: if T[J]<r6;
 gto 40
38: T[J]→r7
39: r6→T[J];r7→T
 [N];r7→r6
40: 1+J→J;gto 36
41: 1+N→N
42: if N#r10;
 gto 34
43: 1→N
44: if T[N]=0;
 gto 47
45: N+1→N
46: gto 44
47: N-1→r5
48: 0→N
49: r5→J
50: T[J-N]→r6;
 T[N+1]→r7
51: r7→T[J-N];
 r6→T[N+1]
52: N+1→N
53: if N#r5/2;
 gto 50
54: ret
55: 1→M;1→r12
56: 0→P[M];0→Q[M
 ]
57: M+1→M
58: if M>I;1→M;
 gto 60
59: gto 56
60: rread 2,R
61: on end 2,76
62: sread 2,X,Y,
 r1,r2
63: if Y<Z-1/16;
 gto 71
64: if Y>Z+1/16;
 gto 75
65: if X<U or
 X>V;gto 70
66: if r1<r15
 or r2>r17;gto
 61
67: if r2<r16;
 gto 61
68: X→P[M];Y→Q[M
 ]
69: M+1→M
70: if Y>Z;gto
 73
71: r12+1→r12
72: if r12=17;
 1→r12;R+1→R
73: if M>I;stp
74: gto 61
75: M-1→M;M→L;
 dsp L
76: if M<2;gto
 94
77: M→L
78: 1→M;1→N
79: P[M]→X;Q[M]→
 Y
80: N+1→N
81: if N>L;gto
 89
82: P[N]→r13;
 Q[N]→r14
83: if r13>X;
 gto 87
84: r13→P[M];
 r14→Q[M]
85: X→P[N];Y→Q[N
 ]
86: r13→X;r14→Y
87: N+1→N
88: gto 81
89: M+1→M
90: if M>L;gto
 94
91: M→N
92: gto 79
93: gto 94
94: ret
95: 1→J;0→B;0→C;
 1/12→r11
96: if L=0;gto
 102
97: P[J]-r11→D;
 P[J]+r11→E
98: if U>D and
 U<=E;E→U;gto
 101
99: if U<D and
 V>E;B+1→B;gto
 104
```

Figure A-9 Program "PSTPLT"-1

```
0: if V>=D
nd V<=E;D→V;
gto 102
01: if J#L;J+
1→J;gto 97
02: plt U,Z,1;
plt U,Z;plt V,
Z;plt V,Z,1
03: gto 166
04: P[J+1]-r11→
F;if F>=V;gto
151
105: if P[J+1]+
r11>V;J+1→L
106: if J=L-1;
gto 119
107: if J=L;gto
152
108: if B#1;gto
114
109: plt U,Z,1;
plt U,Z;plt D,Z
110: plt D,Z,1;
plt E,Z,1
111: F-E→C
112: if C>0;plt
E,Z
113: gto 118
114: if C>0;plt
D,Z;plt D,Z,1;
plt E,Z,1
115: if C<0;plt
D,Z,1;plt E,Z,1
116: F-E→C
117: if C>0;plt
E,Z
118: gto 131
119: P[J+1]+r11→
G
120: if G>V;gto
129
121: if Z>1;gto
129
122: F-E→C
123: plt U,Z,1;
plt U,Z;plt D,
Z;plt D,Z,1
124: plt F,Z,
125: if [illegible];gto
1[illegible]
126: plt F,Z,1;
plt G,Z,1;plt
G,Z
127: plt V,Z;
plt V,Z,1;gto
166
128: plt E,Z;
plt F,Z;gto 126
129: if C>0;plt
D,Z;plt D,Z,1;
plt E,Z,1
130: if C<=0;
plt D,Z,1;plt
E,Z,1
131: F-E→C
132: if C<=0;
gto 136
133: if C>0;plt
E,Z;plt F,Z;
plt F,Z,1
134: plt G,Z,1;
plt G,Z;plt V,
Z;plt V,Z,1
135: gto 166
136: plt F,Z,1;
plt G,Z,1;plt
G,Z
137: plt V,Z;
plt V,Z,1
138: gto 166
139: if B>1;gto
146
140: F-E→C
141: plt U,Z,1;
plt U,Z;plt D,
Z;plt D,Z,1
142: plt E,Z,1
143: if C>0;gto
145
144: plt F,Z,1;
plt V,Z,1;gto
166
145: plt E,Z;
plt F,Z;gto 144
146: if C>0;plt
D,Z;plt D,Z,1;
plt E,Z,1
147: if C<0;plt
D,Z,1;plt E,Z,1
148: F-E→C
149: if C>0;gto
145
150: if C<=0;
gto 144
151: if B#1;gto
155
152: plt U,Z,1;
plt U,Z;plt D,
Z;plt D,Z,1;
plt E,Z,1
153: plt E,Z;
plt V,Z;plt V,
Z,1
154: gto 166
155: if C<=0;
gto 159
156: if C>0;plt
D,Z;plt D,Z,1;
plt E,Z,1
157: plt E,Z;
plt V,Z;plt V,
Z,1
158: gto 166
159: plt D,Z,1;
plt E,Z,1;plt
E,Z
160: plt V,Z;
plt V,Z,1;gto
166
161: plt U,Z,1;
plt U,Z;plt V,Z
162: plt V,Z;
gto 166
```

Figure A-9 Program "PSTPLT"-2

```
163: if B=0;gto
 102
164: if C>0;plt
 V,Z;plt V,Z,1
165: if C<=0;
 plt V,Z,1
166: ret
167: 1→N
168: if P[N]=0;
 gto 171
169: 0→P[N];0→Q[
 N]
170: N+1→N;gto
 168
171: 1→N
172: r8→Z;1/16→S
173: Z+S→Z
174: if Z>r9;
 gto 183
175: 1→W
176: gsb 27
177: T[W]→U;T[W+
 1]→V
178: gsb 55
179: gsb 95
180: W+2→W
181: if W>r5;
 gto 173
182: gto 177
183: end
*14576
```

Figure A-9 Program "PSTPLT"-3

*U.S.Government Printing Office: 1980 — 657-084/478