

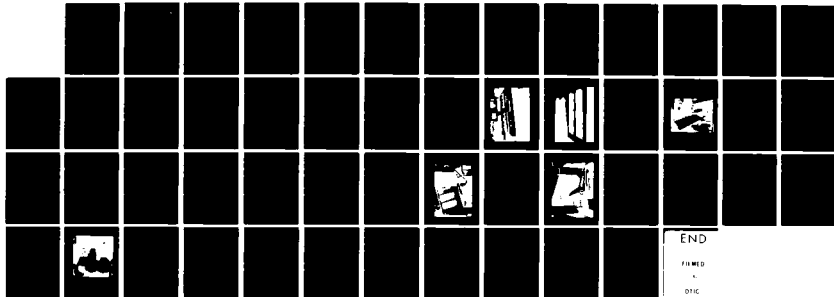
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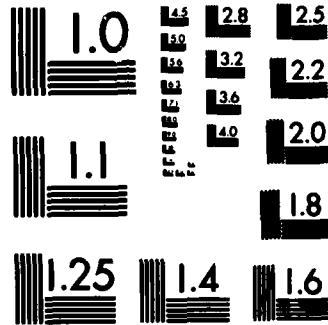
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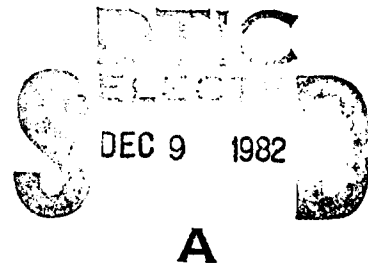
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Bethesda, Maryland 20884

DESIGN, FABRICATION, AND STRUCTURAL EVALUATION OF AN ADVANCED COMPOSITE HYDROFOIL CONTROL FLAP

by
William P. Couch



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STRUCTURES DEPARTMENT
TEST AND EVALUATION REPORT

November 1982

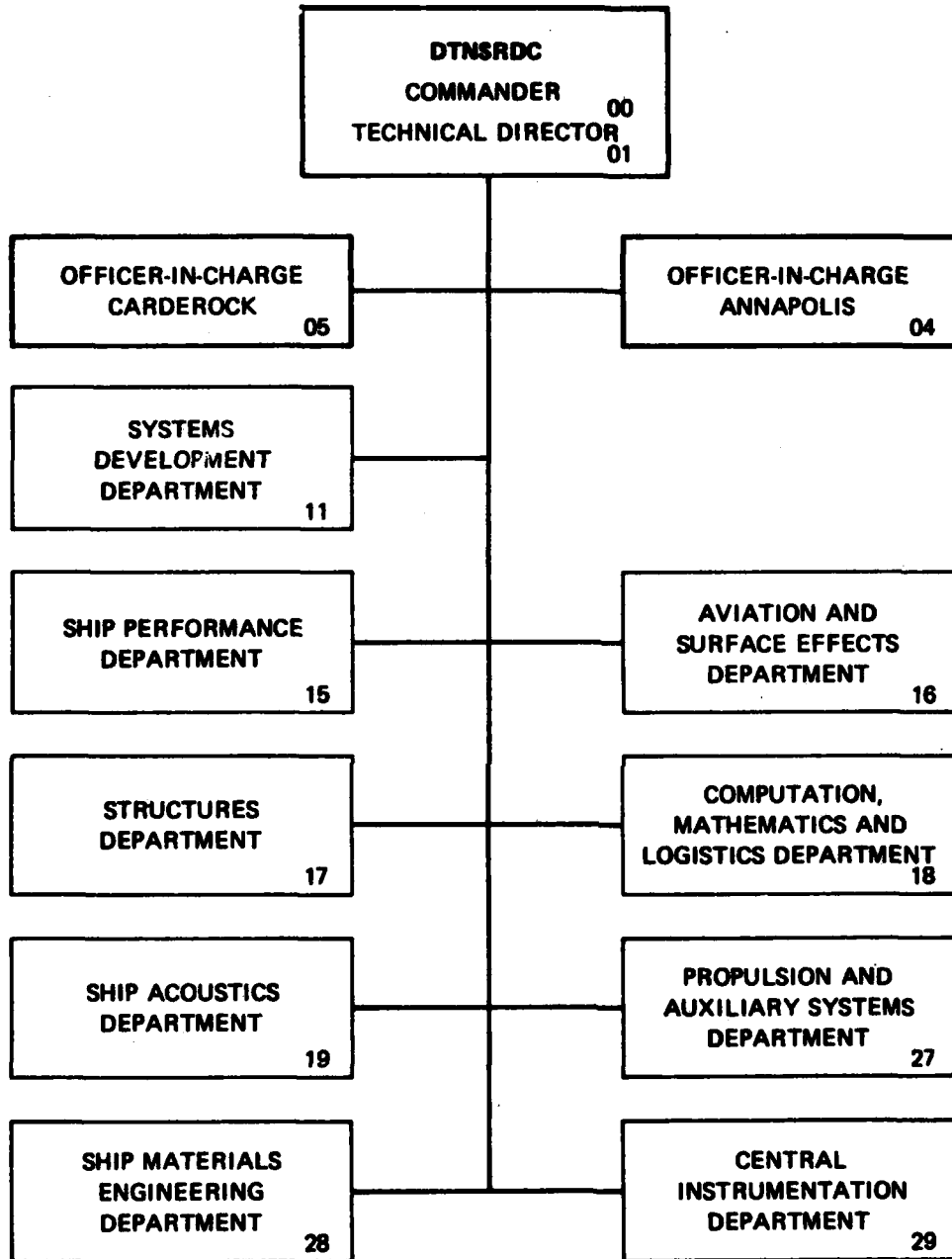
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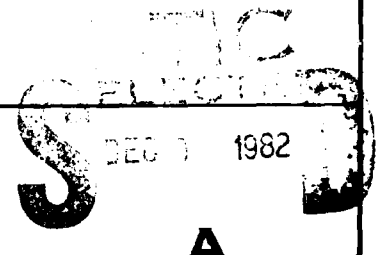
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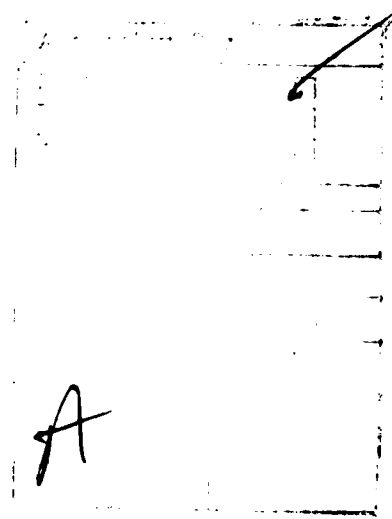
After being instrumented with 52 strain gages and calibrated for gage response as a function of applied load, the flap was installed on PCH-1. The flap remained on the boat for 26 months, but only saw 18 hours of foilborne operations due to unrelated mechanical difficulty with PCH-1. The 18 hours were dedicated to calm-water trials. Although the flap performed satisfactorily, attempts to relate composite material strains to flap pressure loads proved unsuccessful due to the complex nature of the flap loading, the flap's structural geometry, and the loss of the majority of strain gages just prior to trials data collection. The flap was then prepared for cyclic testing in the Structural Evaluation Laboratory, but failed during the initial static test because of an overload caused by a malfunction of the control system.

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ABSTRACT

A hydrofoil control flap was designed and fabricated by the Boeing Company under contract to the Naval Sea Systems Command. It consisted of two graphite epoxy-titanium clad skins bolted and bonded to a titanium crank-spar assembly. It was tested statically at the Boeing Company to calibrate the response of electrical-resistance strain gages to strip loads; installed on the aft inboard foil of the hydrofoil PCH-1 (HIGH POINT) to demonstrate the ability of the composite to withstand the hydrofoil environment and to obtain service loads information; and tested in the laboratory at the David W. Taylor Naval Ship Research and Development Center to demonstrate its compliance with a four-times-design-life capability.

After being instrumented with 52 strain gages and calibrated for gage response as a function of applied load, the flap was installed on PCH-1. The flap remained on the boat for 26 months, but only saw 18 hours of foilborne operations due to unrelated mechanical difficulty with PCH-1. The 18 hours were dedicated to calm-water trials. Although the flap performed satisfactorily, attempts to relate composite material strains to flap pressure loads proved unsuccessful due to the complex nature of the flap loading, the flap's structural geometry, and the loss of the majority of strain gages just prior to trials data collection. The flap was then prepared for cyclic testing in the Structural Evaluation Laboratory, but failed during the initial static test because of an overload caused by a malfunction of the control system.

ADMINISTRATIVE INFORMATION

This investigation is part of an Exploratory Development Program at the David W. Taylor Naval Ship Research and Development Center, sponsored by the Naval Sea Systems Command (NAVSEA 03R24 and 05R15), and funded under the Center's Program Element 62534N, Project SF 43 400 391, and Work Unit 1730-035.

INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) has been conducting a program to evaluate the use of advanced composites for high performance naval ship structures. As a result of feasibility studies performed by the McDonnell Douglas Astronautics Company^{1*} and the Grumman Aerospace Corporation² and a review of high payoff areas for structural application of advanced composites by the

*A complete listing of references is given on page 43.

naval ship composites community,* the hydrofoil strut-foil system was selected as the primary structural element to assess the current technology status of advanced composites for marine application.

A hydrofoil control flap, consisting of two graphite epoxy-titanium clad skins (bolted and bonded to a titanium crank-spar assembly), was designed and fabricated by the Boeing Company.^{3,4} The flap was designed to be interchangeable with the existing inboard starboard HY-130 steel flap on the aft foil system. Studies based on the detailed preliminary design showed that, under critical loading, its deflections were equal to or less than the existing steel design, which indicated equivalent hydrodynamic performance. These results also showed that the composite design was 44 percent lighter than the existing steel design.

It was originally planned that two flaps would be fabricated; one for in-service evaluation to demonstrate the ability of the composite to withstand the hydrofoil environment and to obtain service loads information, and one for laboratory evaluation to demonstrate its compliance with a four-times-design-life capability. Because the design concept for the titanium crank-spar assembly lead to excessive fabrication costs, only one flap was fabricated for both the in-service and laboratory evaluations. This report describes the design, fabrication, nondestructive evaluation (NDE), calm water trials, fatigue load spectrum development, and laboratory evaluation tasks for the composite flap.

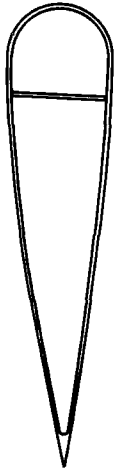

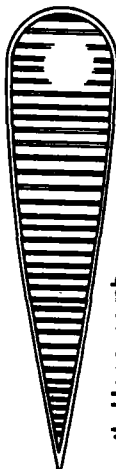



DESIGN AND ANALYSIS

The Boeing Company developed six design concepts during the contract proposal stage, and selected the Metal Clad Composite Skin concept as the Baseline Design; see Table 1. The flap had to be interchangeable with the existing inboard starboard steel flap on the aft foil system of the hydrofoil PCH-1 (HIGH POINT), a Navy R and D platform used to develop and validate new technology for future hydrofoils; see Figure 1. The composite flap was designed to the following criteria:

1. The flap was required to carry a critical pressure loading of 6300 lb/ft^2 without buckling, without exceeding the material allowable yield strength, and without

*NAVSEA "Long Range Research and Development Plan for Advanced Composites for High Performance Surface Ships," Review Draft (27 Sep 1974).

TABLE 1 - CONCEPT RATING FOR CONTROL FLAP

Design Concepts and Weighting Factor	Weight	Cost	Damage Tolerance	Maintainability	Inspectibility	Total
 Existing All-Metal (Welded)	35	35	10	10	10	380
 Baseline Metal Clad Composite Skins	35	140	60	60	50	495
 Full Depth Honeycomb	140	175	40	50	60	340
 Sandwich Shell	175	105	20	30	10	200
 Multirib and Spar	105	35	10	10	40	250
 Filament Wound	70	70	50	40	20	430

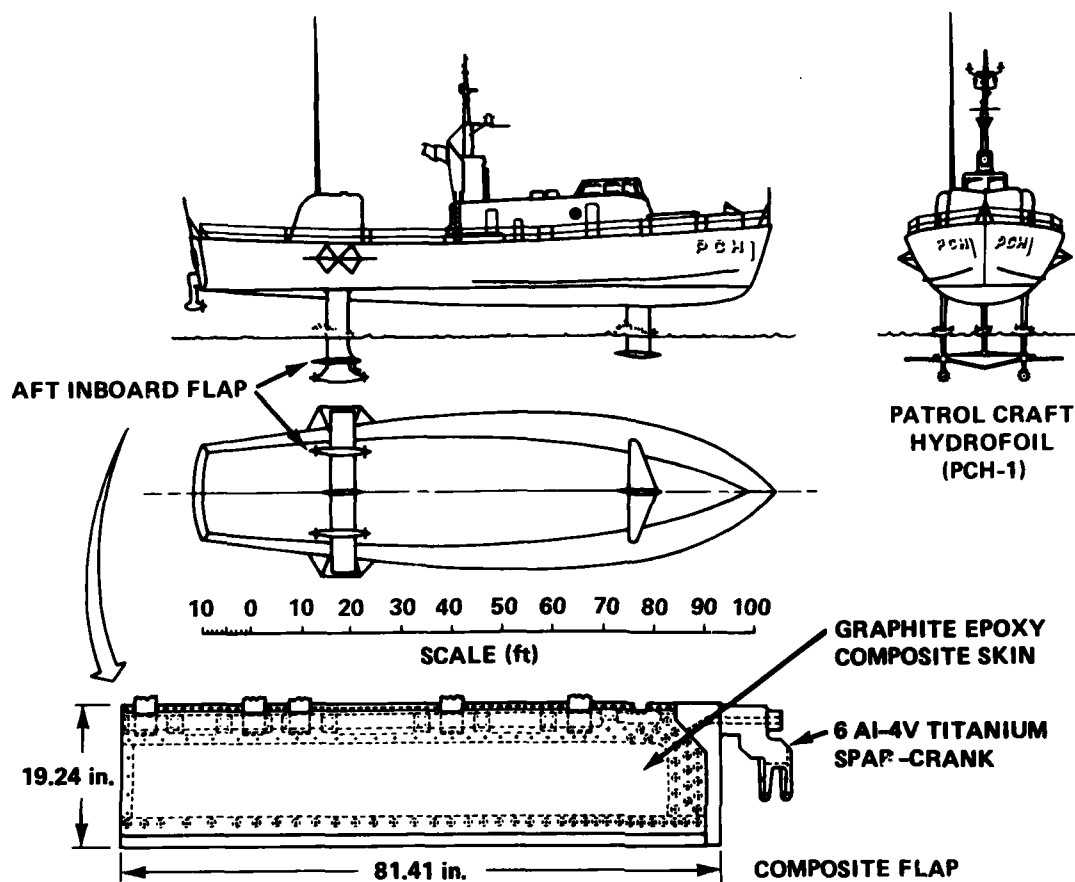


Figure 1 - Patrol Craft Hydrofoil (PCH-1), Composite Flap

binding at the hinges. Under this pressure loading, maximum tip deflection was limited to 0.53 in. and maximum chordwise deflection to 0.23 in.

2. A spanwise deflection of 0.17 in., imposed by the foil, was considered.
3. The flap was designed to be free from unacceptable loss of control effectiveness or hydroelastic instability to a speed of 100 knots.
4. A design environment of:
 - Service Temperature: -65°F to $+180^{\circ}\text{F}$
 - Operating Temperature: $+32^{\circ}\text{F}$ to $+80^{\circ}\text{F}$
 - Service Environment—all weather conditions and exposure
 - Operating Environment—saltwater exposure
5. A service life of fifteen years.

The baseline flap was originally designed with an upper and lower graphite epoxy-titanium clad skin of variable thickness bonded and bolted to a titanium

crank-spar assembly. A NASTRAN computer code finite element analysis (FEA) performed by the Center indicated that the skin panel and maximum tip deflections would be excessive under the critical pressure loading of 6300 lb/ft². Subsequently, Boeing redesigned the upper and lower surface skins to a constant thickness of approximately 0.5 in. using its own NASTRAN FEA. Figure 2 shows the Boeing analysis and the critical stress areas of the redesigned composite flap. This thickness was made up of 36 plies of T 300/934 graphite epoxy fabric oriented at $\pm 45^\circ$ and 10 mils of 6Al-4V titanium bonded to the exterior surfaces of each skin. The cladding was incorporated as a barrier to water absorption by the graphite epoxy skins, to prevent cavitation erosion of the epoxy matrix, and to add a measure of protection against small object impact. The skins were bolted and bonded to a crank-spar assembly made of ELI grade 6Al-4V titanium. It incorporated five sets of integral hinge lugs and a load crank machined to the same geometry as the existing steel design; see Figure 2 for details.

To provide supporting data showing that the graphite epoxy titanium clad composite laminate concept used in the flap cover design would perform successfully under hydrofoil environmental conditions, a full range of static and fatigue tests were conducted; see Table 2. The results of these tests indicated no significant degradation in material performance after exposure up to 270 days. As a result of a study* to evaluate the relative merits of several nondestructive evaluation techniques, ultrasonics was chosen as the primary method to locate fabrication flaws and damage resulting from operating loads; see Appendix A.

In order to verify the design and fabrication processes and to evaluate joints, a full-scale portion of the flap was built and tested. This feasibility component incorporates the first 20 inches of the flap, end joint, and crank fitting; see the shaded area in Figure 3. The feasibility component sustained a static proof test to the maximum operating load, or 40 percent of design ultimate. The component failed after approximately 12,000 cycles (safe life = 16×10^6 cycles) due to a debond along the leading edge, which changed the load path and resulted in a catastrophic failure of the titanium end fitting. In order to simulate actual service experience in the

*Couch, W.P., et al., "Nondestructive Evaluation of a Graphite Epoxy-Titanium Clad Panel with Twelve Fabricated Induced Artificial Flaws," DTNSRDC Technical Memorandum TM 77-173-67 (Jun 1977).

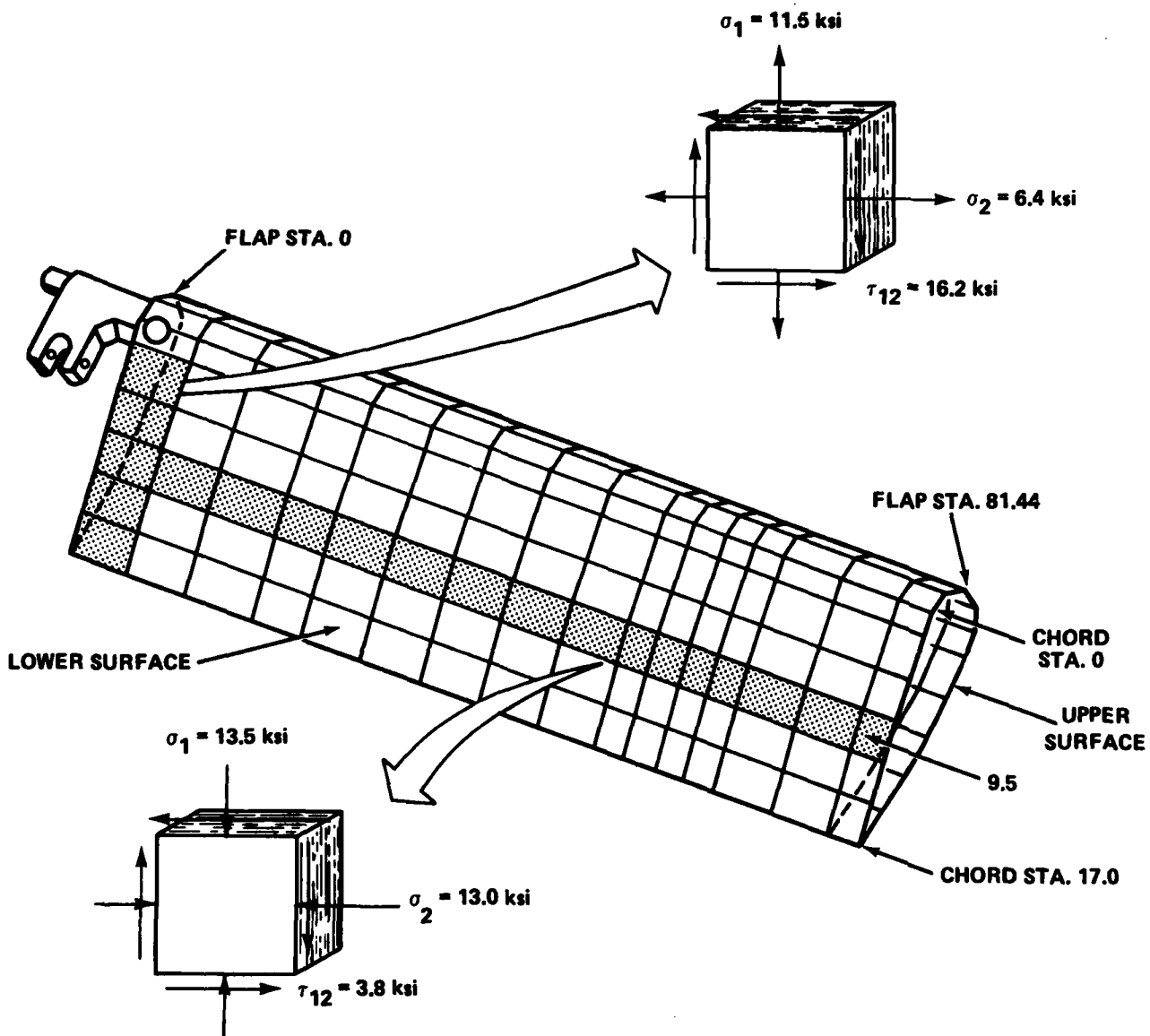
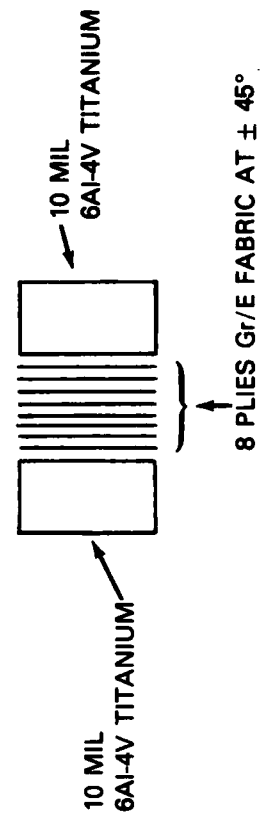


Figure 2 - Boeing NASTRAN FEA Model and Critical Stress Areas of the Composite Flap

TABLE 2 - COMPOSITE HYDROFOIL FLAP MATERIAL PROPERTY TESTS

Item	Exposure Before Test	Test Environment	Load Type	Specimen Configuration	Number of Specimens	Test Objectives	Notes
1	None	RT/Air	Static compr. Rail shear Static tension Interlam. shear Compr. fatigue Rail shear fatigue Tension fatigue Fracture Fracture	D6-4671-341	5	E_c, F_{cu}, F_{cy}	6 ea. 5/16-dia. Holes, 6 W/O Holes
2					5	G, F_{su}, F_{sy}	
3					5	E, F_{tu}, F_{ty}	
4					5	F_{isu}	
5					12	S-N Curve	
6					12	↓	
7					12	↓	
8					3	Fracture stress	
9					3	↓	
10	90 Day exposure to salt water	RT/Air	Static compr. Rail shear Static Interlam. shear		3	E_c, F_{cu}, F_{cy}	Gouges Dents
11					3	G, F_{su}, F_{sy}	
12					3	E, F_{tu}, F_{ty}	
13					3	F_{isu}	
14		RT/Salt Water	Compr. fatigue Rail shear fatigue Tension fatigue Fracture Fracture	D6-4671-341	12	S-N Curve	6 ea. 5/16 Holes, 6 W/O Holes
15					12	↓	
16					12	↓	
17					3	Fracture stress	
18					3	↓	



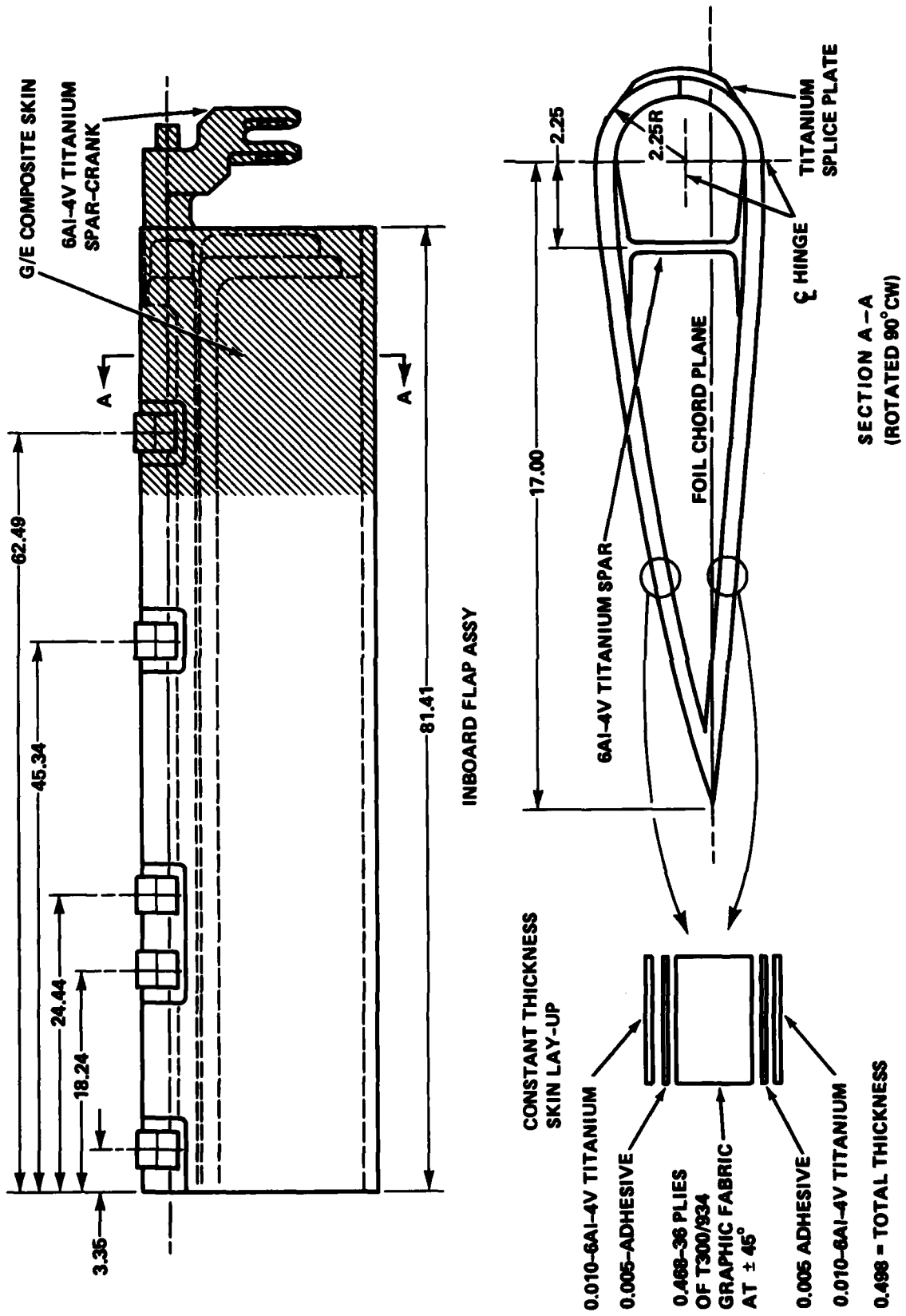


Figure 3 - Details of Preliminary Design

planned laboratory test, operational data taken from the existing PCH-1 flap system have been examined and a fatigue load spectrum developed*, see Table 3. The loading spectrum was derived from a projected typical 15-year lifetime for the craft which was normalized for all ship headings in various sea states and maneuvers. A more detailed NASTRAN analysis was performed, and the component was repaired and strengthened in the leading edge joint and end fitting areas. A second fatigue test resulted in catastrophic failure of the titanium end fitting after 145,000 cycles.

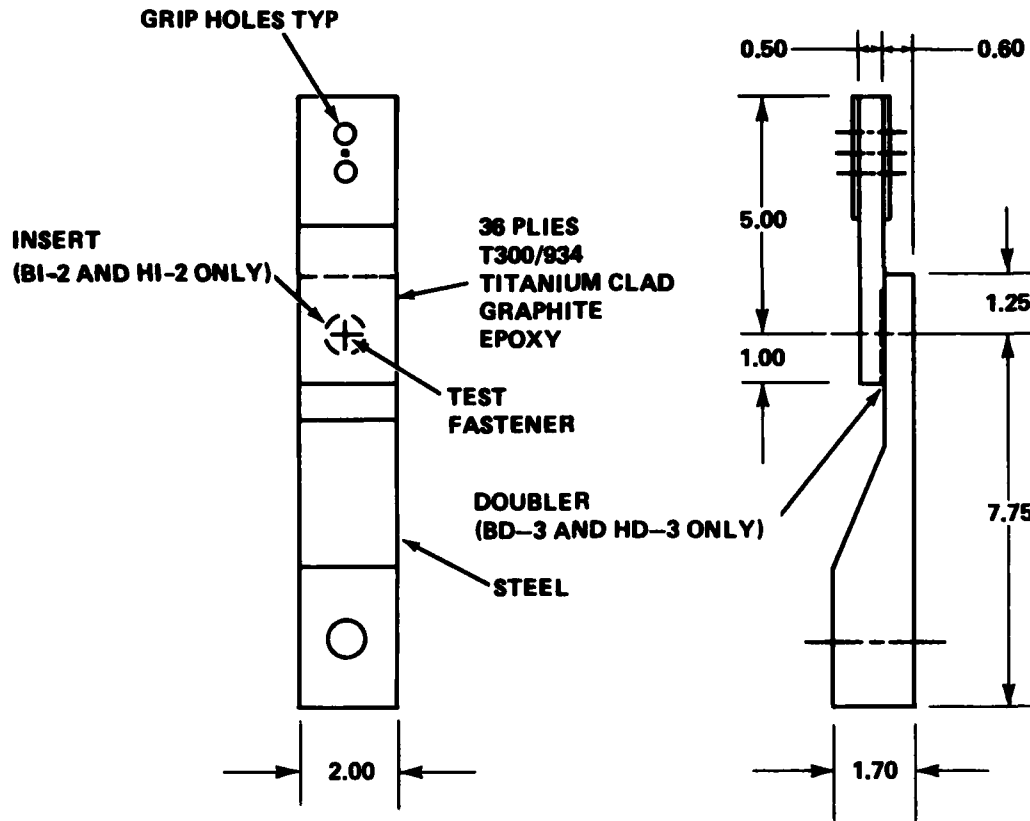
TABLE 3 - COMPOSITE FLAP FATIGUE LOAD SPECTRUM

<ul style="list-style-type: none">● In Salt Water● Based on Ultimate Load = 487.5 in. kips (6300 lb/ft²)<ul style="list-style-type: none">- Cyclic Block = 1000 Cycles544 Cycles at 30 percent312 Cycles at 35 percent137 Cycles at 40 percent, with every 20th Cycles at 20 percent reversal load● Cyclic Rate = 3Hz
--

Because of attachment failures experienced during both tests of the demonstration component, several mechanical fastener joints were evaluated; see Table 4. The results from the mechanical fastener tests demonstrated that composites assembled with torqued bolts are much superior to the Huck-bolt blind fasteners in fatigue. The Visulock blind fastener performed equally to the torqued bolts. It was concluded that this fastener retained its preload during the complete fatigue test. The specimen with the 10 degree inclined torqued bolt performed equally to the perpendicular torqued bolts. Since this bolt head configuration was similar to the most severe condition in the composite flap design, it demonstrated that the full fatigue capability of the torqued bolt concept could be used in the flap design.

*Deppa, R.W., "Development of a Fatigue Load Spectrum for Evaluation of Advanced Composite Hydrofoil Control Flaps," DTNSRDC Technical Memorandum TM 77-173-50 May 1977).

TABLE 4 - MECHANICAL FASTENER FATIGUE TEST EVALUATION



Specimen Number and Concept	Description	Load Mean \pm Alt Pounds	Cycles to Failure	Type of Failure
B-1	B30SW6 Bolt	1507 ± 1493 \downarrow	6,047,000	No failure
BI-2	B30SW6 Bolt with insert		3,640,000	No failure
BD-3	B30SW6 Bolt with doubler		6,617,000	No failure
H-1	3/8 Huckbolt		539,300	Bolt shear
HI-2	3/8 Huckbolt with insert		335,700	Bolt shear
HD-3	3/8 Huckbolt with doubler		482,900	Bolt shear
V-1	3/8 Visulok		13,293,000	No failure
A-1	B30SW6-18 Bolt at 10° angle		1507 ± 1493	10,233,000

The results of the component test and fastener evaluation led to a redesign of the crank-spar assembly and removal of all blind fasteners for the final design; see Figure 4 for details of the final design. The composite covers remained the same as shown in Figure 3. The spar was changed from an I-beam to a flat bar, and threaded inserts were incorporated in the lower cover to accommodate the use of torqued through-bolts. Special machined nut plates were installed in place of the blind fasteners. All welds except the primary electron beam welds were removed from the crank-spar assembly. The diameter of the crank stub shaft was increased, as well as the radius at its base. Also, all surfaces of the crank-spar assembly were shot peened prior to final flap assembly.

Two types of analysis were performed to establish compliance of the design with PCH-1 aft foil requirements. A NASTRAN model was first used to establish internal load distribution and cover shear flows. A fatigue analysis was then performed on all critical titanium details to establish the life capabilities of the composite flap design. From the NASTRAN analysis it was determined that the maximum composite shear stress was 5795 psi, well below the 20 ksi endurance limit, and that the maximum tip deflection was 0.436 in. which was below that of the steel design. The fatigue load spectrum, given in Table 3, was used in the fatigue analysis of the titanium details. The design life goal used was 15 years or 15,000 hours of foil-borne operation and the fatigue reliability factor was 1.0. The fatigue life estimates were based on both a 95 percent probability of survival and that a typical failure would occur at four times the 95 percent life. A summary of the fatigue lives calculated for the metal details is shown in Table 5. As shown in this table, the fatigue lives of all of the details are more than sufficient to meet the approximately 200 hours required for sea trials on the PCH-1 hydrofoil. A few are shy of the 15,000 hour design life, which was caused by the design requirement specifying that the composite flap must be interchangeable and remain within the envelope of the existing steel flap.

FABRICATION

A full-scale flap was then fabricated using the techniques developed during the fabrication of the feasibility component. Titanium billets were cut to the approximate shape of the crank and spar details with a plasma torch, and roughly machined to their approximate final configuration. The crank was then rotated 12 deg relative to the integral closure rib by heat forming. The crank and two spar sections were

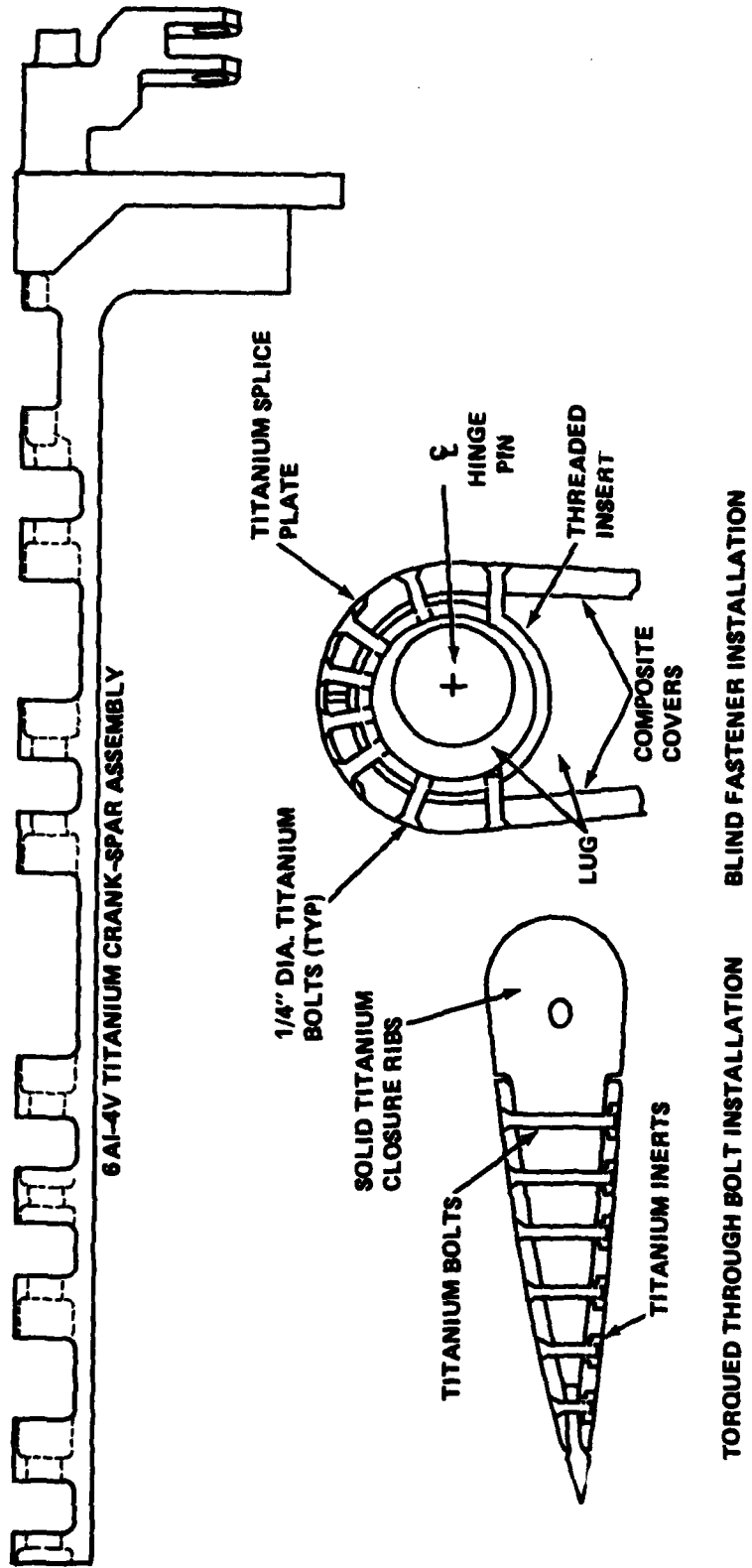


Figure 4 - Details of Final Design

TABLE 5 - FATIGUE LIFE SUMMARIES

Item	N _{0.95/1.0} Life (hours*)
Hinge lug	>100,000
Leading edge bulkhead shell at hinge lug-fastener holes	15,000
Closure rib — aft bay fastener holes	26,000
Closure rib shoulder fillet	63,000
Leading edge bulkhead shell at closure rib	9,000
Crank arm neck	12,000
Crank arm hinge stub radius	>100,000
Crank arm drive lugs**	
Lug hole	5,700
Base of clevis	2,000
<p>*Foilborne operating hours **Fatigue test flap will be strengthened to increase life.</p>	

then electron beam welded into a single assembly. This part was then sent to the machine shop for milling and boring to its final configuration. The nose plates were chip formed on a break, thermally sized using ceramic dies, and then machined to their final geometry. The remaining titanium details, the trailing edge, closure rib, and inserts, were made using conventional milling and turning methods. The covers were laid-up on steel tools, bagged, and cured in an autoclave at 350°F. The cured laminates were installed in a holding fixture and trimmed on a milling machine. Insert holes were then drilled in the lower cover using a diamond core drill and then titanium inserts were installed and bonded in place. The flap detail parts (Figure 5) were assembled and held together with a holding fixture, the assembly being placed on a milling machine and through-bolted holes were line drilled. The bottom cover was removed and tapped. The top cover and spar were drilled up to bolt body size, with the upper cover countersunk to accept the high torque bolt head. The covers were instrumented with 52 strain gages and one water detection channel on their inner surfaces as shown in Figure 6. This instrumentation was installed with 50-ft leads which were routed through a 3/4-in. diameter hole passing through the crank stub. Hysol 9628 film adhesive was placed at the bond interface surfaces and the assembly

Figure 5 - Composite Flap Detail Parts



Figure 5a - Titanium Details

Figure 5 (Continued)

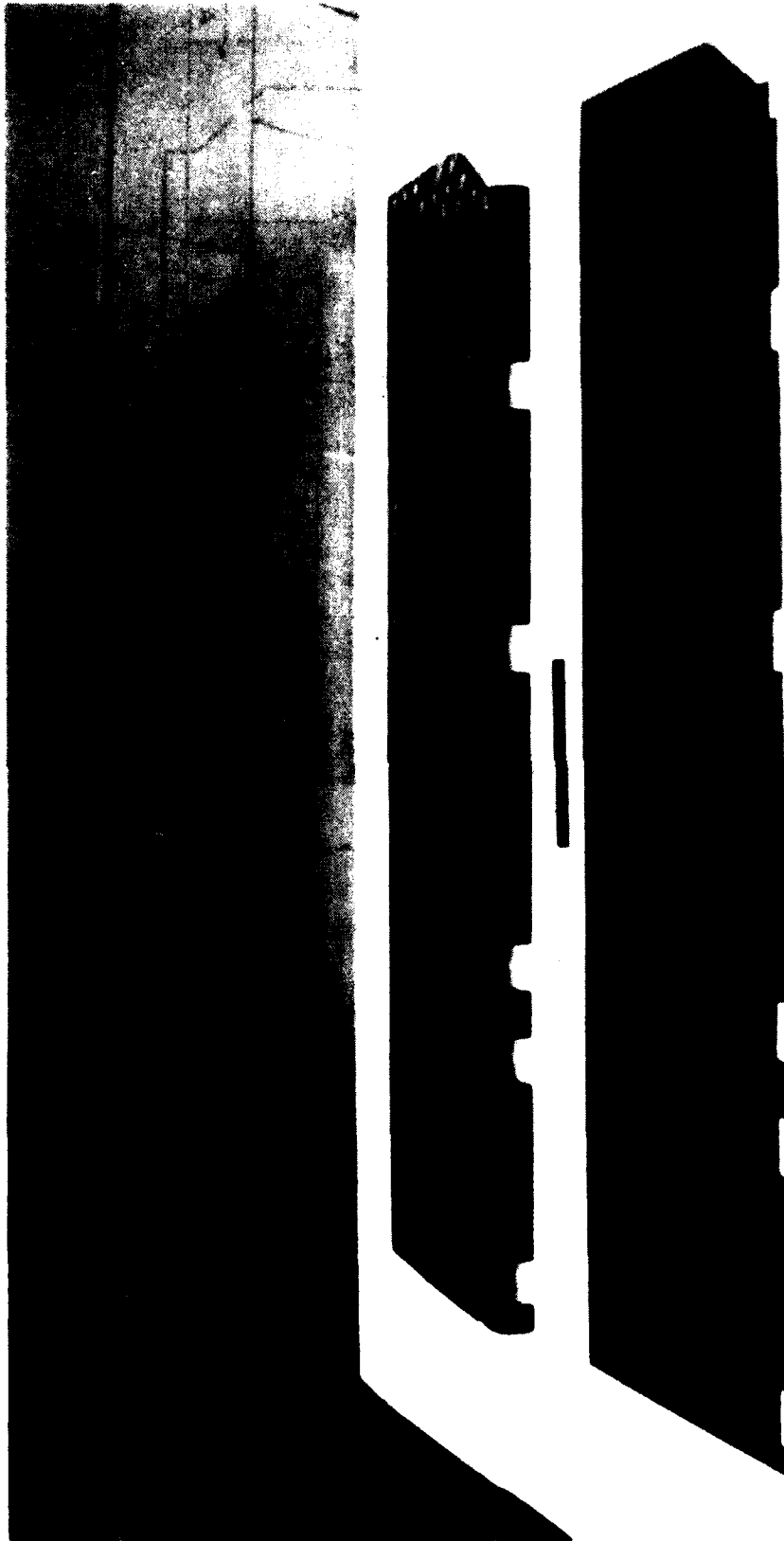
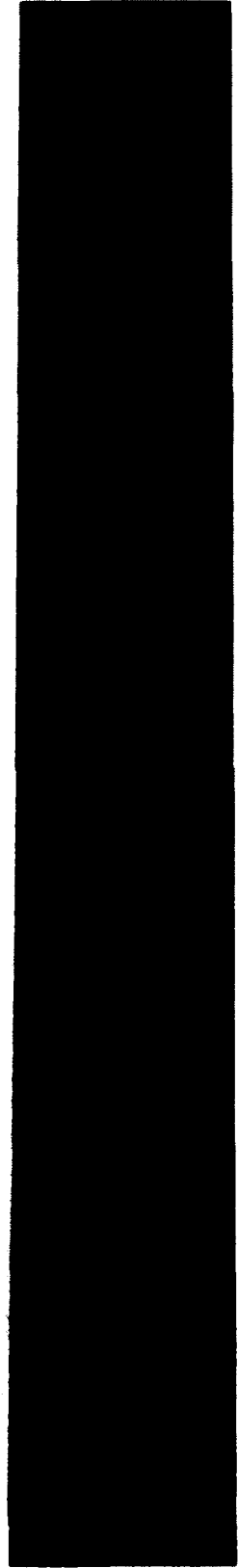


Figure 5b - Graphite Epoxy Skins



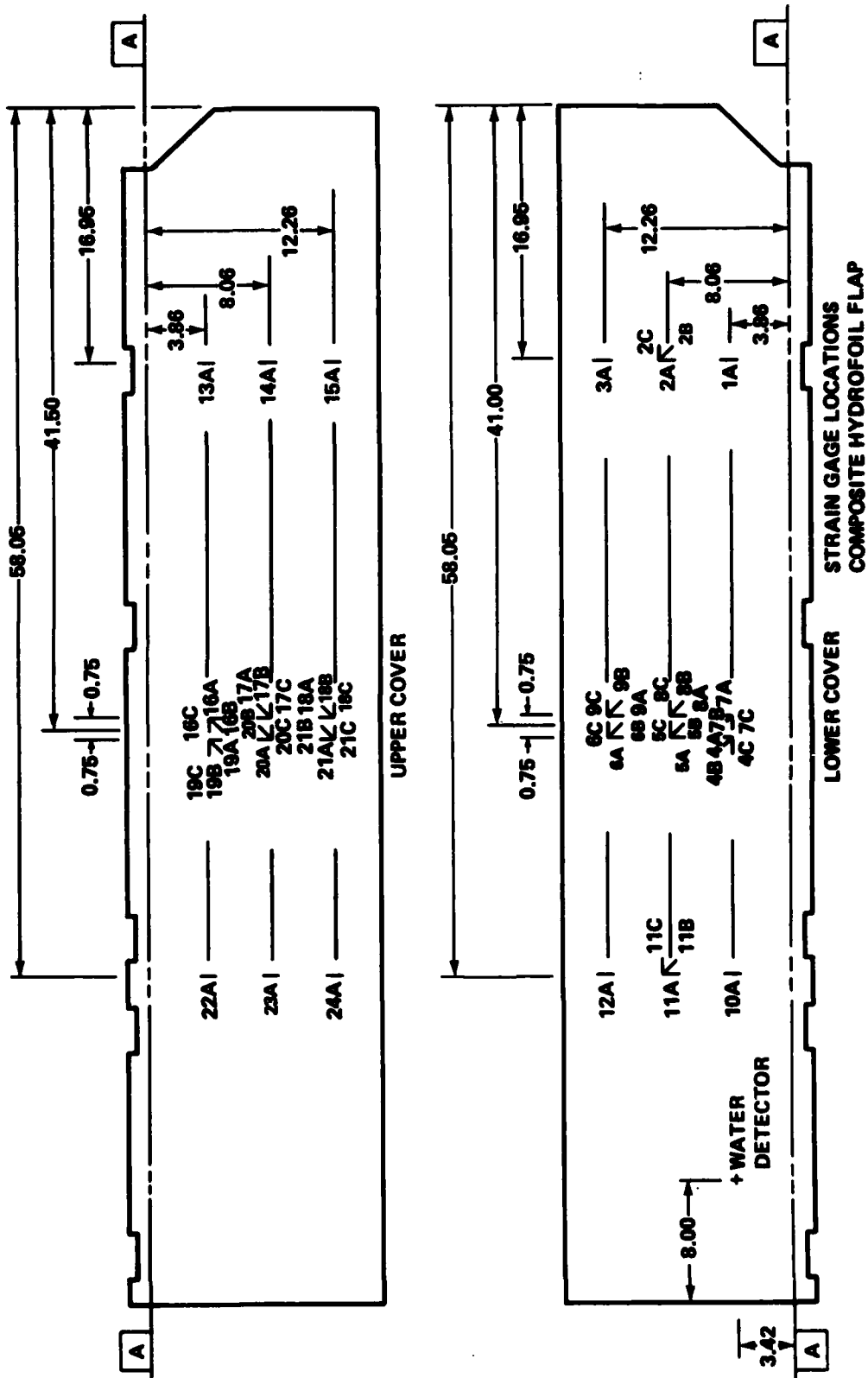


Figure 6 - Cover Strain Gage Locations

was bolted with titanium fasteners. It was bagged, placed in an autoclave and processed through an adhesive cure cycle of 250°F for 90 min at a pressure of 50 psi. The assembly was removed from the autoclave and visually inspected; the bolts were retorqued; and the bolt heads in the countersunk holes were then primed and fairing compound installed, troweled smooth, and then cured to complete the assembly. Figure 7 shows the assembled flap as installed on PCH-1.

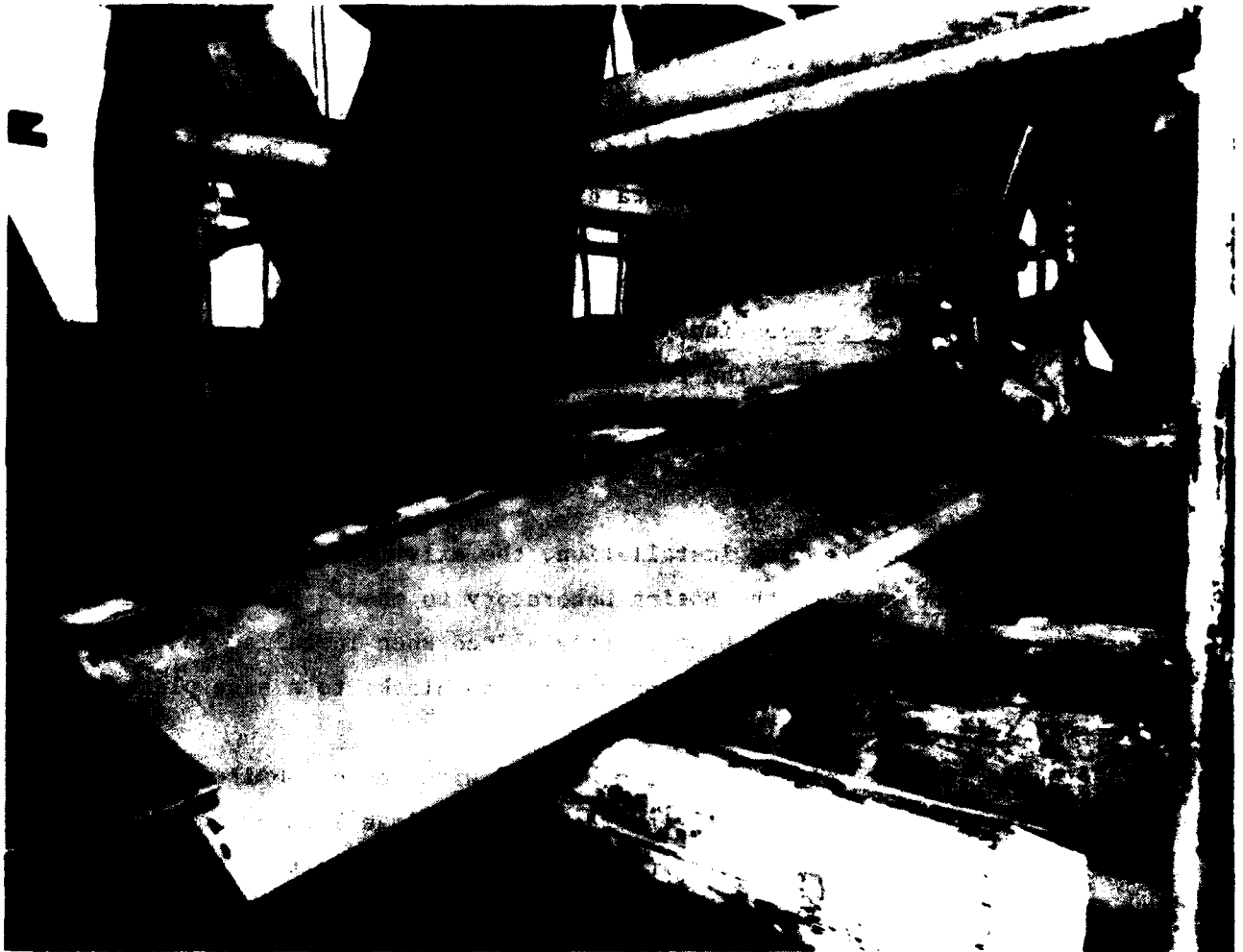


Figure 7 - Installed Foil Flap

CALIBRATION TESTS AND FLAP INSTALLATION

The flap was calibrated in the 90- and 120-in. test frames in the Boeing Material and Structures Test Laboratory to determine gage outputs as a function of six sequentially applied loads around the flap. Test fixtures were fabricated and

installed in the test frames with the flap hinge blocks bolted down to the base plates of the test frames, see Figure 8. A 23-kip hydraulic actuator was attached to the flap crank arm through a spherical ball bushing at a 25 deg angle to the hinge line and its other end mounted to a beam assembly attached to the test frame columns. A load reaction beam with a 2-in. thick foam rubber pad, 5 in. wide and the length of the flap, was also mounted by a spherical ball bushing to the test frame columns. The reaction beam was positioned sequentially at six different positions around the flap to provide a uniform reaction pressure of up to 20 psi.

Loads were applied to the flap crank to produce a maximum reaction pressure of 20 psi over the 5-in. wide foam rubber pad. The reaction beam was first located at one of six load strip areas on the flap. Load was increased in 10 percent increments until the maximum reaction pressure of 20 psi had been attained. The strain data were recorded at each increment, and if data differed from previous zero loading by more than 10 percent, the load sequencing was repeated. If data proved to be repeatable, the reaction beam was moved to the next load strip area and the loading process was repeated. This was continued until strain gage data were attained after loading all six load strip areas. The reaction beam was then returned to the initial load strip area and incremental loading was repeated. The data obtained from the second set of loadings matched the initial data well within the required 10 percent tolerance.

To initiate the composite flap installation, the existing steel flap was removed from the PCH-1 and sent to the Boeing Laboratory to ensure that the bearing blocks for the composite flap would be correctly aligned when installed on the PCH-1 foil. This was accomplished by bolting the steel flap blocks to a base plate prior to their removal from the steel flap.

The continuous titanium pin designed to be used with the composite flap was inserted in the fixed bearing blocks to ensure that the hinge line was within tolerance for both flaps. The hinge pin was inserted without difficulty. After testing the alignment, the hinge pin was removed and the hinge blocks were inserted in the composite flap. Fabroid spacers were machined and inserted adjacent to the bearing block closest to the crank to ensure that it was at its proper location along the length of the hinge line. The hinge pin was inserted and then locked in place with a bolt through the covers, and the end closure plate was bonded and bolted in place to complete the assembly. The composite flap-bearing assembly was then shipped to the Bremerton Naval Ship Yard to be installed on the PCH-1, under cognizance of

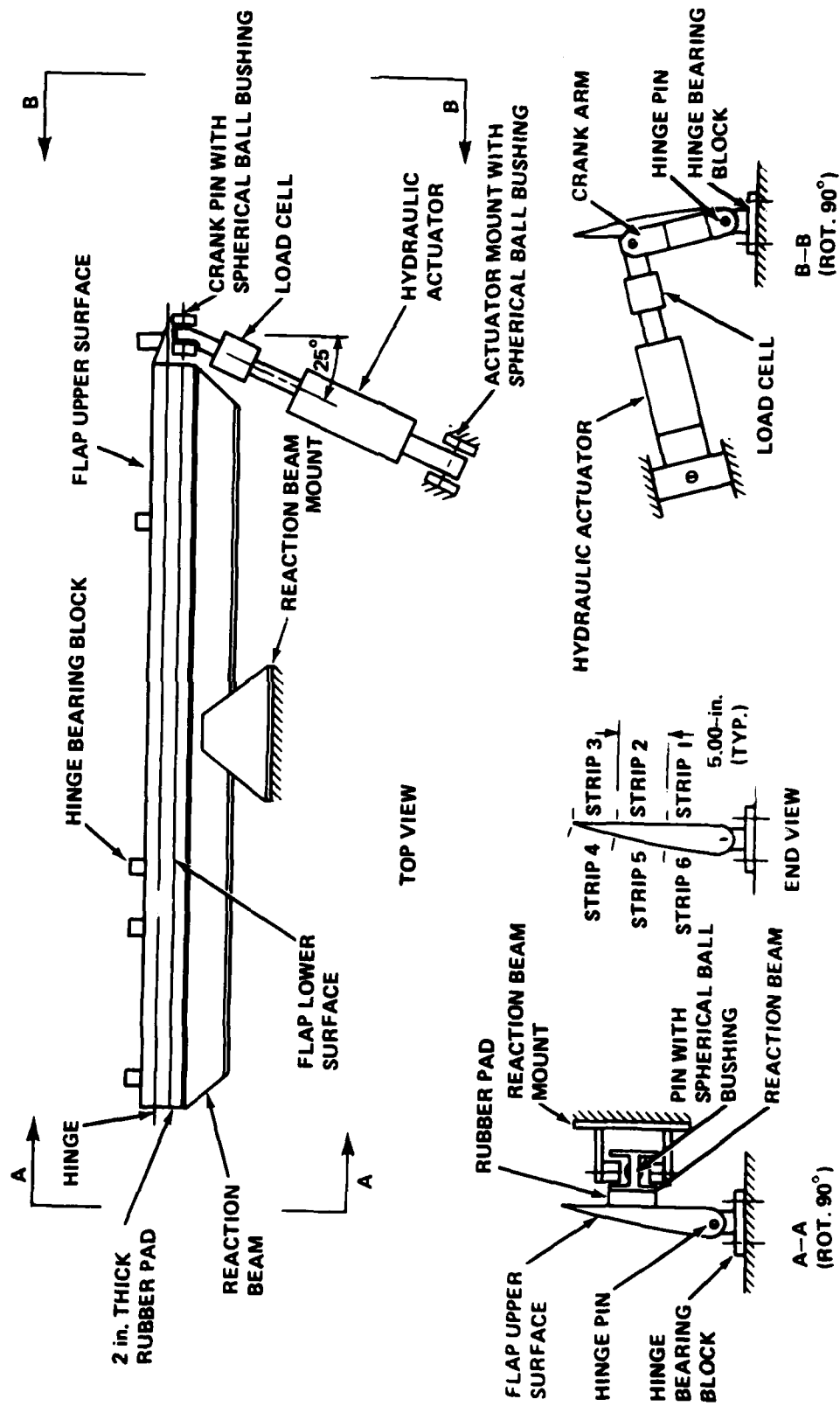


Figure 8 - Flap Assembly in Test Fixture for Calibration Test

DTNSRDC, Hydrofoil Special Trials Unit (HYSTU). As a result of the laboratory alignment procedure described above, the composite flap hinge blocks mated perfectly with the steel foil. Minor grinding of the foil trailing edge and the flap crank and linkage were required to alleviate two interference problems. The flap crank was attached to the actuator, the strain gage leads hooked-up to the ship's data system, and a single strip load applied to the flap prior to putting the ship back into the water. All gages met the 10 percent repeatability criteria with respect to the original laboratory calibration. A second purpose of the dockside calibration was to establish a relationship between the recorded flap link strains and the applied hinge moment.

IN-SERVICE EVALUATION

All flap gages were up and functioning normally from the time the flap was installed on PCH-1 until the ship was placed in the water. After the ship was lowered into the water and the struts fully extended, a check of the strain gages revealed that 75 percent of the gages were inoperable. The water detection gage did not show the presence of water in the flap, so it was assumed that the gage leads had been severed when the struts were extended to the fully submerged condition. The actual cause of gage malfunction has never been determined. Calm water trials were initially tried in October 1979, but were terminated before completion due to unrelated mechanical difficulty with PCH-1. Calm water trials were rescheduled and conducted in July 1980; only those gages circled in Figure 6 were active to monitor flap strains for the purpose of determining pressure loads.

Inspection of the composite flap following the calm water trials of October 1979 and July 1980 revealed that the only visible damage was a bolt on the corner of the inboard side and leading edge that had worked its way out of the flap assembly. The head of the bolt was completely worn off from contact with the harder foil structure. The area in and around the bolt showed no signs of delamination or other material degradation. The bolt was in an area that made repair (by replacing the bolt) impossible without removing the composite flap. It was felt that the adhesive bond, in addition to the other bolts in this area, would provide sufficient strength without the necessity of making repairs.

As previously reported, the initial calm water trials were terminated before completion due to mechanical difficulties of PCH-1; therefore, the data were not analyzed or reported. A short description of each event conducted during the July

1980 composite flap calm water evaluations is given in Table 6. Flap inner skin strain data from the remaining operable strain gages were recorded on strip chart recorders during the events that pertained directly to the composite flap evaluations. The zero setting for all events was taken with the ship sitting still at dockside with the struts fully extended. All strain excursions are reported herein with respect to this reference level. Data were monitored continually during the calm water flap evaluations to assess the flap's performance during each event and to try and detect any unanticipated degradation of the composite flap structure. Analysis* of the calm water trials was carried out with two primary objectives in mind. The objectives were: (1) to determine, from all the data records for these events, that strain levels on the flap's inner skin were within the safe operating range with respect to the composite material's strength; and (2) to determine the hydrodynamic pressures on the flap which caused these flap inner skin strains based on laboratory static calibration. The first objective was relatively simple and consisted of visually examining the data records and selecting the maximum strain excursions for each event. Table 7 lists the maximum strains recorded during each event for four typical gage locations from the remaining active strain gages and the corresponding hinge moments. Data traces for two of the more demanding events for the composite flap, a forward foil broach and a rapid helm reversal, are given for these same gages in Figures 9 and 10 along with the corresponding hinge moments. It should be noted that in a few instances the voltage output from the gages exceeded the setup sensitivity of the strip chart recorder. To arrive at the strain values that were most likely experienced by the flap's skin when the data traces were clipped through recorder saturation, the data records were extrapolated over this range. It can be seen that even a very liberal extrapolation would result in flap strains well below the composite material's allowable strain of 8000μ in. The second objective of the data analysis was to relate the strains on the flap's inner skin to the hydrodynamic pressures causing these strains. The approach for doing this is conceptually simple and direct. In the laboratory, a strip of known pressure load was applied spanwise to the flap and the resulting strains were measured on

*Swanek, R.A. and D.E. Oreschak, "Calm Water Evaluations of a Graphite Epoxy Composite Foil Flap on HIGH POINT (PCH-1)," DTNSRDC Technical Memorandum M52 (Mar 1981).

TABLE 6 - COMPOSITE FLAP CALM WATER TRIALS EVENTS

Event*	Event Code	Event Description
Foilborne		37-knot "S" turns at 90 deg helm command
Spiral turn	5C	38-knots, starboard
Spiral turn	5D	38-knots, port
Spiral turn	5B	34-knots, starboard
Spiral turn	5A	34-knots, port
Helm reversal	6A	Rapid commands from STBD** 90 deg to port 90 deg to zero at 34 Knots
Helm reversal	6B	Rapid commands from STBD 135 deg to port 135 deg to zero at 34 Knots
Helm reversal	6D	Rapid commands from STBD 90 deg to port 90 deg to zero at 38 Knots
Helm reversal	6E	Rapid commands from STBD 135 deg to port 135 deg to zero at 38 Knots
Sinus.** load, hullborne	7E	27-knots, ± 2 and ± 5 deg, 1 Hz flap command
Sinus, load, hullborne	7F	27-knots, ± 2 and ± 5 deg, 5 Hz flap command
Sinus. load, foilborne	8A	33-knots, 0.3 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8P	33-knots, 0.3 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8B	33-knots, 1.0 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8Q	32-knots, 1.0 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8C	33-knots, 2.0 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8R	33-knots, 2.0 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8D	34-knots, 4.0 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8S	34-knots, 4.0 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8E	34-knots, 6.0 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8T	34-knots, 6.0 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8F	37-knots, 0.3 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8U	36-knots, 0.3 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8G	35-knots, 1.0 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8V	36-knots, 1.0 Hz, ± 5.0 deg flap command
Sinus. load, foilborne	8H	36-knots, 2.0 Hz, ± 2.0 deg flap command
Sinus. load, foilborne	8W	36-knots, 2.0 Hz, ± 5.0 deg flap command
Broach	9B	8-ft. depth setting, 33 knots, zero helm position
Broach	9C	8-ft. depth setting, 39 knots, zero helm position

*All events occur foilborne with 7-ft depth setting except as noted. **Starboard ***Sinusoidal

TABLE 7 - SUMMARY OF MAXIMUM STRAINS AND HINGE MOMENTS

Event*	Event Code	Event Description	Maximum Excursion ($\mu\epsilon$)				MOM (ft-lb)
			Flap gages				
			5B	6B	18B	20A	
Foilborne						Link	
Spiral turn	5C	37-knot "S" turns at 90 deg helm command	- 5	90	- 88	-200	6015
Spiral turn	5D	38-knots, starboard	20	106	- 83	-230	7518
Spiral turn	5B	38-knots, port	30	70	- 63	-180	9082
Spiral turn	5A	34-knots, starboard	- 25	30	- 67	-110	8421
Helm Reversal	6A	34-knots, port	50	115	-105	-210	11729
Helm Reversal	6B	Rapid commands from STBD** 90 deg to port 90 deg to zero at 34 knots	90	205	-170	-302	15638
Helm Reversal	6D	Rapid commands from STBD 135 deg to port 135 deg to zero at 34 knots	160	250	-288	-320	18646
Helm Reversal	6E	Rapid commands from STBD 90 deg to port 90 deg to zero at 38 knots	60	195	-170	-310	15939
Sinus.† load, hullborne	7E	Rapid commands from STBD 135 deg to port 135 deg to zero at 38 knots	155	165	-290**	-350**	21652
Sinus. load, hullborne	7F	27-knots, ± 2 and ± 5 deg, 1 Hz flap command	40	65	- 75	-110	9624
Sinus. load, foilborne	8A	27-knots, ± 2 and ± 5 deg, 5 Hz flap command	40	75	- 90	-120	9624
Sinus. load, foilborne	8P	33-knots, 0.3 Hz, ± 2.0 deg flap command	- 15	95	- 89	-187	9624
Sinus. load, foilborne	8B	33-knots, 0.3 Hz, ± 5.0 deg flap command	- 30	100	-100	-200	10225
Sinus. load, foilborne	8Q	33-knots, 1.0 Hz, ± 2.0 deg flap command	- 30	85	- 90	-180	9323
Sinus. load, foilborne	8C	32-knots, 1.0 Hz, ± 5.0 deg flap command	- 40	90	-105	-185	10526
Sinus. load, foilborne	8R	33-knots, 2.0 Hz, ± 2.0 deg flap command	- 20	90	- 90	-185	9624
Sinus. load, foilborne	8D	33-knots, 2.0 Hz, ± 5.0 deg flap command	- 30	95	-105	-195	10526
Sinus. load, foilborne	8S	34-knots, 4.0 Hz, ± 2.0 deg flap command	- 30	100	-100	-200	10826
Sinus. load, foilborne	8E	34-knots, 4.0 Hz, ± 5.0 deg flap command	- 50	85	-100	-205	10526
Sinus. load, foilborne	8T	34-knots, 6.0 Hz, ± 2.0 deg flap command	- 50	75	-110	-200	10526
Sinus. load, foilborne	8F	34-knots, 6.0 Hz, ± 5.0 deg flap command	- 50	75	-110	-205	10826
Sinus. load, foilborne	8U	37-knots, 0.3 Hz, ± 2.0 deg flap command	- 30	90	-100	-210	10225
Sinus. load, foilborne	8G	36-knots, 0.3 Hz, ± 5.0 deg flap command	- 50	110	-125	-255	12029
Sinus. load, foilborne	8V	35-knots, 1.0 Hz, ± 2.0 deg flap command	- 35	85	-105	-215	10225
Sinus. load, foilborne	8H	36-knots, 1.0 Hz, ± 5.0 deg flap command	- 50	90	-120	-220	12029
Sinus. load, foilborne	8W	36-knots, 2.0 Hz, ± 2.0 deg flap command	- 35	80	-120	-220	10225
Sinus. load, foilborne	8V	36-knots, 2.0 Hz, ± 5.0 deg flap command	- 55	110	-125	-225	11729
Broach	9B	8-ft. depth setting, 33 knots, zero helm position	120	430**	-340**	-390**	-1203
Broach	9C	8-ft. depth setting, 39 knots, zero helm position	-234	375**	-312**	-609**	22254

*All events occur foilborne with 7-ft depth setting except as noted. **Extrapolated strain values † Sinusoidal ***Starboard † Sinusoidal

FORWARD FOIL BROACH - EVENT 8C

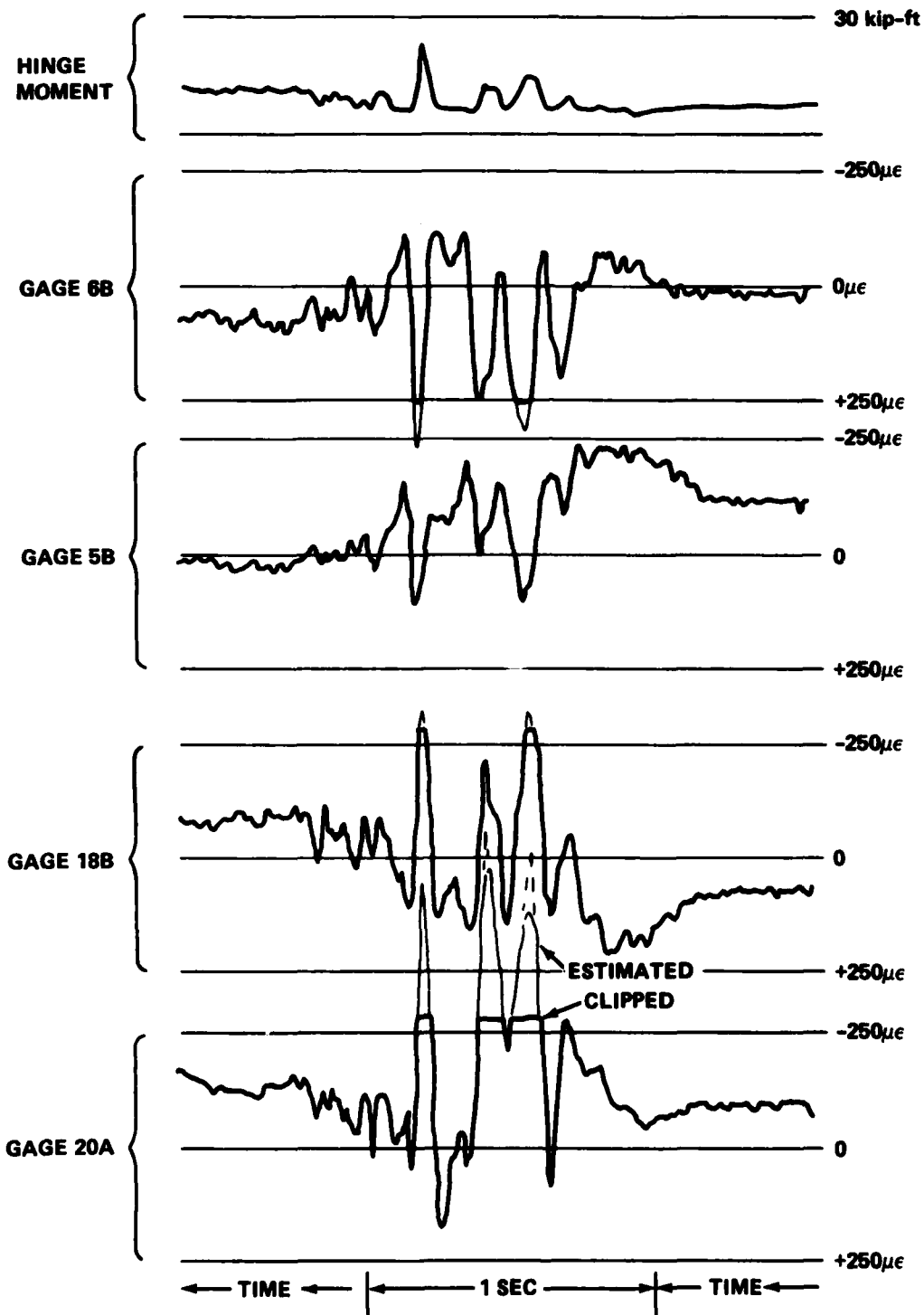


Figure 9 - Flap Response Time Histories for a Forward Foil Broach

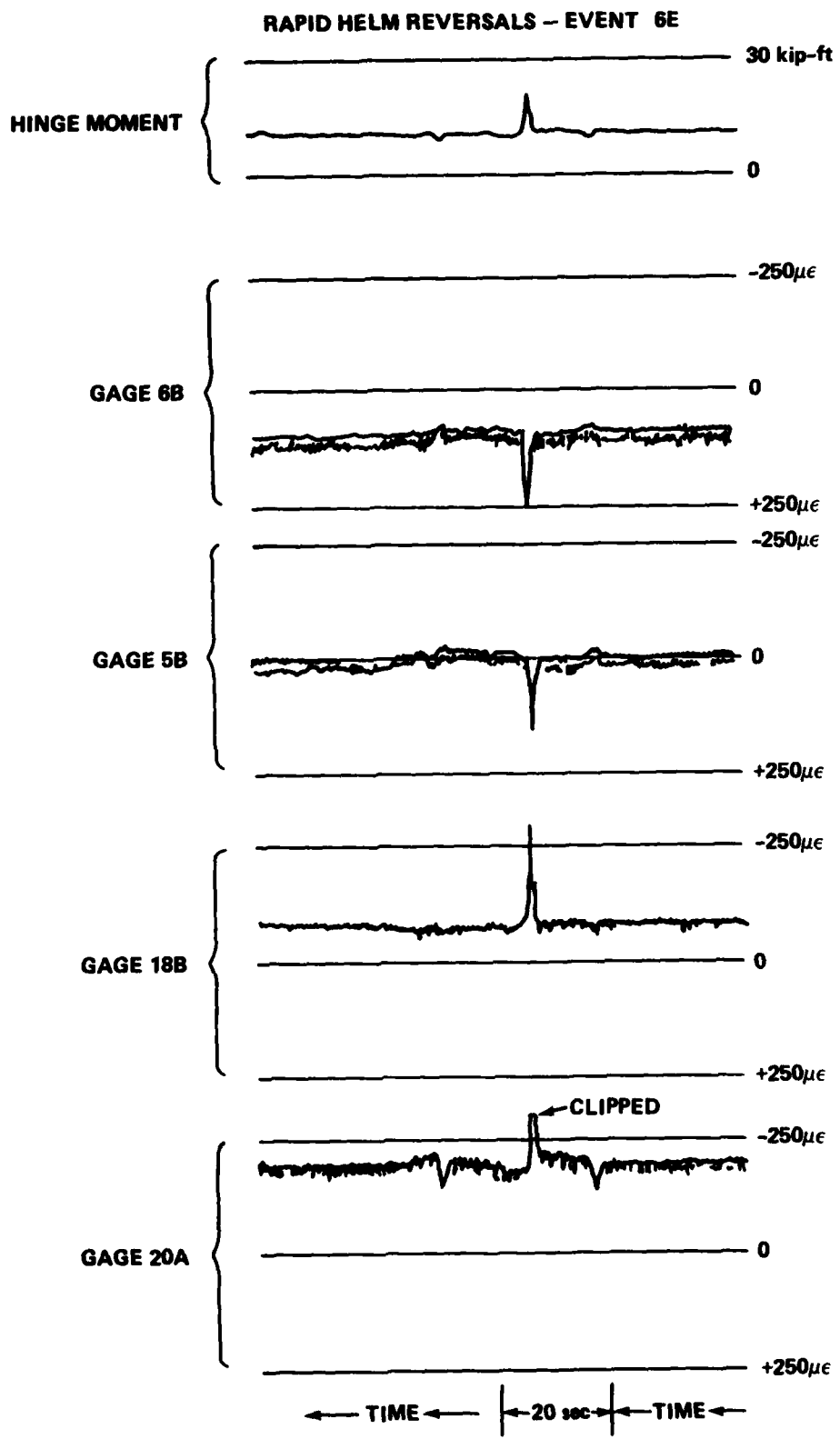


Figure 10 - Flap Response Time Histories for Rapid Helm Reversals

gages in different chordwise locations on the flap's inner skin. Each particular chordwise location is sensitive to a particular spanwise strip of applied pressure load to a varying degree, and it is the sum of these individual strains from each strip of pressure load which would represent the total strain at a particular gage location for a certain pressure distribution.

Although the resulting pressure distribution calculated from the measured operating strain levels need not be unique, the strips of pressure load thus derived should provide a reasonable estimate of the actual pressures. The reasonableness of the flap pressures predicted using this approach could be checked by comparing these values with those calculated analytically, or by calculating the hinge moment from the pressure distribution and comparing it with the hinge moment calculated from the flap link hinge moment. It was regrettable that the attempts to relate inner skin flap strains to the hydrodynamic pressures proved unsuccessful due to the loss of the majority of strain gages just prior to the trials' data collection.

Soon after the second set of calm water trials was completed, PCH-1 again experienced mechanical difficulties. The ship was again set up on the pier out of the water and the flap was removed without difficulty in preparation for the laboratory evaluation.

LABORATORY EVALUATION

As previously noted, a fatigue load spectrum was developed for the laboratory evaluation based on operational data taken from the existing PCH-1 flap systems. The Boeing Company designed and fabricated a steel test fixture which was bolted to the floor in the Structural Evaluation Laboratory at DTNSRDC; see Figure 11 for details of the test setup.

The approach followed in developing the control flap spectrum was simplified by the previous development of a load spectrum for the tapered box beam program. The content of the spectrum for the box beam which represents a structural element of the forward foil of PCH-1, constitutes an operational envelope for the ship. The loading spectrum for the box beam evaluation program was determined by projecting an operational lifetime for a fleet hydrofoil craft. The service history was normalized for all ship headings in various sea states. The 15-year lifetime was divided into 7500 blocks, each representing 2 hours of average foil-borne operation. Each block contains a total of approximately 1000 cycles at stress levels which represent operational sea states 3, 4, and 5, as well as broaches, landings, and takeoff. As such,



Figure 11 - Laboratory Evaluation Test Setup

the box beam spectrum was employed in defining the input function of the control flap spectrum. Data collected during trials of the PCH-1 were examined to establish the responses of the flaps to given operational load conditions. Early in the program planning, the decision was made to concentrate development efforts on an inboard aft flap of the PCH-1. This location was chosen because it offers the least risk from impact damage or of risk to the ship if the flap should be lost or damaged. The reaction loads on the inboard flaps are lower than those of either the outboard or forward flaps. To provide worthwhile data for the design of any future flap systems, it was decided to subject the laboratory evaluation flap to the most severe conditions encountered by any of the flaps. Thus, load levels representative of the outboard and forward flaps have been included in the load spectrum. Broach loads, which in operation are seen only by the forward flaps, were also investigated for inclusion in the spectrum. However, broach load levels were found to be no more significant than normal maximum operating loads and were thus neglected.

As can be seen in Figure 11, the load is applied to the crank arm of the flap by a 50-kip hydraulically-actuated jack and reacted by a rubber water bag on the lower surface or rubber pads on the upper surface. The bag/pads are placed between the flap and free floating I-beams in order to evenly distribute the reaction load over the flap surfaces. The reaction beams are also designed to aid in obtaining an even distribution of loads. The loading jack was controlled by a closed-loop, servohydraulic computer control system. This system was capable of applying a programmable fatigue load spectrum with variable loads and frequencies.

The flap was loaded in both directions to check out the test frame and loading system in a preliminary run to 5 kips. Both the pressure gage connected to the water bag and the potentiometer measuring deflection of the jack actuator functioned properly, as did the computer controlled loading system. However, during the initial static test to the maximum operating load of 24 kips, the control system malfunctioned leading to an overload of unknown magnitude which resulted in catastrophic failure of the flap; see Figure 12 which shows the twisting of the hinge-block support beam on the load frame. A visual inspection of the flap, and subsequent pulse-echo ultrasonic contact inspection, revealed the failure to be restricted to the lower flap skin in the area of the hinge blocks; the most severe damage in the hinge-block areas was near the crank arm, as shown in Figure 13. It should be pointed out that additional damage may exist, but could not be found using the aforementioned inspection techniques.

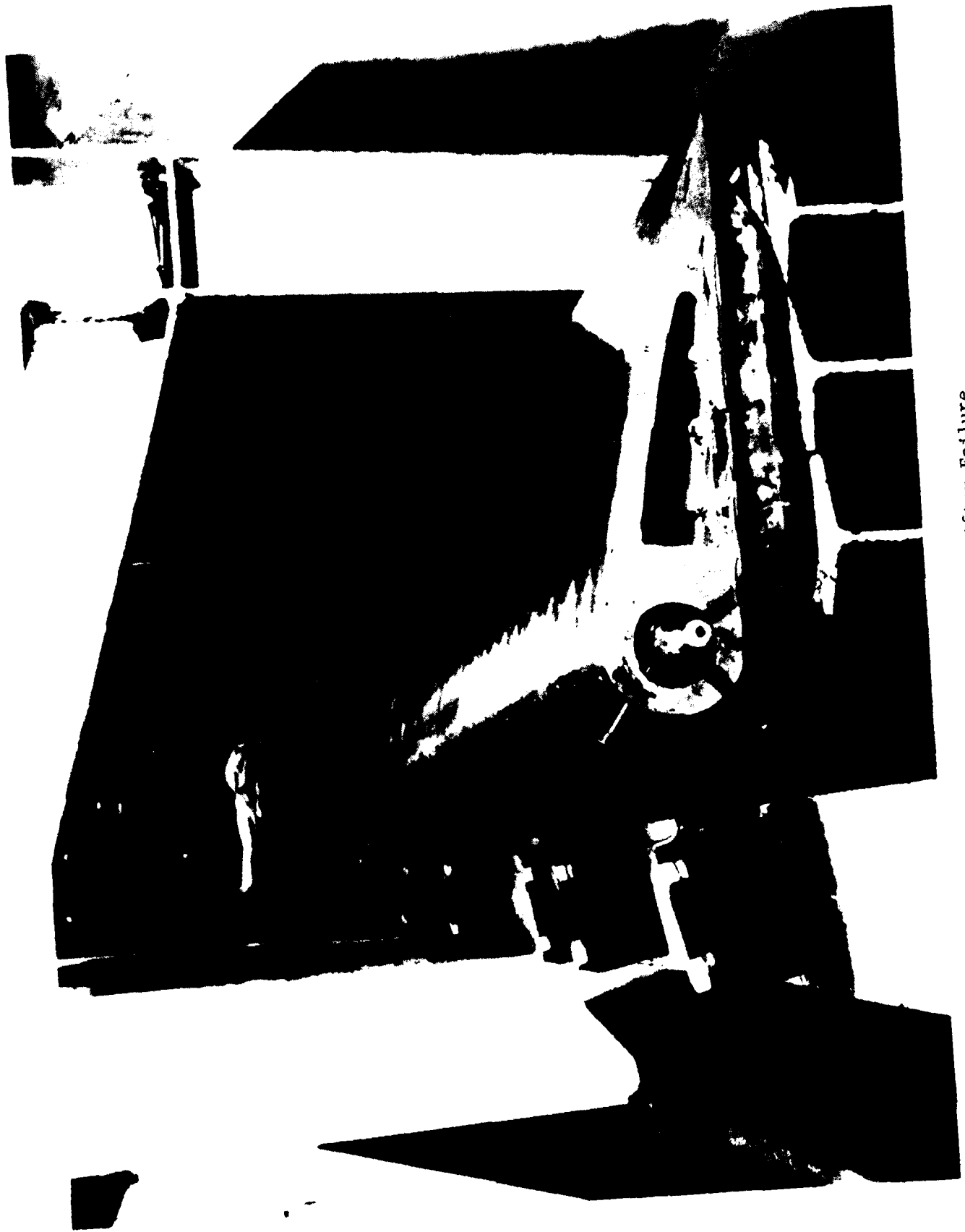
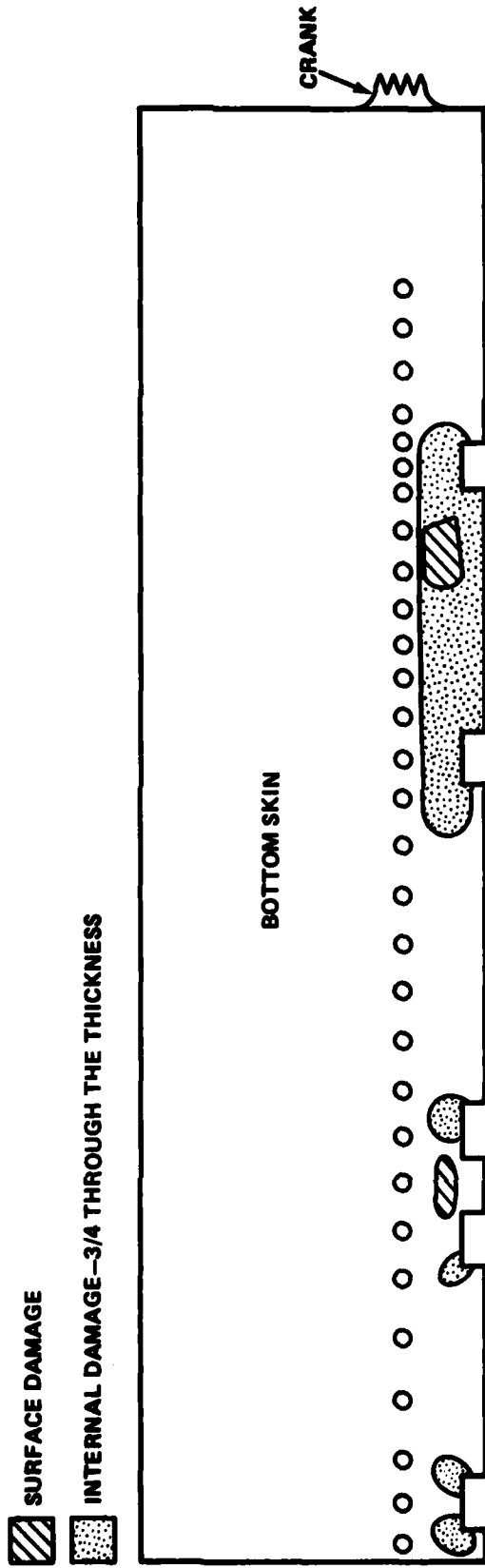


Figure 12 - Composite Flap After Failure



NOTES:

1. IN GENERAL, DAMAGE GREATEST IN HALF CLOSEST TO CRANK.
2. TOP SURFACE UNDETECTED.
3. UNABLE, WITH AVAILABLE TRANSDUCERS, TO EXAMINE CURVED LEADING EDGE.
4. DAMAGE CONFINED TO AREA BETWEEN CURVED LEADING EDGE AND FIRST ROW OF BOLTS ON BOTTOM SURFACE.
5. TWO HINGES FARTHEST FROM CRANK-DAMAGE AT CORNERS ONLY.
6. SLIGHT SURFACE DAMAGE AROUND BOLTS BETWEEN FOURTH AND FIFTH HINGES.
7. DAMAGE BETWEEN THIRD AND FOURTH HINGES - SURFACE AND POSSIBLY INTERNAL DAMAGE EXTENDS ONE-HALF WAY FROM HINGES TO BOLTS.
8. CLOSER TO CRANK END, DAMAGE EXTENDS ALL THE WAY TO THE ROW OF BOLTS.

Figure 13 - Ultrasonic Inspection of Composite Flap after Static Overload

DISCUSSION AND CONCLUSIONS

Although the in-service evaluation was limited to the extent given in Table 8,* and the flap failed during its initial static test prior to cyclic testing, several positive events occurred during the advanced composite hydrofoil control flap program.

TABLE 8 - TIME DATA FOR COMPOSITE FLAP INSTALLATION ON PCH-1

● Installation Date	21 December 1978
● Hullborne Operations (Diesel Propulsion)	550 hours (approx.)
● Hullborne Operations (Gas Turbine Propulsion)	87 hours 32 minutes
● Foilborne Operations	18 hours 23 minutes
● Submergence (Nominally at 4 or 15 ft)	18 weeks (approx.)
● Removal Date	24 February 1981

Ship speed during the diesel-powered hullborne operations was typically 6 to 7 knots. The hullborne gas turbine operations were usually performed using a single engine and speeds varied between 12 to 14 knots. Foilborne speeds varied between 32 and 42 knots, with the majority of the operation being at 38 to 40 knots.

A composite material system was developed that has the potential for application to marine structures operating in a harsh environment. The graphite epoxy-titanium clad flap skins used during this program were evaluated extensively in the laboratory with no significant degradation, and performed flawlessly (even if for a short period of time) during the in-service evaluation on PCH-1.

The author, with the aid of a NASTRAN finite element analysis was able to discover a major design flaw (the variable-thickness skin concept) prior to initiation of the contract, avoiding a potential cost overrun and/or schedule delay.

*DTNSRDC-HYSTU Memorandum ANW075-P345 of 25 February 1981; Subj:FRP Composite Flap Installation on PCH-1, Time data for.

It appears that the Boeing Company was able to optimize the final design without going through an expensive prototype "test and redesign" effort. The design was optimized with the aid of: NASTRAN, an indepth material evaluation program, a full-scale feasibility component fatigue evaluation, and a fastener evaluation task.

A hydrofoil control flap fatigue loading spectrum was developed based on the existing box beam spectrum and analysis of PCH-1 trials data.

A study of nondestructive evaluation techniques pointed out the relative merits of ultrasonics and radiography when applied to finding different types of flaws in a graphite epoxy-titanium clad laminate.

Procedures were established for the design, fabrication, and installation of an advanced composite hydrofoil control flap which was completely interchangeable with the existing steel flap, with no degradation in performance of the ship's control system.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the following persons for their interest, support, and guidance given throughout this project: Messers Samuel Oken, John Hoggatt, Howard Johnson, Slim Kihl, Thomas Ray, Don Blanchard, and Dwain Sorenson of The Boeing Company; Robert Johnson, Steve Zemanek, Rich Swanek, Diane Oreschak, Joseph Balun, Walter Kielert, Douglas Paunil, Frederick Koehler, Milton Critchfield, Jeffery Beach, Joseph Corrado, Nat Nappi, Alexander Macander, Murray Silvergleit, Harold Edelstein, Verne Whitehead, James Mason, and Donald Rieg of the Center; Irv Woloch and Dan Mulville of NRL; and Thomas White, William Graner, Carl Poehler, Hans Vanderveldt and James Gagorik of NAVSEA.

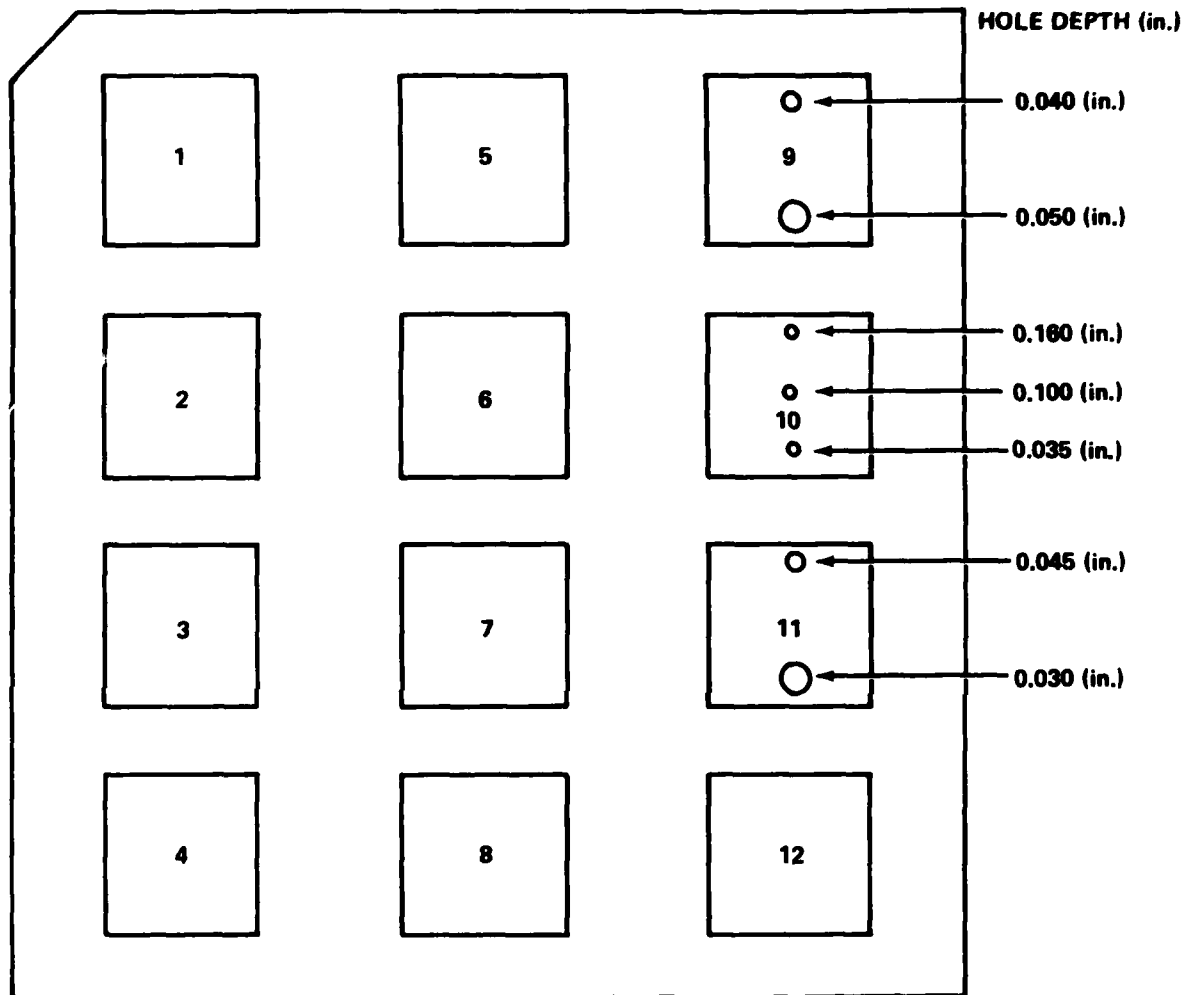
Special acknowledgment is given to Roy Deppa of the Center for managing the project through difficult times during the detail design and fabrication phases.

APPENDIX A
NONDESTRUCTIVE EVALUATIONS OF A GRAPHITE
EPOXY-TITANIUM CLAD PANEL

As part of the Boeing Company's contract to design and fabricate the PCH-1 control flap, a test panel representing the flap skins and containing twelve areas in which artificial flaws were induced was constructed. This panel was inspected by three different activities using several NDE methods to determine the detectability of these known conditions; The Boeing Company used through-transmission and pulse-echo ultrasonics; radiography; a sondicator; a thermal technique; and Fokker, harmonic, and audible bond testers with varying degrees of success. The Center used pulse-echo ultrasonics and radiographic analysis with an image enhancement system, and the Virginia Polytechnic Institute and State University (VPI&SU) used pulse-echo ultrasonics and thermography.

A test panel, containing twelve areas in which artificial flaws were induced, was fabricated to determine the capability of existing NDE methods to find and characterize defects that are typical to composite structures. The test panel was prepared by autoclaving 36 plies of Thornel - 300 graphite fiber fabric preimpregnated with Fiberite 934 epoxy resin. Titanium cover sheets (cladding) 0.010-in. thick were postbonded on each side with EA9628 adhesive which was cured for 90 min at 50 psi. The defects were induced in the bondline between one of the titanium sheets and the graphite epoxy laminate, and in some cases, by drilling holes in the graphite laminate. The location and description of these planned flaws are shown in Figure A.1. Although care was taken to be sure the identification of the flaws was correct, the radiographic analysis with an image enhancement system indicated that at least one of the flaws was different than planned. In order to confirm this discrepancy, the titanium cover sheet was chemically removed and the actual flaws were noted. A photograph of the actual flaws is shown in Figure A.2.

To determine the relative merits of the different methods of flaw detection, the following procedure was used. The test piece was scanned with the particular machine or equipment, and all flaw indications recorded and subsequently sketched. Next, an overlay showing the defect areas was laid over the inspection sketch and the results compared. The overall performance of each method can be seen by comparing Figures A.3 through A.7 with Figure A.2. To be sure the defect areas were not lost, they were etched onto the titanium cladding. Only x-ray with image enhancement found the etch marks, as well as nearly all the defects. Table A.1 summarizes the flaws found by each method and activity.



DEFECTS

- | | |
|--|--|
| <ul style="list-style-type: none"> 1. PARTING AGENT 2. 0.5 MIL TEFLON 3. 2 MIL TEFLON 4. 5 MIL KAPTON AND PARTING AGENT 5. NO ADHESIVE 1.5 in. sq. 6. AIR BAG (FEP) 7. NO ADHESIVE - FEP (2 mil) 8. NO ADHESIVE - 131 FABRIC | <ul style="list-style-type: none"> 9. 1/4-in. DRILLED HOLE, 2-3 PLIES DEEP 1/2-in. DRILLED HOLE, 2-3 PLIES DEEP 10. 1/8-in. DRILLED HOLE, 20 PLIES DEEP 1/8-in. DRILLED HOLE, 10 PLIES DEEP 1/8-in. DRILLED HOLE, 5 PLIES DEEP 11. 1/4-in. DRILLED HOLE, 3-4 FEP FILM 1/2-in. DRILLED HOLE, 3-4 FEP FILM 12. PAPER 1.5-in. sq. (TOP) |
|--|--|

Figure A.1 - Planned Composite Panel Flaws

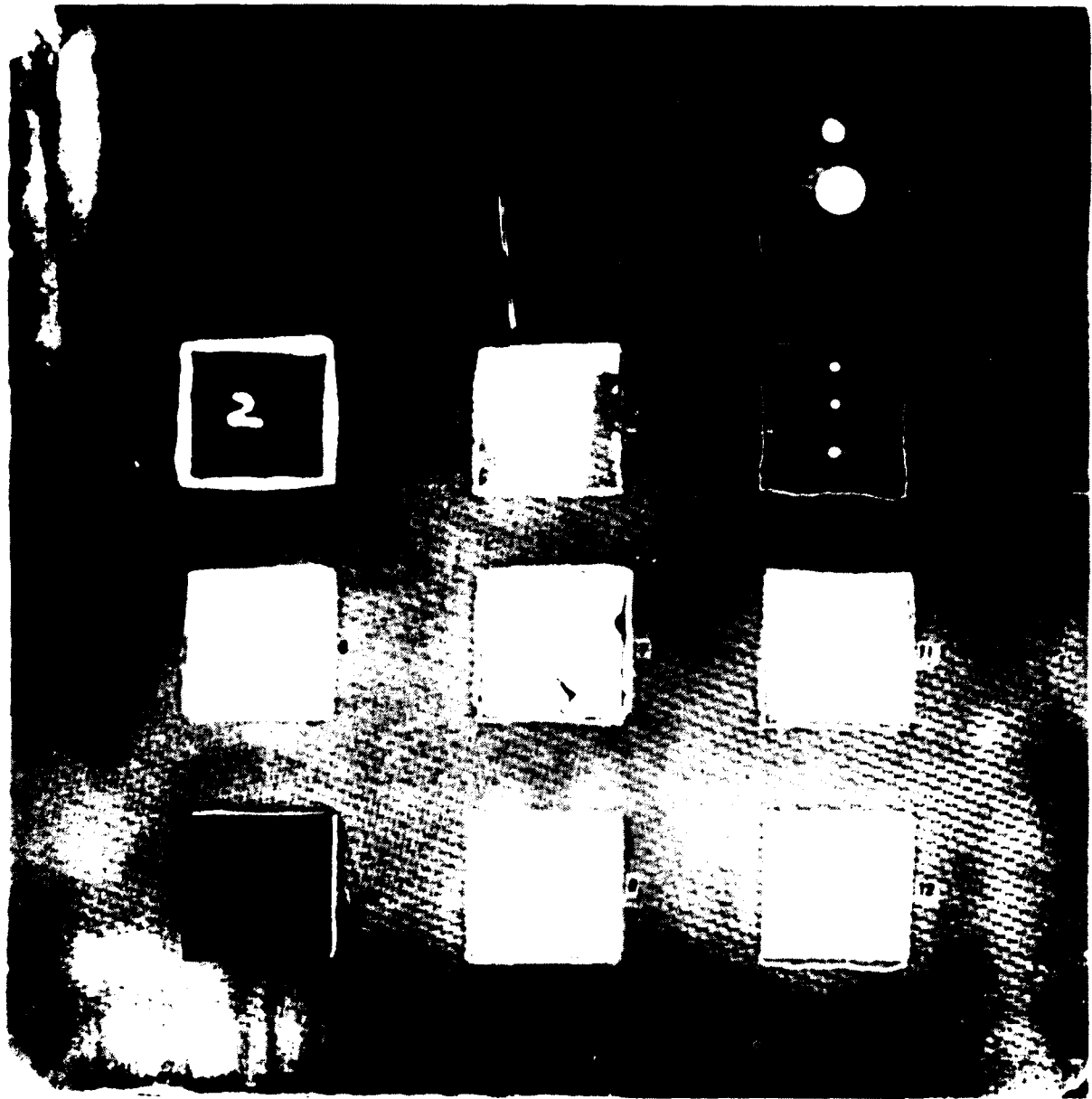


Figure A.2 - Actual Composite Panel Flaws

Of the two-dimensional characterization NDC methods, through-transmission ultrasonics appeared to be the most definitive and accurate for identifying flaws in graphite epoxy-laminated plates and shells. This method is best suited for inspection of the laminate after cure and prior to assembly as part of a structural component, because this method required water coupling between the transducer and

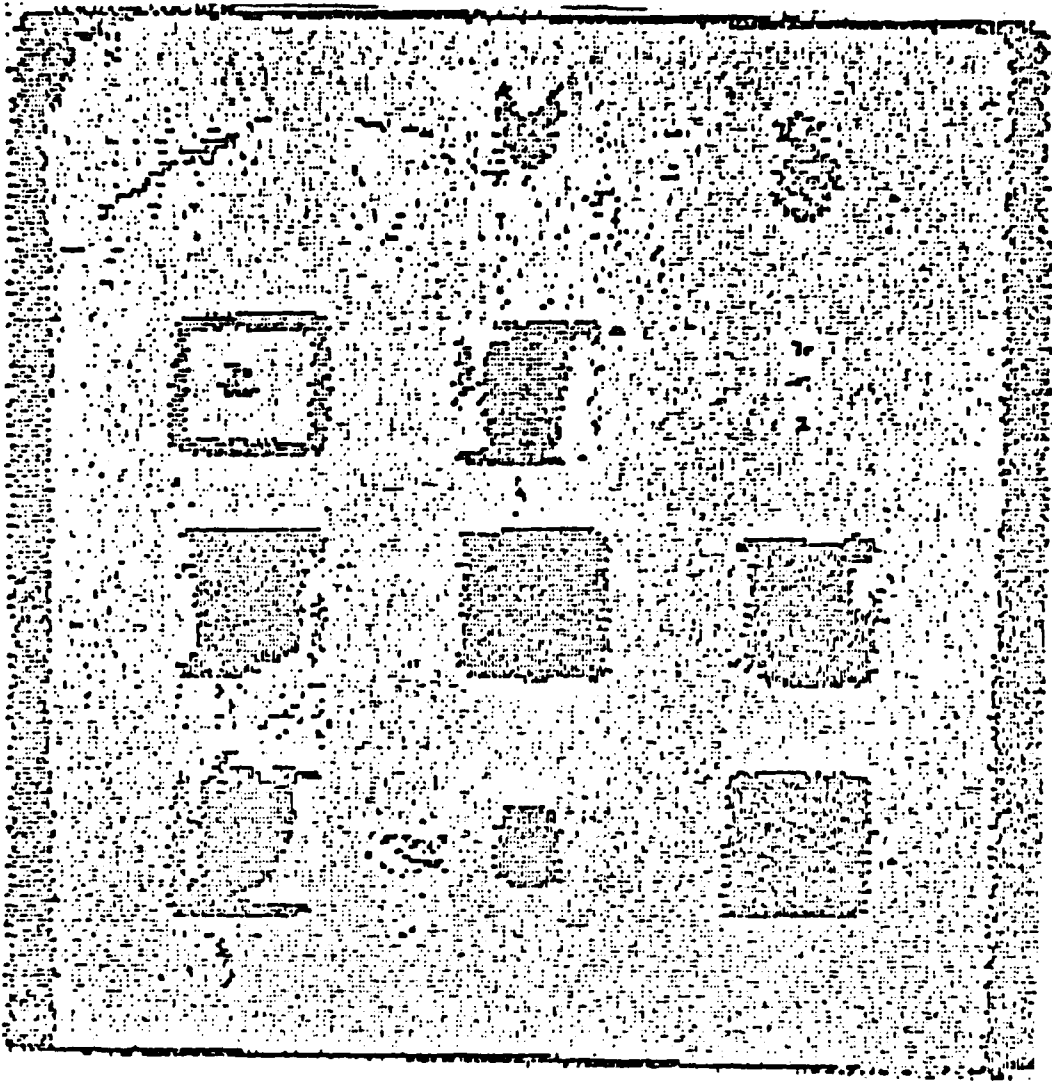


Figure A.3 - Recording of Through-Transmission Ultrasonics

the laminate (water tank or water jet) and because the small transducer required to concentrate the ultrasonic energy leads to a large amount of time for inspection (unless multiple transducers are used). If flaws in the post cured laminate are detected with this method, the radiographic analysis with an image enhancement system and a calibrated density profiler can be used to give an accurate three-dimensional characterization of the flaws. The pulse-echo ultrasonics should be used when both sides of the laminate can be inspected and when the more sophisticated through-transmission ultrasonics is not available, or when the component is too large to make through-transmission feasible.

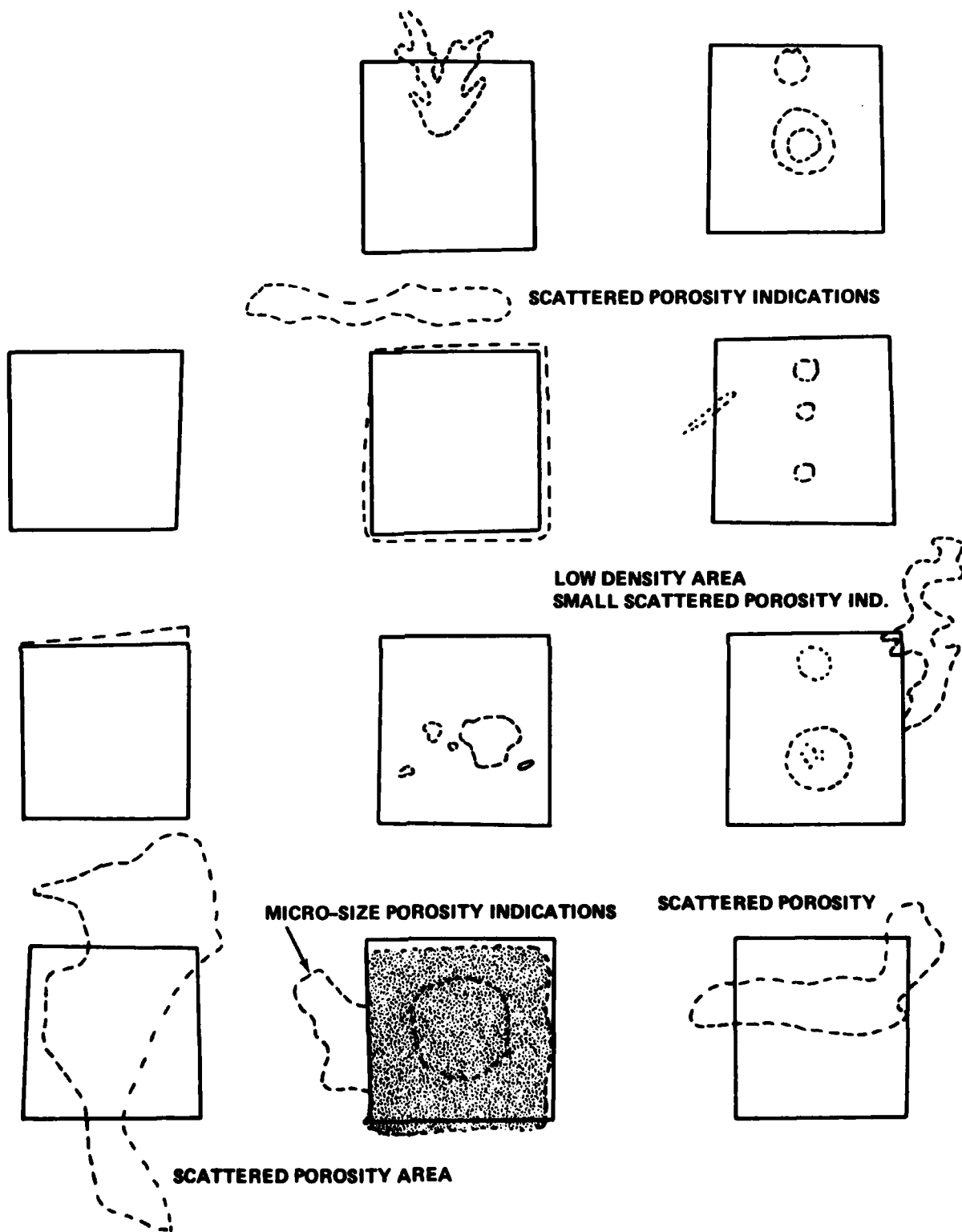


Figure A.4 - Results of X-Ray with Image Enhancement Analysis

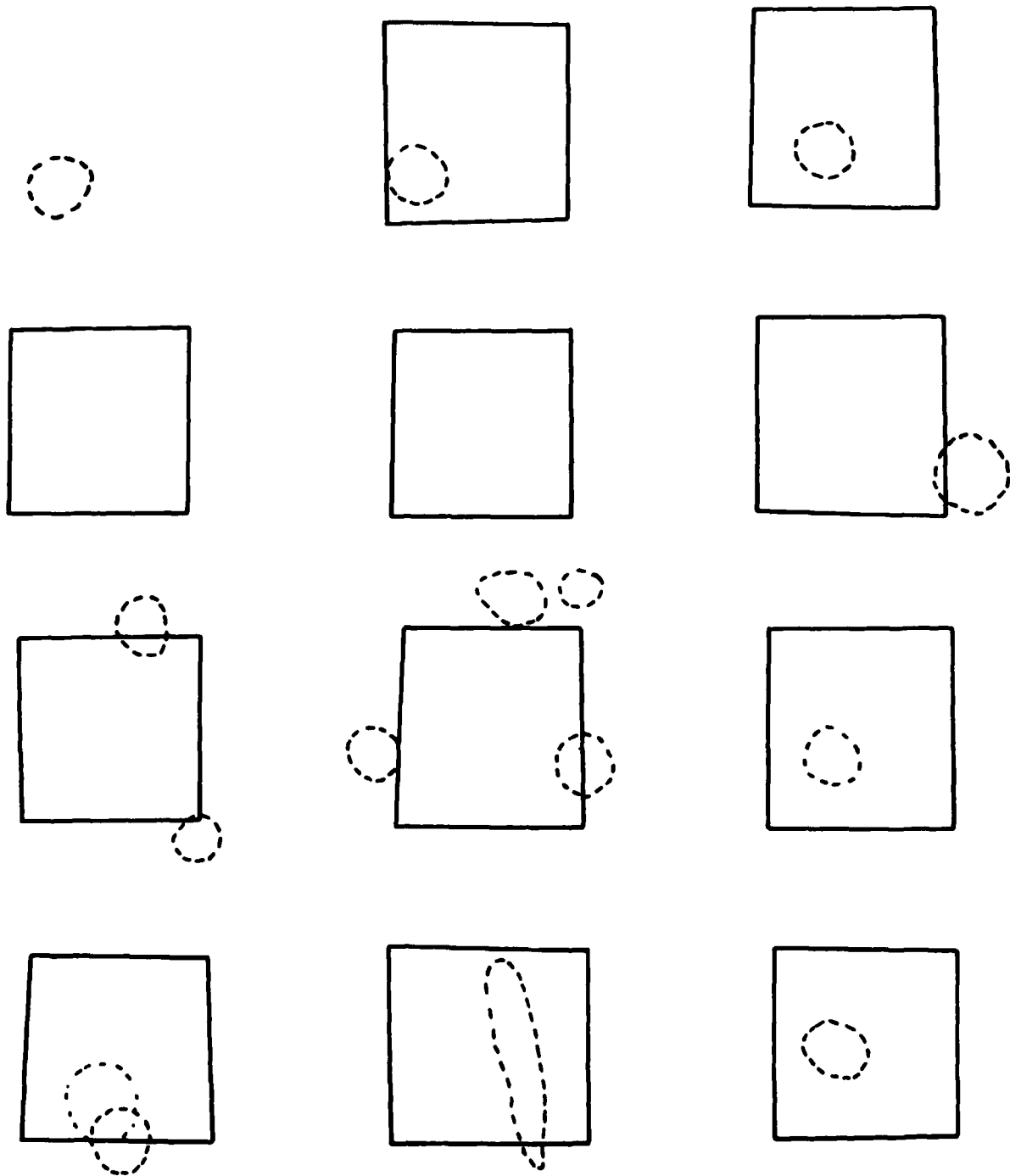


Figure A.5 - Results of Pulse-Echo Ultrasonic Analysis (Performed at VPI and SU)

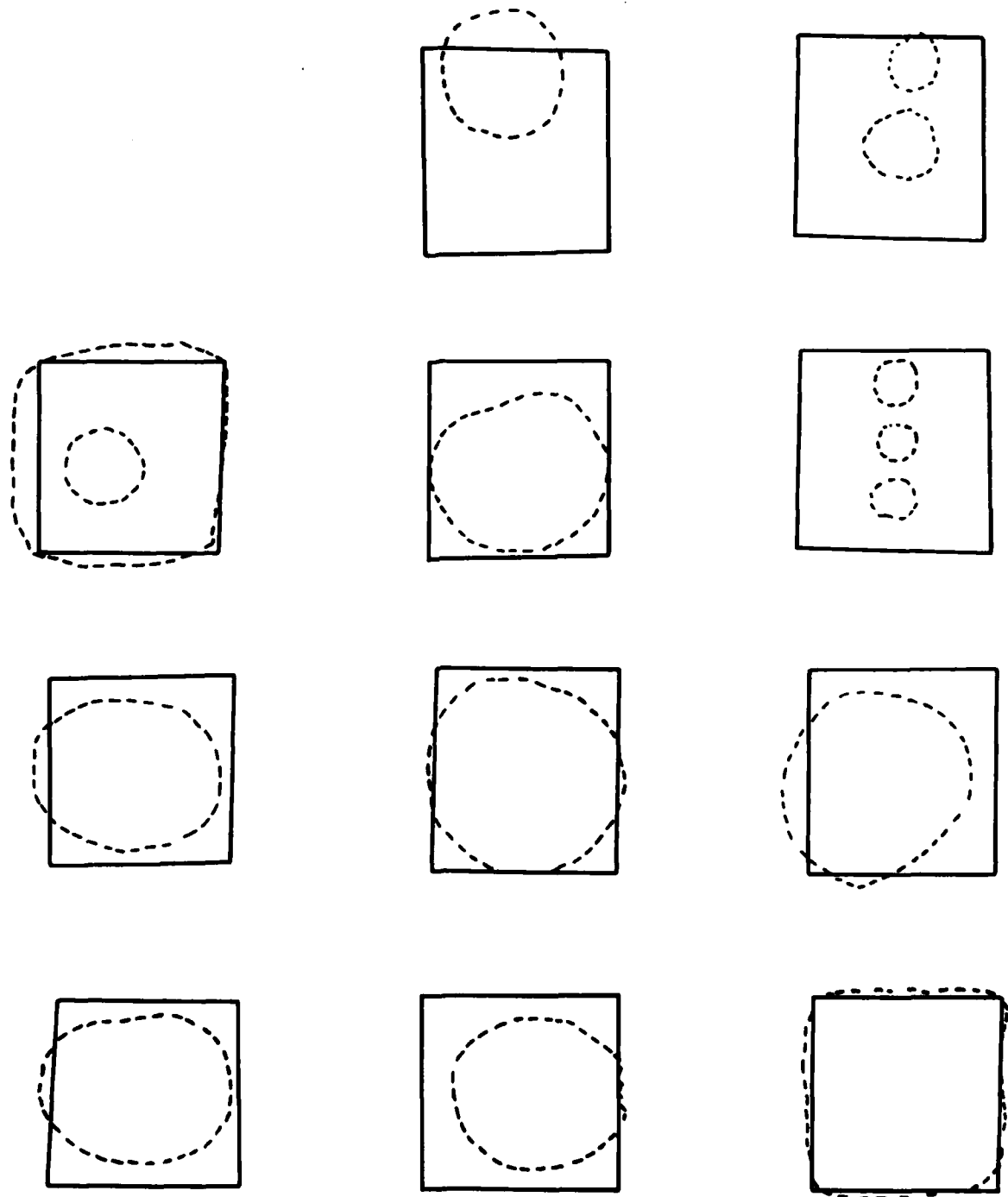


Figure A.6 - Results of Pulse-Echo Ultrasonic Analysis (Performed at DTNSRDC)

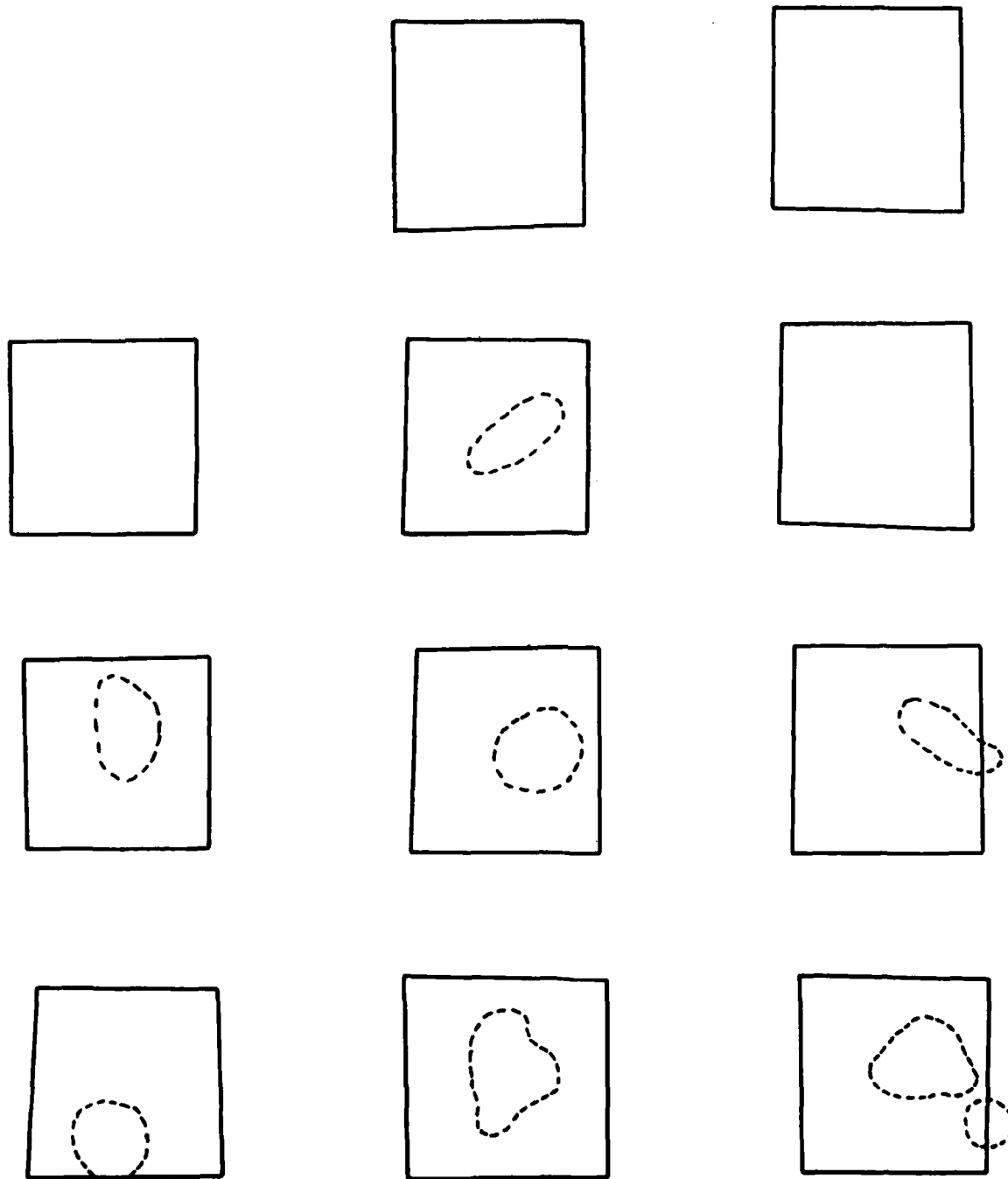


Figure A.7 - Results of Thermographic Analysis

TABLE A.1 - SUMMARY OF FLAW DETECTION TESTS

Flaw Identification	NDE Procedure										
	Ultrasonic			X-Ray		Bond Testers			Thermal	Thermography	Sondicator
	Through-Transmission	Pulse-Echo		Radiographic	Image Enhancement	Fokker	Harmonic	Audible			
		The Boeing Co.	VPI and SU						DTNSRDC		
1	X										
2	X			X			X				
3	X		X	X		X	X	X			X
4	X	X	X	X		X	X	X			X
5	X			X	X	X	X			X	
6	X	X		X	X	X	X	X	X		X
7	X	X	X	X	X	X	X	X	X	X	X
8	X	X	X	X	X	X	X	X	X	X	X
9	X		X	X	X	X	X				
10	X	X		X	X	X					
11	X	X	X	X	X	X	X		X	X	X
12	X	X	X	X			X				X

For in-service evaluation of graphite epoxy structural components, it appears that pulse-echo ultrasonics or the Fokker bond tester are the best methods available to give a general description of flawed areas. This evaluation would then have to be followed up with a "field exposure" radiographic analysis with an image enhancement system and a calibrated density profiler to give an accurate three-dimensional characterization of the structural component.

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