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NASA CR-134707

IMPACT RESISTANCE OF COMPOSITE FAN BLADES

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Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA-LEWIS RESEARCH CENTER

Contract NAS3-16777

1. Report No. NASA CR-134707	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IMPACT RESISTANCE OF COMPOSITE FAN BLADES		5. Report Date December 1974
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No. R74AEG320
		10. Work Unit No.
9. Performing Organization Name and Address Aircraft Engine Group General Electric Co. Cincinnati, Ohio 45215		11. Contract or Grant No. NAS3-16777
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

This report presents the results of a program to determine the impact resistance of composite fan blades subjected to foreign object damage (FOD) while operating under conditions simulating a short take-off and landing (STOL) engine at takeoff. The full-scale TF39 first-stage fan blade was chosen as the base design for the demonstration component since its configuration and operating tip speeds are similar to a typical STOL fan blade and several composite configurations had already been designed and evaluated under previous programs.

The first portion of the program was devoted toward fabricating and testing high impact resistant, aerodynamically acceptable composite blades which utilized only a single material system in any given blade. The material systems utilized were a graphite/epoxy system (AU/PR 288) and a boron/epoxy system (4.0 mil/5505). It was determined that the blades of each material system were both capable of sustaining impact equivalent to a half bite of a 624-gram (22-ounce) bird without total failure. Beyond this point, both blades broke off at the root at impact.

In order to increase the blade impact capability beyond this point, several mixed material (hybrid) designs were investigated using S-glass and Kevlar as well as boron and graphite fibers. These hybrid composite blades showed a marked improvement in resistance to bird impact over those blades made of a single composite material.

The work conducted under this program has demonstrated substantial improvement in composite fan blades with respect to FOD resistance and has indicated that the hybrid design concept, which utilizes different types of fibers in various portions of a fan blade design depending on the particular requirements of the different areas and the characteristics of the different fibers involved, shows a significant improvement over those designs utilizing only one material system.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Composites; Impact Resistance; Graphite/Epoxy; Boron/Epoxy; Hybrid Designs; Fan Blades; Foreign Object Damage (FOD)	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	135	$4.50

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This technical report was prepared by the Aircraft Engine Group of the General Electric Company under NASA Contract NAS3-16777 and covers work performed during the period July 1972 through May 1974 on a program to study impact resistance of composite fan blades.

The NASA Project Manager was Mr. R. Johns of the Lewis Research Center. For the General Electric Company, Mr. C. Steinhagen was the Program Manager, and Mr. C. Salemme was the Technical Manager. The portion of the program conducted at General Electric's Space Science Laboratory was under the direction of Mr. A. Coppa.

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Design - Messrs. D. Dahlseid, T. Irwin, M. Lawrence, and R. Ravenhall

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1.0 SUMMARY

This report presents the results of a program to determine the impact resistance of composite fan blades subjected to foreign object damage (FOD) while operating under conditions simulating a short take-off and landing (STOL) engine at take-off. The full-scale TF39 first-stage fan blade was chosen as the base design for the demonstration component, since its configuration and operating tip speeds are similar to a typical STOL fan blade and several composite configurations had already been designed and evaluated under previous programs.

The first portion of the program was devoted toward the fabrication and testing of high impact resistant, aerodynamically acceptable, composite blades which utilized only a single material system in any given blade. The material systems utilized were a graphite-epoxy system (AU/PR 288) and a boron/epoxy system (4.0 mil/5505). The lay-up patterns for these blades were designed to produce blades with the proper aeromechanical properties. A total of 10 of these blades, 5 of each material, was fabricated. The blades were tested in a rotating-arm test facility at a blade tip speed of 244 m/sec (800 ft/sec) under various conditions of gravel, hail, and bird ingestion which simulated a STOL engine at takeoff. No significant damage resulted from the gravel or hail impact. The bird impact was targeted at the center of mass, 10.16 cm (4 inches) from the tip of the blade at a 22-degree incidence angle. It was determined that the blades of both material systems were capable of sustaining impact equivalent to a half bite of a 624-gram (22-ounce) bird without total failure. Beyond this point, both blades broke off at the root at impact.

To increase the blade impact capability beyond this point, several mixed material (hybrid) designs were investigated using S-glass and Kevlar as well as boron and graphite fibers. A screening program was conducted using panel specimens which represented the outer 31 cm (12 inches) of the blade. Some panels were of standard 0/22/0/-22 lay-up, while others incorporated cross plies to strengthen the tip, and S-glass on the surface at the root to give the blade bending strength. The panel specimens were tested with starling-size and pigeon-size simulated birds and were evaluated for damage; two hybrid designs were selected from which full-scale blades were fabricated and tested.

These hybrid composite blades showed a marked improvement in resistance to bird impact over those blades made of a single composite material. A total of six blades was tested, three of each design. The threshold of blade failure was increased to a 680-g (24-ounce) slice of a 1360-g (48-ounce) simulated bird. A blade of each design was also tested using a 1150-g (2.5-pound) wild mallard duck with a slice size averaging 625 g (22 ounces) without causing catastrophic blade failure.

The work conducted under this program has demonstrated substantial improvement in composite fan blades with respect to FOD resistance and has indicated that the hybrid design concept, which utilizes different types of fibers in various portions of a fan blade design depending on the particular requirements of the different areas and the characteristics of the different fibers involved, shows a significant improvement over those designs utilizing only one material system. It is felt that this program has demonstrated design concepts which now make composites a viable material for fan blade design with reasonable assurance that such blades will be able to withstand the required FOD conditions without catastrophic blade failure or unacceptable damage to the engine, although the latter condition must be demonstrated by actual engine tests.

2.0 INTRODUCTION

High-bypass turbofan engines, in the last decade, have become the standard power plant for subsonic aircraft because of their light weight and low fuel consumption. The cost and weight of such engines is strongly influenced by the fan because of its large size and weight compared to the rest of the engine. Any major improvement in the fan can significantly reduce life cycle costs for subsonic aircraft. Composite fan blades promise to make such a major improvement in the fan with significant improvements expected in cost, weight, efficiency (fuel consumption), and maintenance.

There has been steady and productive work conducted over a period of years to solve the problems associated with composite blades, the most difficult of which has proven to be bird impact resistance. Aeromechanical, processing, reproducibility, quality, and erosion, as well as ice and small object impact, generally have been brought under control. Progress in resisting bird impacts, however, has been much slower.

Composite blades are more susceptible to damage from this type of loading than metal blades because of their generally lower strain energy storage capability and their lack of ductility. It was, therefore, the objective of this program to evaluate the resistance of typical state-of-the-art composite fan blades to standard types of foreign object damage (FOD), and then to develop improved lay-up configurations and to employ hybrid material concepts in order to significantly improve their capability in this area.

As a baseline state-of-the-art component, the TF39 first stage composite fan blade, designed and developed under both Air Force Contract F33657-72-C-0241 and IR&D funding, was selected. This selection was based on the fact that an aerodynamically acceptable composite design was already complete, tooling was on hand, and manufacturing processes were defined so that a comprehensive testing program could begin without delay and at minimum cost. In addition, this composite design had already demonstrated its ability to withstand starling impact with minimal damage, thus holding promise of taking even larger birds.

The following sections present the results of this program to improve the FOD resistance of composite fan blades, with emphasis on the ability to withstand bird strikes. The various internal blade designs are shown, and the results of the individual tests are presented and evaluated with recommendations made as to the types of blade design which are most appropriate for large fan blade design and thus should be further pursued.

3.0 DESIGN

The objective of this program was to evaluate the resistance of composite fan blades to impact damage from foreign objects while operating under conditions similar to that of an advanced STOL aircraft engine. The approach taken to meet this objective was (1) to thoroughly evaluate the level of FOD resistance of an existing developmental graphite/epoxy blade design, (2) to compare its performance to a blade of identical design except using a boron/epoxy material system, and (3) to develop and demonstrate blades of improved impact resistance through the use of hybrid materials. The design work on this program was limited to the development of the lay-up patterns of the hybrid blade configurations investigated in the latter stages of the program. The basic aerodynamic design, initial lay-up patterns, blade root design, and leading edge protection system were developed under other programs and are briefly discussed in the following paragraphs only to provide continuity and completeness to this report.

The baseline composite design was the Phase IIb design of the TF39 first-stage fan blade generated under Air Force Contract F33657-72-C-0241. This design was selected because the aerodynamic and mechanical design was already complete; tooling was on hand; processing techniques were defined; and, graphite/epoxy versions of the blade had demonstrated the ability to withstand starling impact. Therefore, the initial testing required by this program could begin with little delay. A description of this blade and some of its major characteristics are contained in Section 3.1, while succeeding sections discuss the boron/epoxy design, hybrid designs, blade root configuration, and leading edge protection system.

3.1 BASIC COMPOSITE BLADE DESIGN

The baseline blade design used throughout this program was the TF39 Phase IIb composite blade. This blade utilizes the same airfoil geometry as the TF39 first-stage metal blade used in the C-5A turbofan engines. The major difference in external blade design consists of a circular arc dovetail as compared to a straight dovetail for the metallic blade.

The rotor configuration consists of a 25-bladed, single-stage fan having a design tip speed of 328 m/sec (1000 ft/sec). A summary of the rotor weights for both the graphite composite and the titanium fan rotor is shown in Table I. This shows a direct substitution weight savings for the composite fan of 32%.

The frequency versus speed characteristics of the Phase IIb blade are presented in Figure 1 along with those for the solid titanium blade. Both metallic and composite blades are shown to be low flex designs, i.e., having their first flex frequency below 2/rev at 100% speed. The 2/rev crossover point occurs at approximately 2100 rpm for the composite blade as opposed to 1700 rpm for the solid titanium blade. The ply orientations and lay-up patterns for the composite blades produced in this program were based on the initial graphite/epoxy blade. This blade used a 0/+22/0/-22° fiber orienta-

Table I. TF39 Stage 1 Fan Rotor, Rotor Weight Comparison, Graphite Vs. Titanium.

	Titanium Blade Rotor			Graphite Blade Rotor		
	kg.	(lbs.)		kg.	(lbs.)	
Blades	80.7	(178)	(Ti)	34.9	(77)	(G/E)
Disc	40.4	(89)	(Ti)	34.0	(75)	(Ti)
Spinner	8.6	(19)	(Alum)	8.2	(18)	(Ti)
Spacer	11.3	(25)	(Ti)	11.8	(26)	(Ti)
Platform	4.1	(9)	(Alum)	5.0	(11)	(Ti)
Blade Retainer	---	---		3.2	(7)	(Ti)
Blade Shims	---	---		1.8	(4)	(Alum)
	145.1	(320)		98.9	(218)	

32% Weight Reduction (Rotor Only)

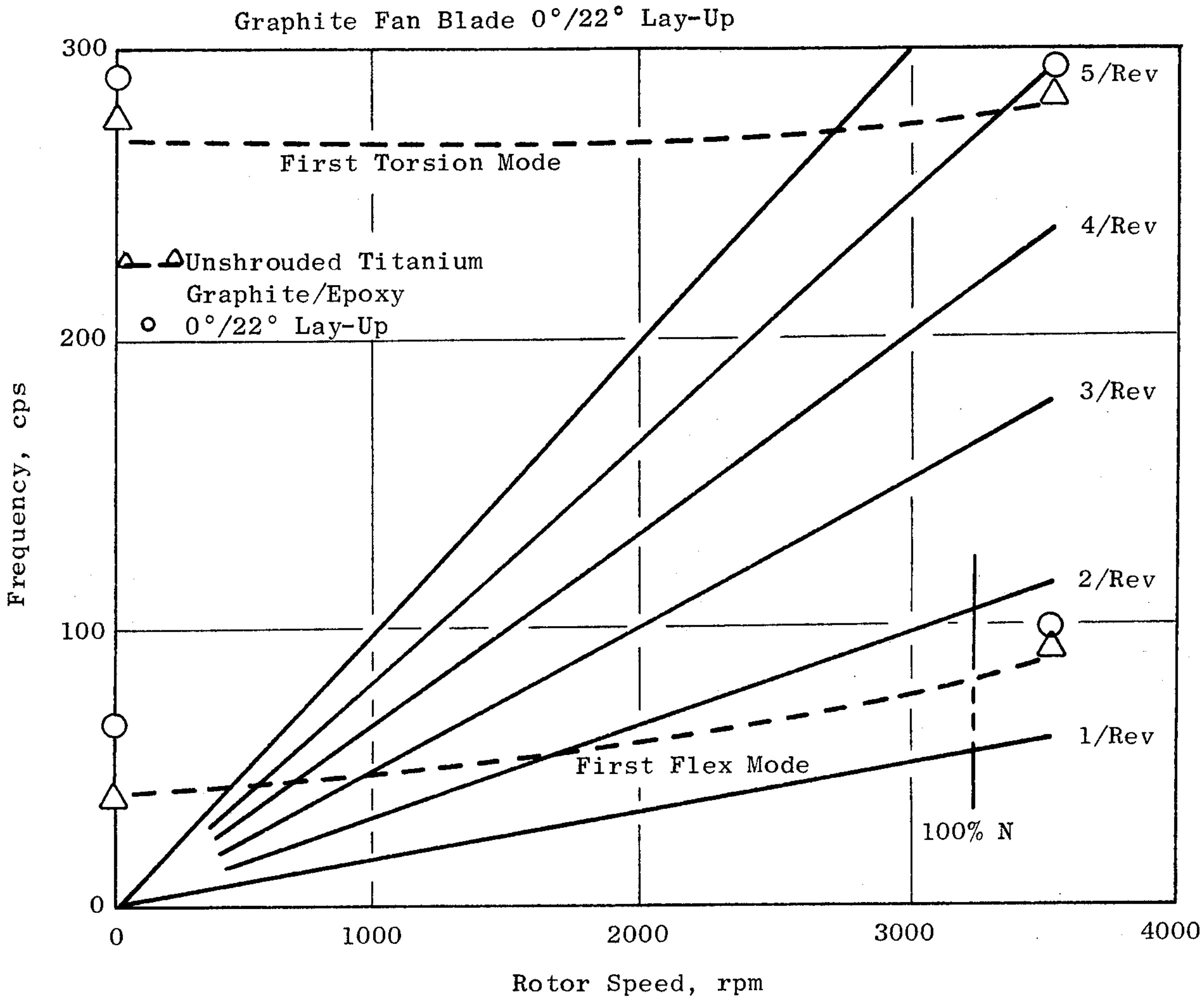


Figure 1. Frequency Characteristics of TF39 Phase II Design Blade.

tion throughout the blade cross section, which provided a good balance between blade frequency characteristics and strength. The basic laminate pattern definition and arrangement is shown in Figure 2 and was used for all the graphite/epoxy and boron/epoxy blades produced during this program.

3.2 HYBRID PANEL DESIGN

In order to evaluate several hybrid designs without conducting full-sized blade tests, it was decided to manufacture seven hybrid panels and a standard graphite/epoxy panel for static impact testing.

The panel design consisted of the outer 31 cm (12 inches) of the TF39 blade to be made from the existing hard tooling blade die. The advantage of having the TF39 configuration for the panels was as follows:

- Typical blade sections with realistic camber, twist and taper would provide better correlation with full-size blades.

- The actual blade die could be used allowing excellent dimensional and quality control.

- Existing test and inspection fixtures could be utilized.

The panel materials and lay-up configurations summarized in Table II were selected as being potential designs having improved impact capability. The S-glass material was selected because of its high strength and improved strain-to-failure characteristics.

The Kevlar 49 material was selected because of its light weight, potential low cost, and greatly improved ballistic impact strength.

3.3 HYBRID BLADE DESIGN

Based on the results of the hybrid panel tests, two configurations were selected for further investigation involving the testing of full-scale blades in the whirligig. The two configurations were selected based on the evaluation of the panel tests as discussed in Section 5.3.3. The two configurations were:

Design 1:	Material:	PR 288/AU 80/S-glass 20 throughout
	Lay-up:	Standard TF39 (0/22/0/-22)
Design 2:	Material:	PR 288/AU and PR 288/Kevlar 49
	Lay-up:	Standard TF39 (0/22/0/-22) with 4 plies each of Kevlar 49 at ± 80° and ± 45° at the tip

The six hybrid blades manufactured in this program utilized the graphite blade lay-ups and orientation angles with the exception of having short ± 10° laminates of S-glass on the surface in the root area of the hybrid blades to provide more compressive strength.

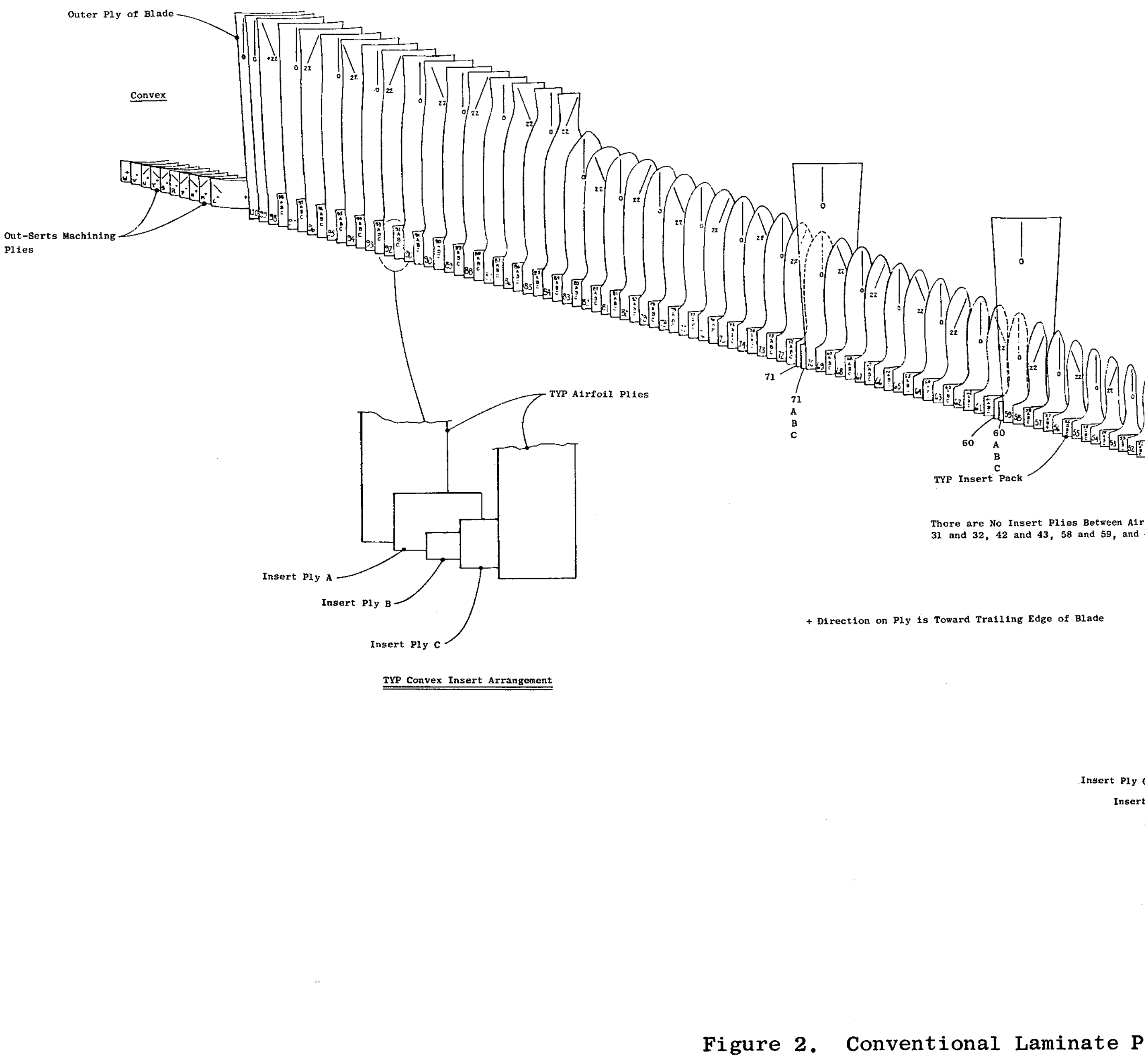
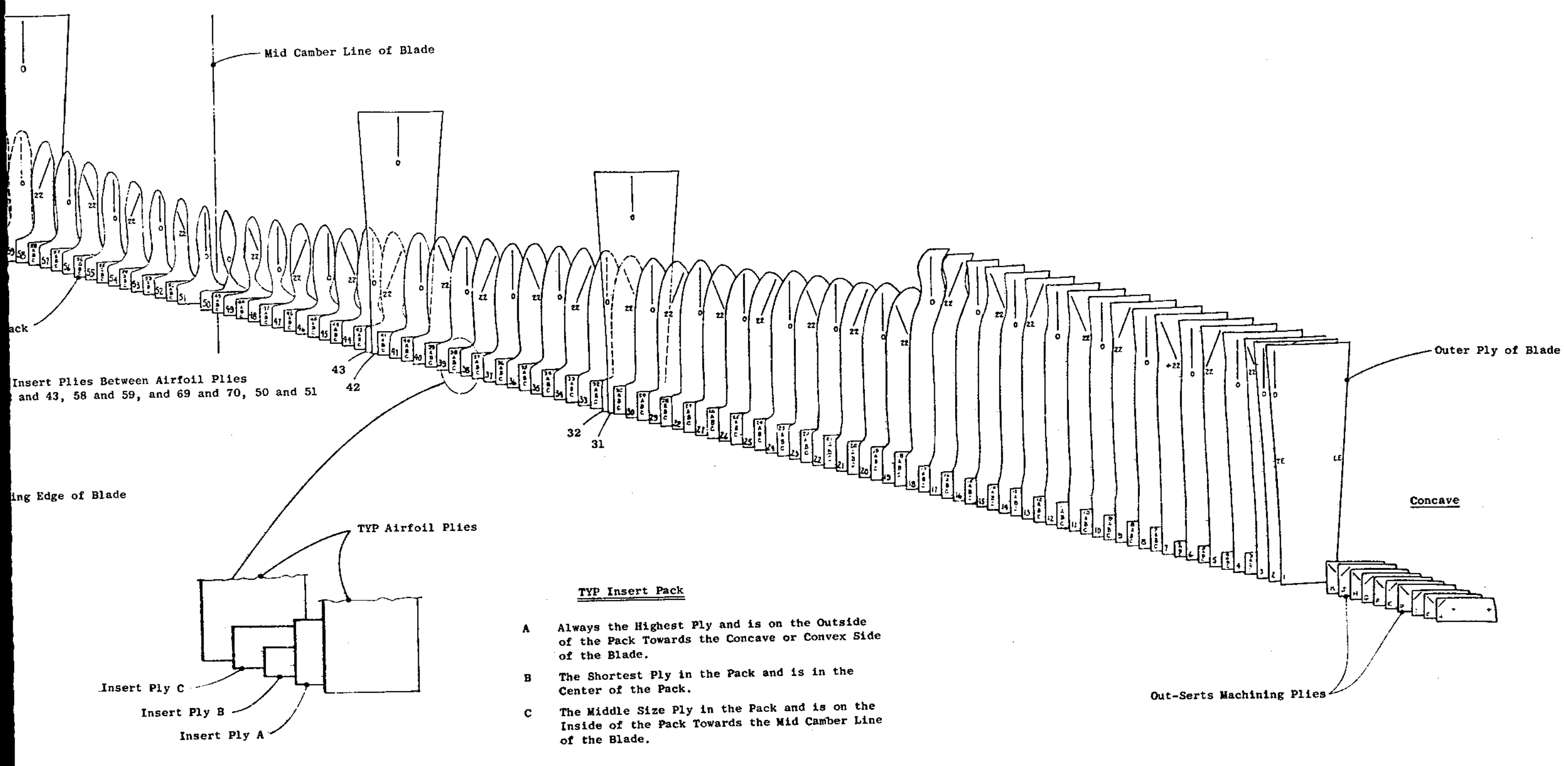


Figure 2. Conventional Laminate P



Laminate Ply Configuration for TF39IIB Blade.

Table II. FOD Panels.

●	Material:	PR288/80% AU/20% Kevlar 49 throughout
	Lay-Up	Standard TF39 (0/22/0/-22)
●	Material:	PR288/80% AU/20% S-Glass throughout
	Lay-Up	Standard TF39 (0/22/0/-22)
●	Material:	PR288/80% AU/20% S-Glass Shell PR288/AU Core
	Lay-Up	Standard TF39 (0/22/0/-22) Shell to Consist of Outer 14 Layers [0.18 cm (0.07 in.)]
●	Material:	PR288/80% AU/20% S-Glass Shell PR288/Kevlar 49 Core
	Lay-Up	Standard TF39 (0/22/0/-22) Shell to Consist of Outer 14 Layers [0.18 cm (0.07 in.)]
●	Material:	PR288/AU Alternating with PR288/Kevlar 49 Shell PR288/AU Core
	Lay-Up	Standard TF39 (0/22/0/-22) Shell to Consist of Outer 14 Layers [0.18 cm (0.07 in.)]
●	Material:	PR288/AU
	Lay-Up	Standard TF39 (0/22/0/-22)
●	Material:	PR288/AU Alternating with PR288/Kevlar 49 Shell PR288/Kevlar 49 Core
	Lay-Up	Standard TF39 (0/22/0/-22) Shell to Consist of 7 Plies Each of PR288/AU and PR288/Kevlar 49
●	Material:	PR288/AU and PR288/Kevlar 49
	Lay-Up	Standard TF39 (0/22/0/-22) with 4 Plies Each of Kevlar 49 at ±80° and ± 45° at the Tip

3.4 DOVETAIL DESIGN

The dovetail design used in this program is a circular arc dovetail design. This design consists of a "bell-shaped" pressure face and a circular arc configuration to provide easy transition to the airfoil shapes. Figure 3 depicts the blade dovetail cross section. This configuration has a long pressure face which is supported through the fillet radius and a large cross-sectional area. Tensile tests on two-dimensional specimens and full-scale blades were conducted to verify the expected strength levels. Dimensional accuracy and arrangement of the laminate patterns were developed by utilizing computer lofting techniques. In addition, the distributon of laminates in the dovetail area has been designed to provide an efficient transition of load from the airfoil to the dovetail and minimizing fiber discontinuities.

3.5 LEADING EDGE PROTECTION

Over the past several years of composite blade development effort, there have been several iterations of blade design. During these iterations several changes, both material and design oriented, were made to improve the overall blade design. The basic leading edge protection system, however, was not altered. This system, containing bonded-on wire mesh with heavy nickel plating, was used on all panel specimens and full-size blades tested in this program. This system, shown in Figure 4, provides not only excellent erosion and small object FOD protection, but also assists in providing bird impact resistance by providing a higher density leading edge and an energy absorbing, ductile, load dissipation member between the bird and the low strain capability composite.

3.6 FREQUENCY SUMMARY

Weight and frequency data on the graphite, boron, and hybrid composite blades are summarized along with the titanium blade in Table III. This shows that the two hybrid designs are similar in weight and frequency characteristics to the solid graphite/epoxy blade.

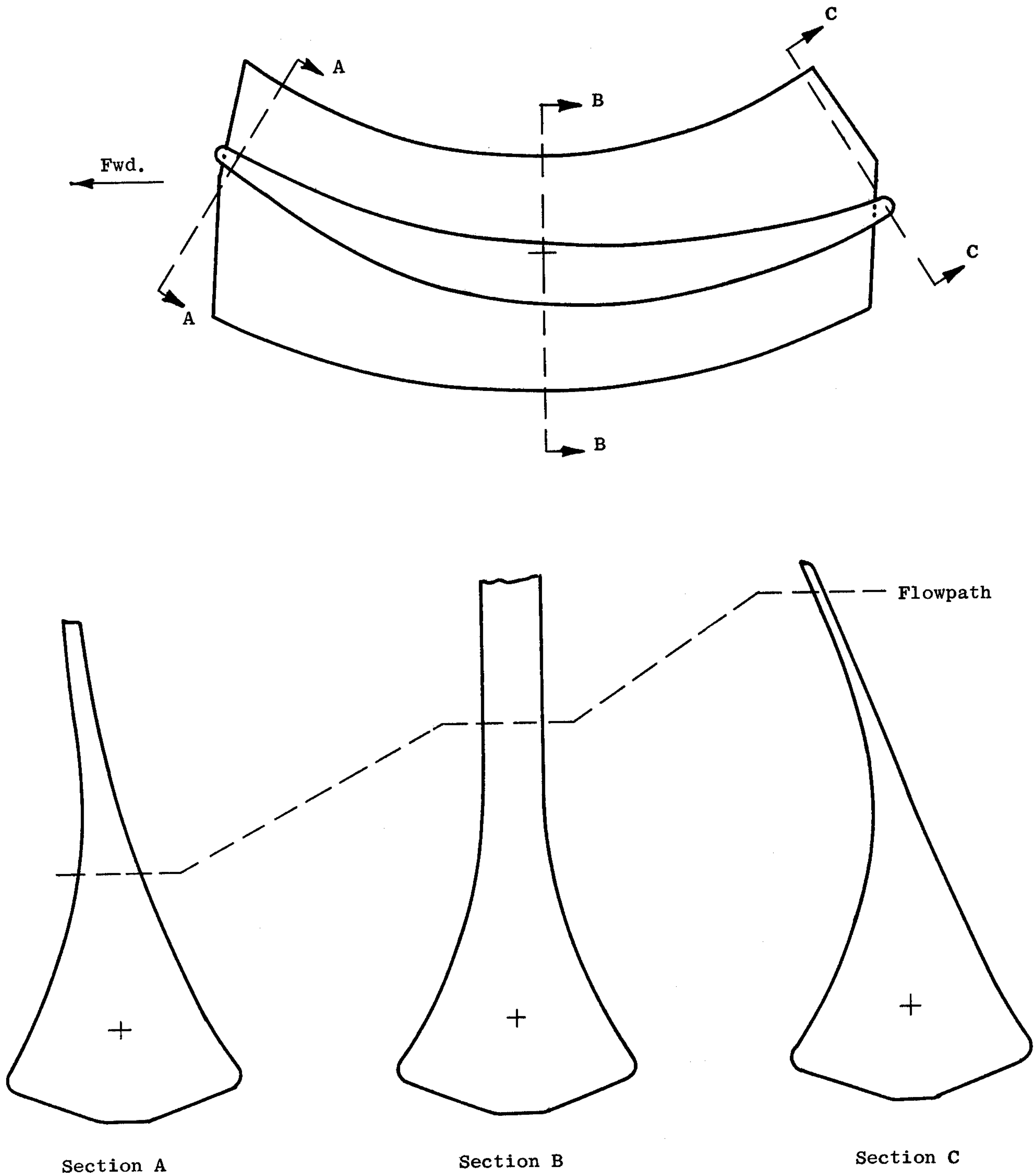


Figure 3. Composite Fan Blade Dovetail.

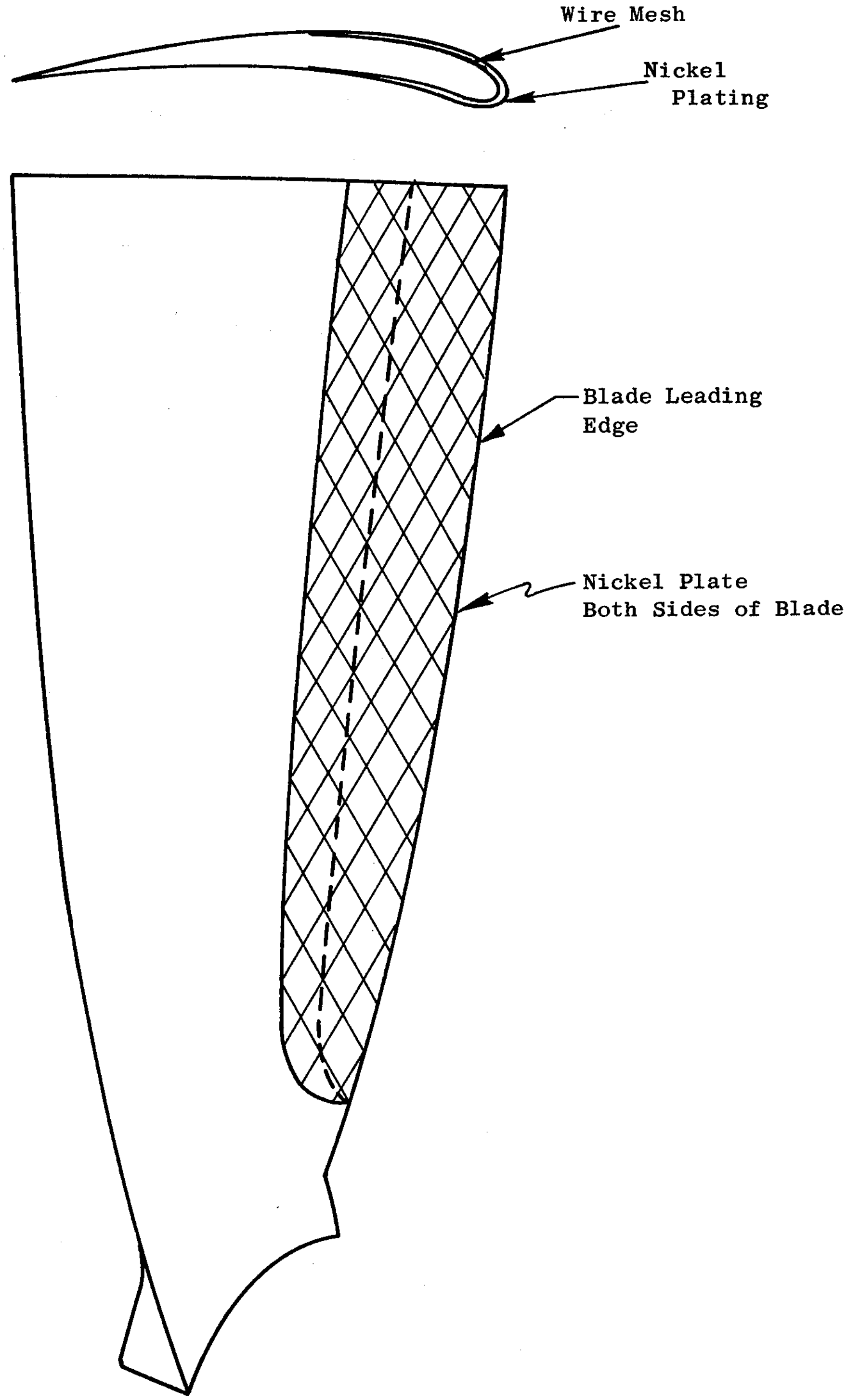


Figure 4. Nickel-Plated Areas on TF39 Polymeric Composite Blades.

Table III. TF39 Composite Blade Frequency Summary.

	As Molded Hz			Finished with FOD Hz			2/Rev Cross Over	R_v *	Final Blade Wt, g
	1F	2F	1T	1F	2F	1T			
Graphite/Epoxy	64	166	334	58	160	296	2100	1.66	1470
Boron/Epoxy	75	193	372	72	192	352	2650	1.4	1826
Hybrid Design 1	---	---	---	58	160	306	2100	1.60	1511
Hybrid Design 2	---	---	---	58	163	300	2100	1.64	1415
Titanium	---	---	---	46	127	272	1700	1.8	3194

* Reduced Velocity Parameter for Flutter Considerations

$R_v = \frac{V}{bw}$

V = Relative Air Velocity
b = Chord/2
} @ 7/8 Span
w = 1T Frequency

4.0 FABRICATION

In order to obtain valid results from this program, it was important to produce verifiably high quality blades so that true comparisons between the various configurations tested could be made. The following paragraphs describe the materials involved and the methods used to assure the required consistency.

4.1 MATERIALS

Six different material systems were used to fabricate a total of 16 blades and 10 FOD panels. The six systems employed were:

1. Narmco 5505/epoxy
2. Type AU/PR 288 epoxy
3. S-glass/PR 288 epoxy
4. Kevlar 49/PR 288 epoxy
5. Type AU/S-glass/PR 288 epoxy
6. Type AU/Kevlar 49/PR 288 epoxy

All of the above materials were procured to General Electric specifications with appropriate modifications for the hybrid combinations.

4.2 RAW MATERIAL CONTROL

An established quality control plan for inspecting incoming epoxy prepregs at General Electric was employed on all materials procured under this program. This plan, which establishes the requirements and methods for selecting satisfactory prepreg material for use in composite blade molding activities, includes the following operations:

1. Checking inventory of incoming material and vendor's certifications for completeness and reported conformance to specification requirements

2. Logging in each lot and roll received

3. Visual inspection of workmanship

4. Sampling of material and verification of compliance with specification requirements, including physical properties, reactivity, and mechanical properties of a molded panel from each combination of fiber and resin batch

5. Handling, storage, and reinspection of out-of-date materials

6. Disposition of materials which fail to meet specification requirements

Specific material properties which were measured and compared to vendor reported data on each prepreg lot are given below:

Prepreg Data	Laminate Data
Fiber(s), g/ft^2	Flexure str. at RT, 394° K (250° F)
Resin, g/ft^2	Flexure mod. at RT, 394° K (250° F)
Solvent content, % wt	Shear str. at RT, 394° K (250° F)
Gel time,minutes at 383° K(230° F)	Fiber content, % vol
Flow, % wt	Resin content, % vol
Visual discrepancies	Voids, % vol
	Density, g/cc

Tables IV and V list the blades and FOD specimens fabricated under this program in addition to the respective material lot number. Detailed quality control information on each lot is presented in the Appendix.

4.3 BLADE AND PANEL MOLDING

The manufacture of all composite blades and FOD specimens made under this program was performed in a specially designed molding press, shown in Figure 5. This 2670 MN (300-ton) capacity press embodied many novel features including:

1. Bottom platen indexes out for preform loading and blade extraction

2. Top platen hinges down for efficient cleaning and application of release agents

3. Variable fast approach speed

4. Variable intermediate slow closing speed

5. Variable dwell cycle

6. Continuously variable slow closing speed down to 0.013 cm (0.005 in.) per minute

7. Timed curing cycle

8. Water cooling and air purging of the platens

All of these unique features built into the press provided an improved, repeatable process control, a semiproductionized method for better product quality, and, in addition, reduced part costs by less inherent scrap rates.

The basic sequence of operations involved in molding the composite blades and FOD specimens is briefly outlined below:

1. The fully assembled mold tool was heated to the prescribed temperature in the press such that all sections of the die were maintained at a uniform temperature.

2. The press was opened, the bottom platen was traversed out of the press, and the top platen was swung down into the vertical position.

3. The mold tool was hydraulically actuated into the "mold position".

4. Release agent was applied to the mold cavity surfaces and any excess removed.

5. The assembled blade preform was loaded into the heated mold cavity.

6. The top platen was hinged back and locked into the horizontal molding position, and the bottom platen traversed into the press. Hydraulically operated dowel pins engaged the platen into true alignment.

7. The press closed at a programmed fast approach speed until the top and bottom portions of the mold engaged.

8. An intermediate closing speed was selected automatically for preliminary debulking of the blade preform until the next limit switch stopped the downward movement and started the dwell cycle timer.

9. The dwell cycle was held for the required time to enable the preform to heat up uniformly and also to advance the resin to the desired viscosity.

10. At the end of the dwell cycle, the dies continued to close at a preselected, slow rate. The movement continued until the die was closed and the prescribed molding load/pressure attained. Figure 6 shows a typical rate of closure and load application curve for molding a PR 288/Type AU composite blade with a gel time of 60 ± 5 minutes at the constant molding temperature 383° K (230° F).

11. At the completion of the cure cycle and prior to opening the die, holes were drilled into the dovetail through hardened steel bushings located in the end of the die. These holes were drilled into the surplus material in the root block and

Table IV. Polymeric Composite Blade Summary.

Blade S/N	Material(s)	Lot No.
NB1	Boron/Epoxy	425
NB2	Boron/Epoxy	426
NB3	Boron/Epoxy	426
NB4	Boron/Epoxy	426
NB5	Boron/Epoxy	427
NG1	Graphite/Epoxy	458
NG2	Graphite/Epoxy	458
NG3	Graphite/Epoxy	467
NG4	Graphite/Epoxy	467
NG5	Graphite/Epoxy	467
H/E4	Graphite/GL/Epoxy	536
H/E5	Graphite/GL/Epoxy	561
H/E6	Graphite/GL/Epoxy	561
H/E1	Graphite/Epoxy	483
	Kevlar 49/Epoxy	532
	S-glass/Epoxy	46
H/E2	Same as H/E1	Same as H/E1
H/E3	Same as H/E1	Same as H/E1

Table V. Summary of Polymeric Composite FOD Panel Specimens.

FOD S/N	Material	Lot No.
1	Graphite/Kevlar/Epoxy	535
2	Graphite/Glass/Epoxy	536
3	Graphite/Glass/Epoxy	536
	Graphite/Epoxy	483
4	Graphite/Glass/Epoxy	536
	Kevlar/Epoxy	532
5	Graphite/Epoxy	483
	Kevlar/Epoxy	532
6	Graphite/Epoxy	483
7	Graphite/Epoxy	483
	Kevlar 49/Epoxy	532
8	Graphite/Epoxy	483
	Kevlar/Epoxy	532

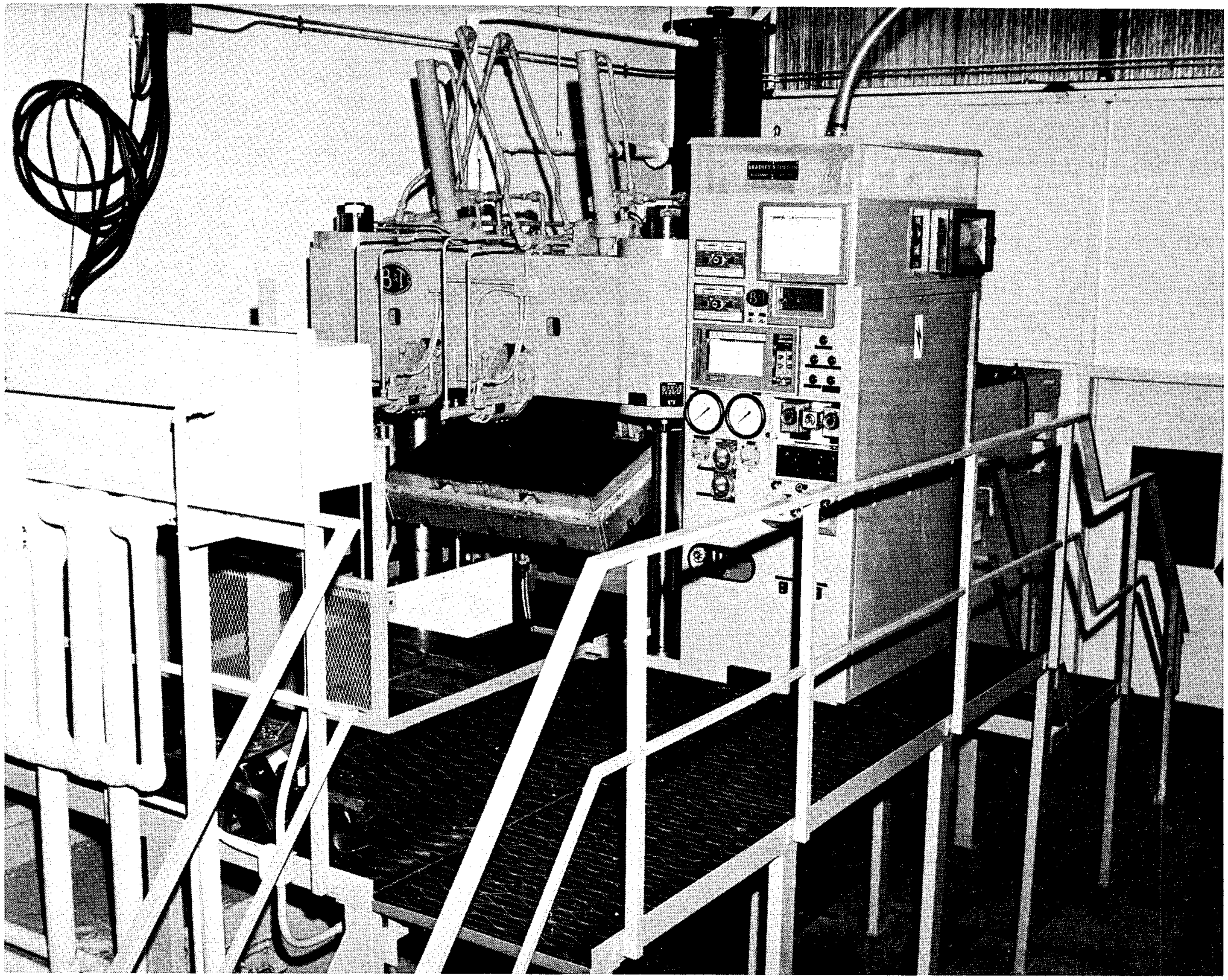


Figure 5. Bradley and Turton 300-Ton Molding Press.

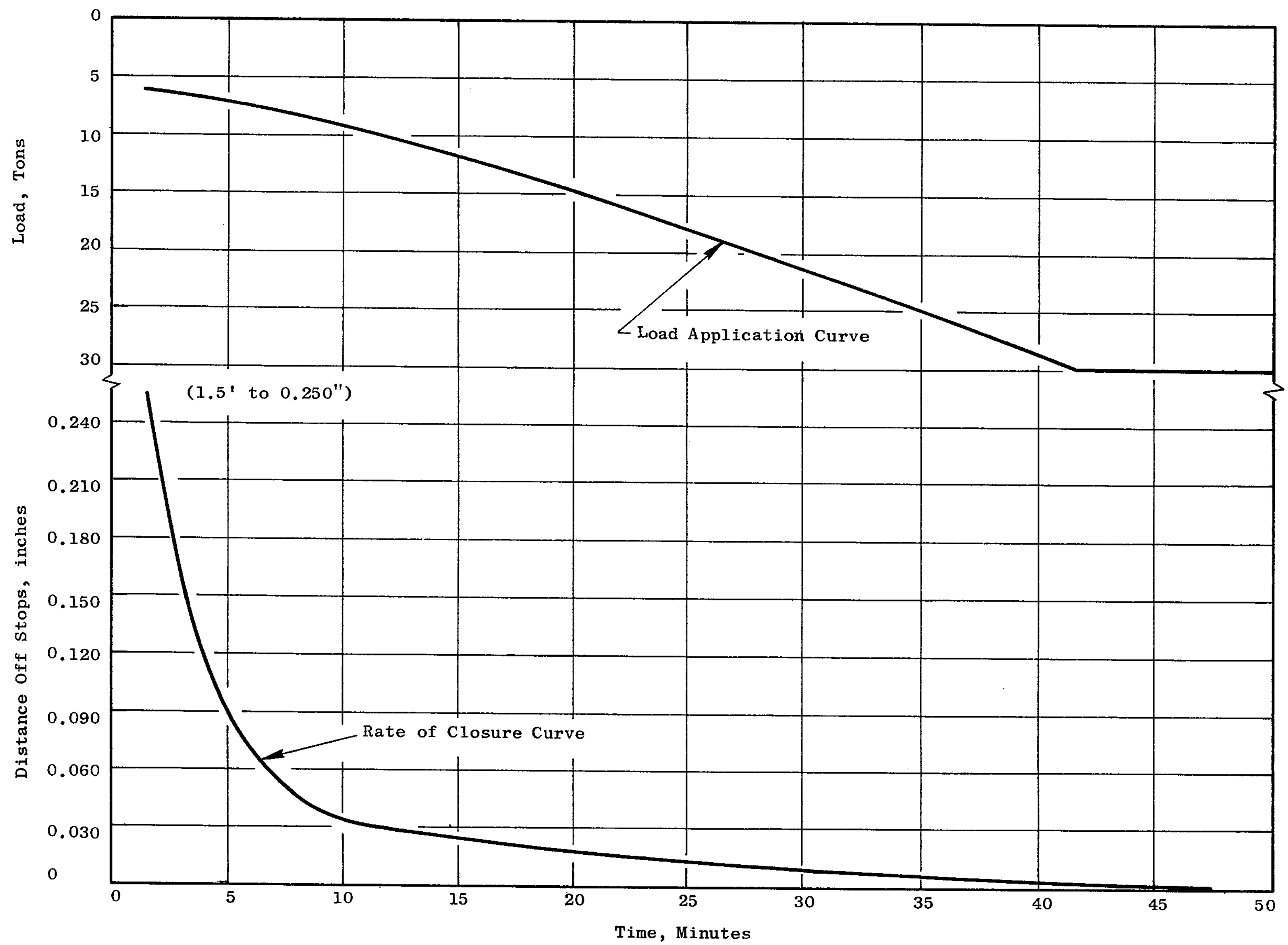


Figure 6. Molding Procedure for TF39 PR 288/Type AU Blade with Gel Time at 124° K (230° F).

do not protrude into the finished machined dovetail profile. The holes were used as positive locations for fixturing the blade for subsequent machining operations.

12. The press automatically opened and returned to the starting position.

13. The mold stops were moved into the ejection position and the switch operated to hydraulically actuate the mold for blade ejection.

14. The blade molding was hydraulically ejected from the die and rapidly transferred into the postcure oven, thus preventing thermal contraction stresses from being set up in the part. The blade was allowed to hang freely in the postcure oven for the predetermined process time necessary to achieve full material properties.

Each blade and FOD panel was layed up in halves and weighed prior to molding. The boron/epoxy blade specimens were all molded at 394 K (250° F) until gelation occurred followed by one hour at 450° K (350° F) in the mold tool. No additional postcure was required. The graphite/epoxy and hybrid/epoxy blades and FOD specimens were molded at 383° K (230° F) followed by oven postcure of four hours at 408° K (275° F). Molding pressure on FOD panels was maintained at approximately 133 MN (15 tons). After cooling and deflashing, the specimens were weighed and density measurements were taken. These data are summarized in Tables VI through IX for boron/epoxy blades, graphite/epoxy blades, FOD specimens, and hybrid/epoxy blades, respectively.

In the cases of boron/epoxy and graphite/epoxy blades, go-by test panels were fabricated concurrently to verify mechanical properties. These data were also shown in Tables VI and VII.

4.4 MOLDING INSPECTION AND FINISHING OPERATIONS

After removing the specimens from the postcure oven and trimming the resin flash, the following inspection operations were carried out:

1. Measurement and recording of molded weight, volume and density

2. Recording of surface defects in sketch form and by photographs taken of both sides of the blade

3. Dimensional inspection and recording of the root and tip maximum dimensions

4. Measurement of blade twist, lean and stagger angles

Table VI. Processing Data on NASA Boron/Epoxy Blade Materials.

Blade S/N No. Boron/Epoxy 5505	NB-1	NB-2	NB-3	NB-4	NB-5
<u>Prepreg</u>					
Lot No.	425	426	426	426	427
GEL Time, Blade Sample, minutes @ 394° K (250° F)	19	20	16	30	17
<u>Molded Blade Data</u>					
Molded Weight, gms.	1879.4	1863.0	1886.2	1916.6	1908.9
Density, g/cc	1.932	1.922	1.947	1.964	1.954
<u>Material Properties</u>					
(0° Orientation)					
Flex. Str./Mod. R.T.; $N/m^2 x10^6/x10^9$ (Flex. Str./Mod. R.T.; ksi/msi)	1723/186 (250/27)	1930/200 (280/29)	1834/207 (266/30)	1517/186 (220/27)	N.T.
Flex. Str./Mod. @ 394° K; $N/m^2 x10^6/x10^9$ (Flex. Str./Mod. @ 250° F; ksi/msi)	1558/193 (226/28)	1593/172 (231/24)	1648/172 (239/25)	1420/172 (206/25)	N.T.
Short Beam Shear Str. @ R.T./394° K, $N/m^2 x10^6$ (Short Beam Shear Str. @ R.T./250° F, ksi)	99.3/77.9 (14.4/11.3)	108.7/45.5 (14.9/6.6)	108.9/47.6 (15.8/6.9)	98.6/46.9 (14.3/6.8)	N.T.
Composite Fiber Volume, % Void Content, %	55.2 0.9	57.4 0.7	55.6 1.1	54.7 1.5	N.T.

Table VII. Processing Data on NASA Graphite/Epoxy Blade Material.

Blade S/N	NG-1	NG-2	NG-3	NG-4	NG-5
Prepreg					
Lot No.	458	458	467	467	467
GEL Time, Blade Sample, minutes @ 383° K (230° F)	70	59	60	58	61
Molded Blade Data					
Molded Weight, gms.	1513.0	1533.4	1528.9	1526.5	1505.0
Density, g/cc	1.569	1.572	1.576	1.580	1.560
Material Properties Sample					
(0° Orientation)					
Flex. Str./Mod. R.T.; $N/m^2 x10^6/x10^9$	1944/119	2027/118	1958/119	1951/120	2020/116
(Flex. Str./Mod. R.T.; ksi/msi)	(282/17.2)	(294/17.1)	(284/17.3)	(283/17.4)	(293/16.8)
Flex. Str./Mod @ 394° K; $N/m^2 x10^6/x10^9$	1317/116	1427/112	1475/115	1296/116	1296/114
(Flex. Str./Mod @ 250° F; ksi/msi)	(191/16.8)	(207/16.3)	(214/16.7)	(188/16.8)	(188/16.5)
Short Beam Shear Str. @ R.T./394° K, $N/m^2 x10^6$	81.4/49.6	82.0/47.6	93.0/59.3	77.9/52.4	73.1/49.6
(Short Beam Shear Str. @ R.T./250° F, ksi)	(11.8/7.2)	(11.9/6.9)	(13.5/8.6)	(11.3/7.6)	(10.6/7.2)
Composite Fiber Volume, %	58.4	58.8	60.9	59.4	56.4
Void Content, %	0.3	0.0	0.0	0.6	1.5

Table VIII. Processing Data on NASA FOD Panels.

	1	2	3	4	5	6*	7	8
Concave Half Wt, g	319.0	349.0	341.0	329.0	314.0	---	304.0	319.0
Convex Half Wt, g	322.5	347.0	345.0	326.0	312.0	---	301.0	316.0
Total Preform Wt, g	641.5	696.0	686.0	655.0	626.0	---	605.0	635.0
Molding Pressure, tons	15	15	15	15	15	---	15	15
Final Molded Wt, g	603.8	656.0	648.4	615.8	593.8	---	569.7	575.6
% Flow	5.9	5.7	5.5	6.0	5.1	---	5.8	9.4
Density, g/cm^3	1.54	1.68	1.64	1.55	1.50	1.58	1.44	1.55

* Tip Half of Blade S/N H60

Table IX. Processing Data on NASA Hybrid/Epoxy Blade Materials.

Blade S/N	H/E-1	H/E-2	H/E-3	H/E-4	H/E-5	H/E-6
Prepreg						
Lot No.	483, 532	483,532	483,532	536	561	561
GEL Time, Blade Sample, minutes @ 383° K (230° F)	N.T.	N.T.	N.T.	N.T.	62	59
Molded Blade Data						
Molded Weight, gms.	1540.3	1538.5	1533.9	1630.6	1644.0	1644.0
Density, g/cc	1.585	1.585	1.586	1.684	1.658	1.656
Material Properties Sample (0° Orientation)						
Flex. Str./Mod. R.T.; $N/m^2 x10^6/x10^9$ (Flex. Str./Mod. R.T.; ksi/msi)	N.T.	N.T.	N.T.	N.T.	1800/115 (261/16.7)	1765/108 (256/15.6)
Flex. Str./Mod. @ 394° K; $N/m^2 x10^6/x10^9$ (Flex. Str./Mod. @ 250° F; ksi/msi)	N.T.	N.T.	N.T.	N.T.	1386/104 (201/15.1)	1393/104 (202/15.1)
Short Beam Shear Str. @ R.T./394° K, $N/m^2 x10^6$ (Short Beam Shear Str. @ R.T./250° F, ksi)	N.T.	N.T.	N.T.	N.T.	73.8/47.6 (10.7/6.9)	73.1/49.6 (10.6/7.2)
Composite Fiber Volume, % Void Content, %	N.T.	N.T.	N.T.	N.T.	59.7 0.0	59.2 0.2

Although the blade form was molded well within the desired envelope tolerances, it was extremely difficult to mold the dovetail profile to the accuracy required. As a result, dovetail profiles were machined to size. Foreign object protection systems were also applied to the blade and FOD specimens after molding. The principal finishing operations performed on the blade specimens under this program are listed below:

1. Dovetail machining
2. Application of wire mesh
3. Application of nickel plating
4. Trimming blade to length and tip forming

4.5 NONDESTRUCTIVE EVALUATION

All blade specimens were subjected to through-transmission ultrasonic C-scan (TTUCS) inspection before and after impact, in addition to holographic and root dye penetrant inspection. Likewise, TTUCS inspection was performed on the FOD panels both prior to and after impact testing.

4.5.1 Through-Transmission Ultrasonic C-Scan

The test technique, shown in Figure 7, is basically a measurement of sound attenuation due to both absorption and scattering. The through-transmission approach (as opposed to pure pulse-echo or reflection-plate pulse-echo/transmission approaches) provides for a more efficient energy transfer with a minimal influence of test equipment configuration or material/component shape. The scanner contour follows the airfoil with a master/slave servomechanism. Even so, the attenuation values must be referenced to a specific ply stackup and process sequence employed in the manufacture of each component.

High-resolution scanning (75 lines per inch for 15,000 units of data per square inch), combined with 10 shades-of-gray (5% to 95% on the oscilloscope) recording on dry fascimile paper, provides an "attenugraph" image which is read much in the same manner as a radiograph. As an example of the type of information that can be obtained using this inspection technique, Figures 8 and 9 show C-scans of blade S/N NB2 and NG2, respectively, before and after test. Blade S/N NB2, after impact with a 170 g (6 oz) simulated bird, was characterized by leading edge separation plus delamination near the root as shown in Figure 8. Figure 9 shows no major damage to the graphite/epoxy blade after impact with gravel and ice balls. Details of this type of evaluation for all of the blades in the program are presented in Section 5.

4.5.2 Laser Holographic Interferometry

The laser holographic facility, Figure 10, was also used to inspect the blades molded during this program. It is highly versatile in that the optical devices may be positioned to accommodate a variety of object types

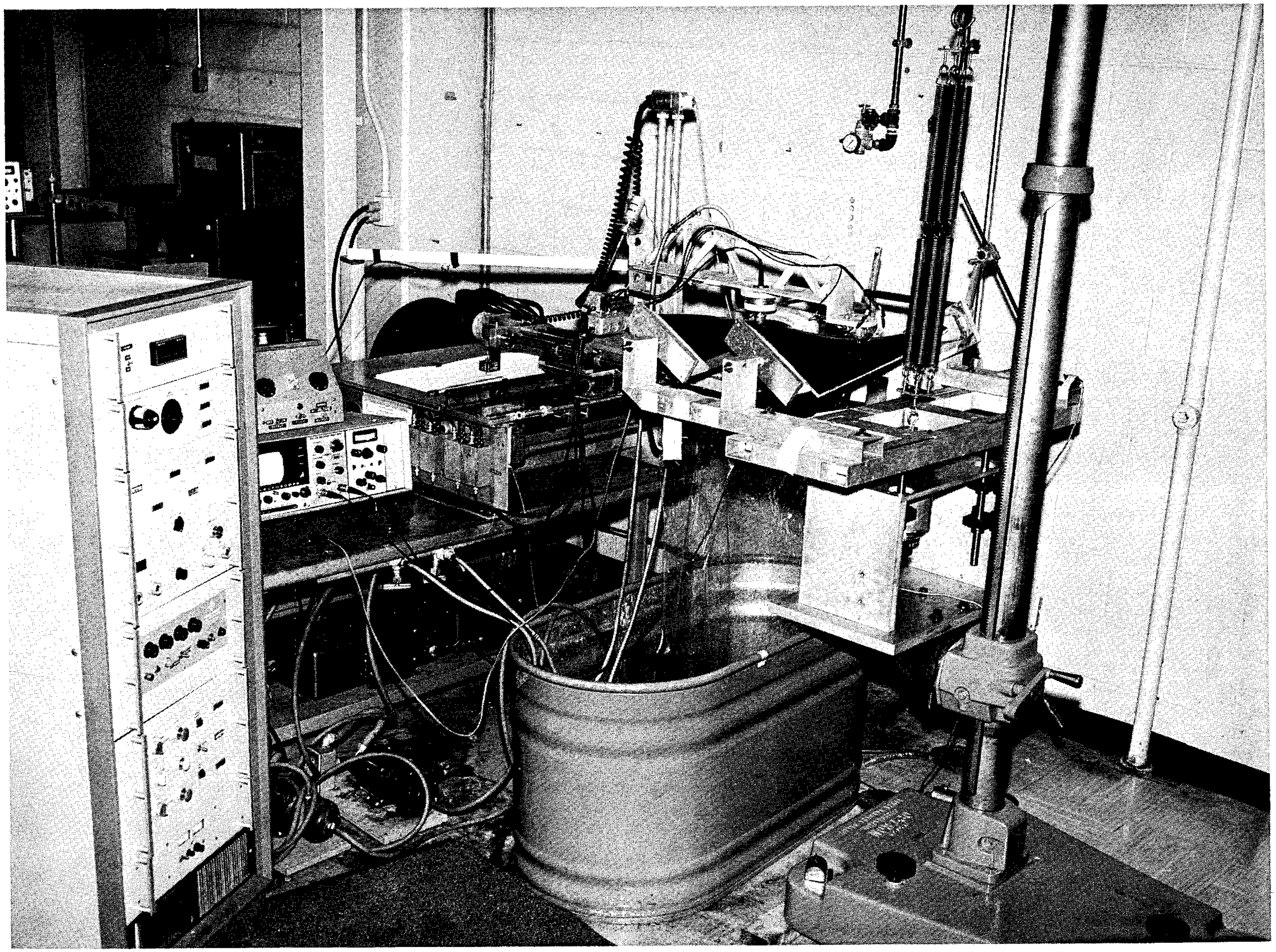
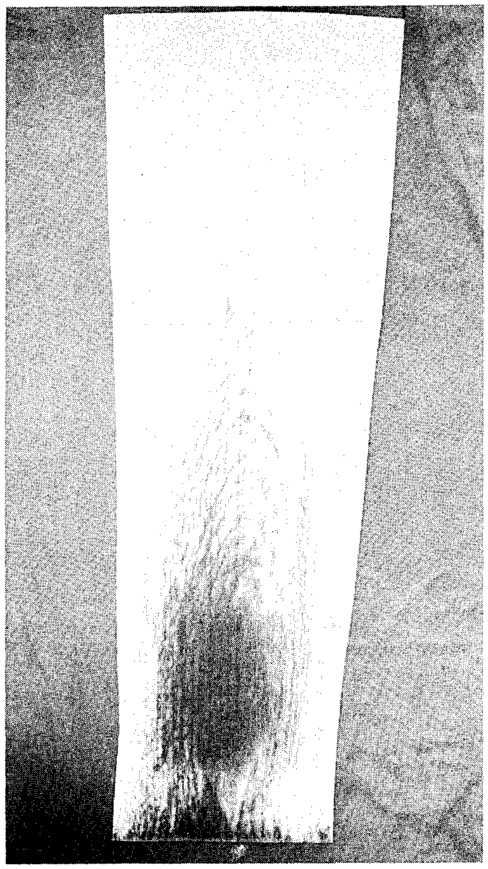
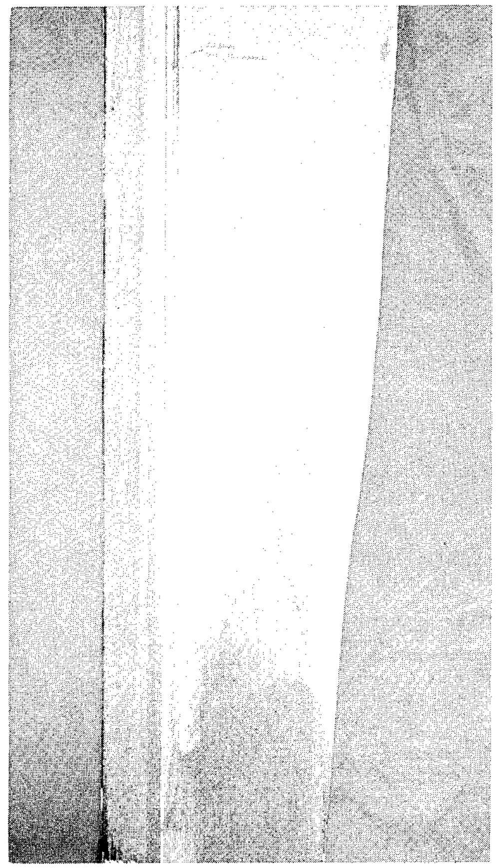


Figure 7. Test Technique for Thru Transmission Ultrasonic C Scan of Composite Blades.

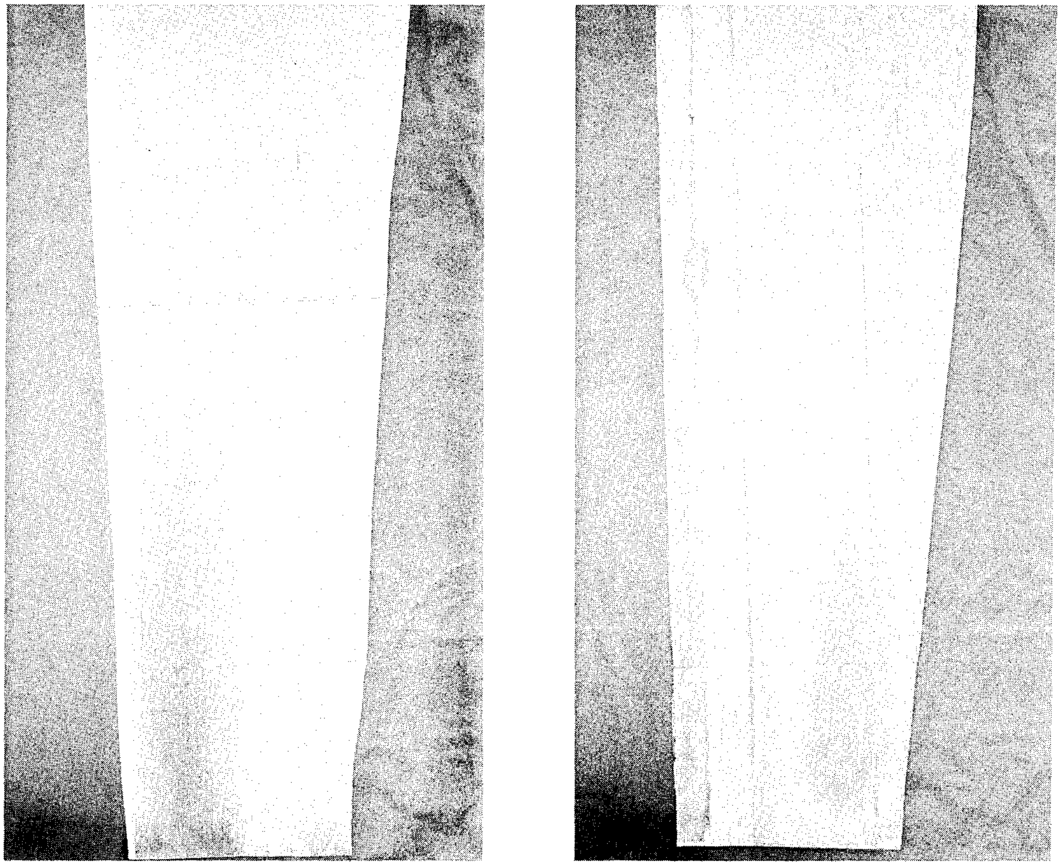


Before Impact



After Impact

Figure 8. TTUCS of Boron/Epoxy Blade S/N NB2.



Before Impact After Impact

Figure 9. TTUCS of Graphite/Epoxy Blade S/N NG2.

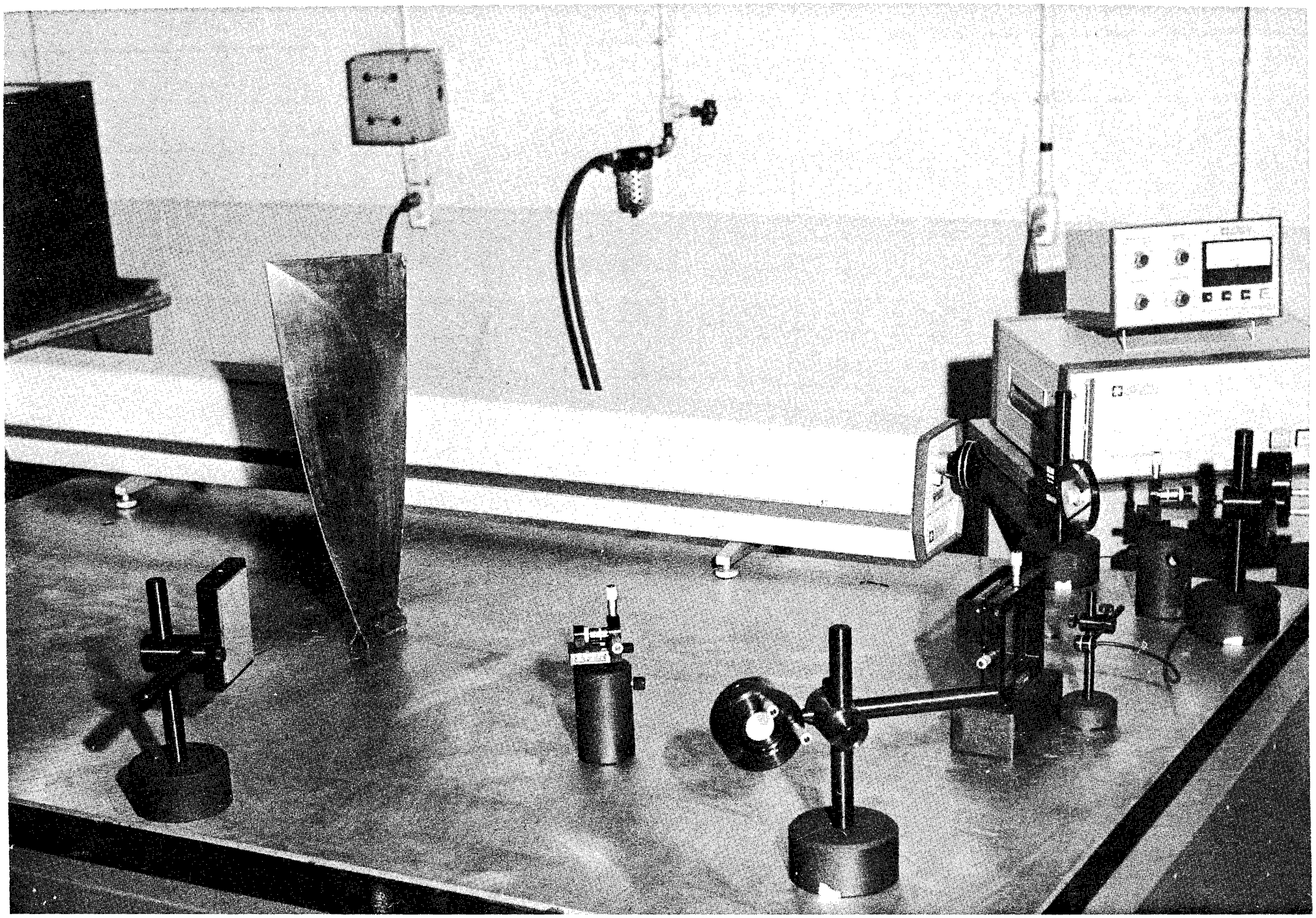


Figure 10. Laser Holographic Facility.

and fields of illumination on panels, blades, and other contoured components. Interferometry relies on secure blade fixturing and consistently reproducible stressing for the second exposure of a double-exposure hologram. Typical interferograms are presented in Figure 11.

4.5.3 Dye Penetrant Inspection

Dye penetrant inspection of the dovetail area was performed on each of the blades. This test was used to detect surface-connected root delaminations in the machined dovetail. The dye penetrant check also gives qualitative indications of root zone porosity. Figure 12 shows a typical graphite/epoxy blade undergoing root inspection.

4.5.4 Acceptance

The final acceptance of the blades was based upon reviewing the visual inspection of the blades and their associated manufacturing and NDE data in conjunction with Engineering. Typical individual record samples of the acceptance of a blade by the Materials Review Board are shown in Figure 13.

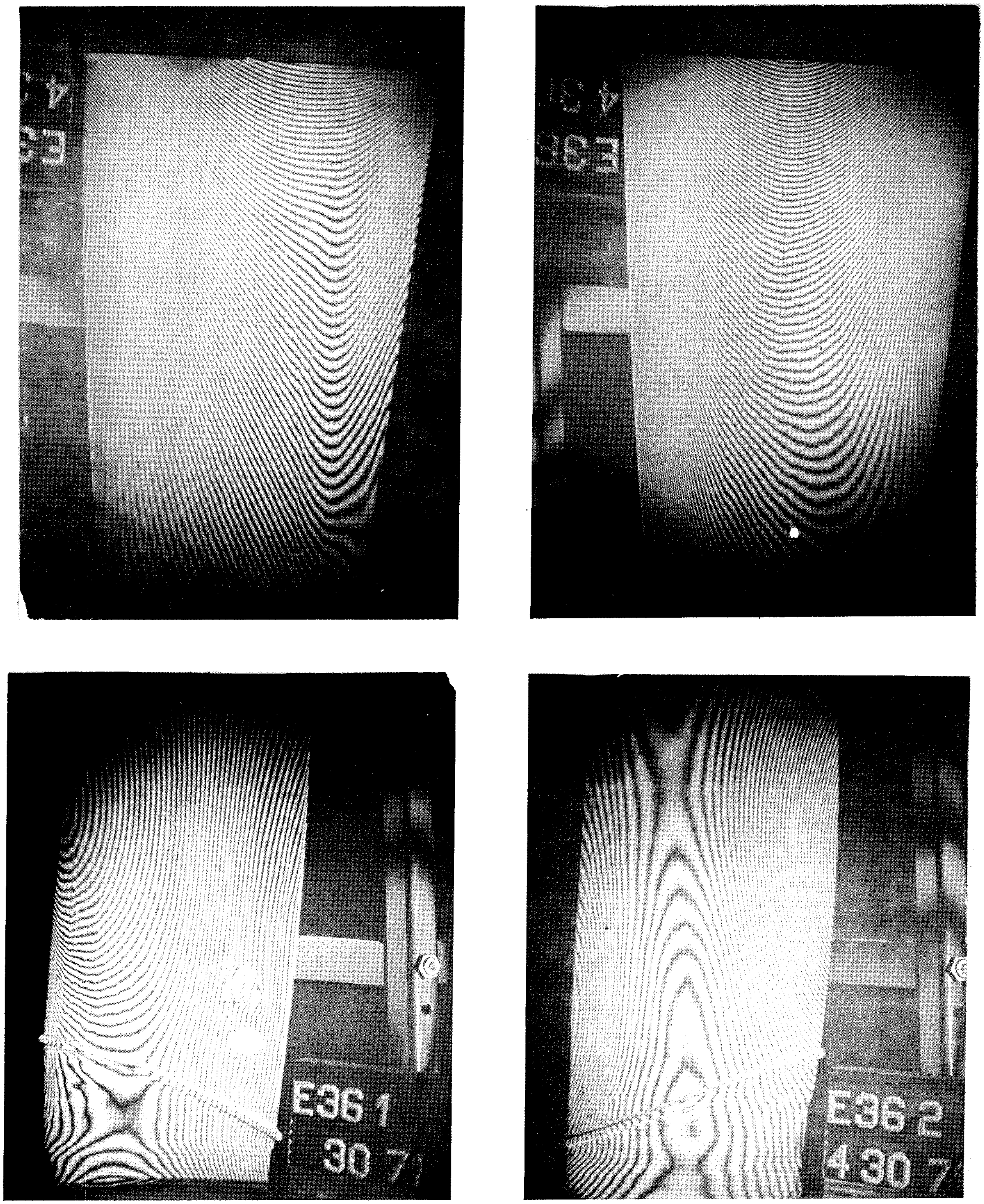
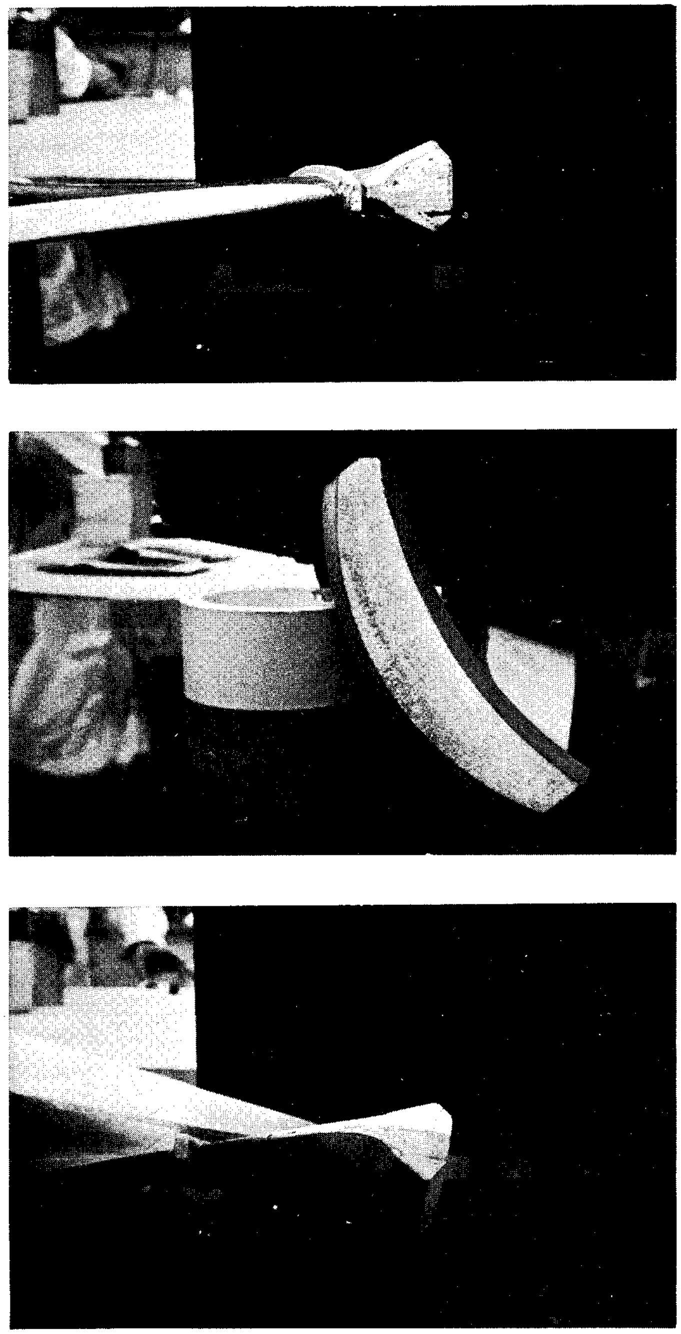


Figure 11. Holographic NDT of Graphite/Epoxy Blade. Upper and Lower Portions of Each Side are Inspected Separately. Leading Edge Disbonds are Prevalent. Note Trailing Edge Discrepancy.



LEADING EDGE

BOTTOM

TRAILING EDGE

Figure 12. Dye Penetrant Inspection of Graphite/Epoxy Blade Root.

E - ENGINEERING
M - M&PTL
Q - QUALITY ASSURANCE

BLADE SERIAL NUMBER ________
REVIEW DATE ________ (initial)
FINAL ________

ACCEPTANCE CRITERIA REVIEW SHEET

ITEM	CRITERIA	REVIEW BOARD DIAGNOSIS ACCEPT			PENDING			REJECT			REMARKS
		E	M	Q	E	M	Q	E	M	Q	
1.	Destructive Analysis of Batch Blade S/N ________ Approval										
2.	Incoming Material Q.C. Results										
	• Mechanical Properties										
	• Physical Properties										
3.	Blade Specimen Results										
	• Mechanical Properties										
	• Physical Properties										
4.	Visual Inspection of Blade										
	• Wrinkles										
	• Fiber Wash										
	• Surface Fiber Gaps										
	• Compaction Areas										
	• Resin Rich Areas										
	• Voids										
	• Plating										
	• Polyurethane										
	•										
	•										

Figure 13. Acceptance Criteria Review Sheet.

E - ENGINEERING
M - M&PTL
Q - QUALITY ASSURANCE

BLADE SERIAL NUMBER ______
REVIEW DATE ______
FINAL ______

ACCEPTANCE CRITERIA REVIEW SHEET

ITEM	CRITERIA	REVIEW BOARD DIAGNOSIS									REMARKS
		ACCEPT			PENDING			REJECT			
		E	M	Q	E	M	Q	E	M	Q	
5.	Dimensional Inspection										
	● Aerodynamic Contours										
	● Twist										
	● Loan										
	● Root										
	● Wear Band										
	● Plating										
	● Polyurethane										
6.	Nondestructive Evaluation										
	● Holographic										
	• Blade Form										
	• Root Area										
	● Ultrasonic										
	• Blade Form										
	• Root Area										
	● Dye Penetrant										
	• Root Area										
	● Frequency										
	• First Flex										
	• Second Flex										
	• First Torsion										

Figure 13. Acceptance Criteria Review Sheet (Continued).

SUMMARY:

REVIEW BOARD ANALYSIS

Initial Analysis

(Prior to plating and polyurethane)

Initial Analysis Grading ________________

Selected for Test (Type) ________________

Review Board Signatures:

Engineering ________________

M&PTL ________________

Quality Assurance ________________

Final Analysis

(Prior to dispatch)

Final Grading ________________

Allocated to Test (Type) ________________

Review Board Signatures:

Engineering ________________

M&PTL ________________

Quality Assurance ________________

Figure 13. Acceptance Criteria Review Sheet (Concluded).

5.0 TESTING

The test portion of this program was designed to evaluate composite fan blades subjected to various types of FOD which could be expected in STOL engine operation. The specific test plan used for the program is shown in Section 5.1 followed by a brief discussion of the test equipment and procedures used and a detailed presentation of the test results.

5.1 TEST PLAN

The nominal conditions under which the composite blades and panels were tested are given as follows:

1. Boron/Epoxy and Graphite/Epoxy Blades

   - Whirligig Impact Testing
     Blade Tip Speed - 244 m/sec (800 ft/sec)
     Impact Location - 10.16 cm (4 inches) from tip
     Incidence Angle - .384 radian (22°)
     Simulated Bird Slice Weight - 170 g (6 oz) and 340 g (12 oz)
     Real Bird Slice Weight - 312 g (11 oz)
     Ice Ball Size and Weight - 3 ea - 5 cm dia, 210 g (2 in. dia, 7.4 oz)
     Gravel Size and Weight - 50 pcs - .38 to .88 cm, (0.15 to 0.38 in.), 20 g (0.7 oz)

   - Inertial Head Testing
     Axial Load - 24.5 and 30.5 KN (5500 and 6850 lbs)
     Impact Location - 10.16 cm (4 in.) from tip
     Incidence Angle .384 radian (22°)
     Simulated Bird Weight - 595 g (21 oz) half bite
     Projectile Velocity - 244 m/sec (800 ft/sec)

2. Hybrid/Epoxy Blades and Panels

   - Static Panel Screening Tests
     Projectile Velocity - 244 m/sec (800 ft/sec)
     Incidence Angle - .384 radian (22°)
     Impact Location - 10.16 cm (4 in.) from tip
     Simulated Bird Weight - 85 g and 227 g (3 oz and 8 oz) - Half Bite

   - Whirligig Impact Testing
     Blade Tip Speed - 244 m/sec (800 ft/sec)
     Impact Location - 10.16 cm (4 in.) from tip
     Incidence Angle - .384 radian (22°)
     Simulated Bird Slice Weight - 227 g and 680 g (8 oz and 24 oz)
     Real Bird Slice Weight - 567 g (20 oz)

All of the graphite/epoxy and boron/epoxy blades were instrumented with strain gages in order to determine stress distributions. High speed movies were taken of all blade and panel tests to assist in determination of deflections and damage sequence.

5.2 TEST EQUIPMENT AND PROCEDURES

5.2.1 Impact Test Facilities

The impact testing was conducted in facilities which enabled testing of all specimens in a controlled and reproducible manner so as to provide realistic comparative measurements of impact capability. These facilities, described below, include the static impact test stand, the rotating whirligig test bed rig, and the inertial head facility for precise measurement of impact energy transfer.

Static Impact Test Facility

The impact testing of hybrid composite laminate panels was conducted in a test cell specifically designed for impact testing of specimens with high velocity, varying mass projectiles.

The specimen test enclosure was a rectangular shape measuring 1.83 m (6 ft) x 1.22 m (4 ft) x 1.22 m (4 ft), as shown in Figure 14. The bed of the enclosure is a slotted table which enables the mounting of a specimen holding fixture so as to position the specimen at any angle relative to the ballistic gun.

The enclosure has a top and side of plexiglass which contains impact debris and allows filming of the event with high speed motion picture equipment.

The ends contain openings to allow the projectile to enter and exit the enclosure and provide a means to recover the spent projectile for examination.

The impacting masses were projected by a ballistic impact gun. The gun barrel diameter varied with the size of the projectile being used. For this testing a 5 cm (2 in.) ID x 7 m (23 ft) long barrel was used for the 35 g (3 oz) projectiles and an 8.9 cm (3.5 in.) ID x 7 m (23 ft) long barrel was used for the 227 g (8 oz) projectiles.

The barrels are made of honed and polished stainless steel pipe with vertical supports mounted to the cell floor. The barrel terminated 45.7 cm (18 in.) from the specimen.

A preliminary checkout using high speed movies showed that when firing a 227 g (8 oz) RTV simulated bird coated with Vaseline at 258 m/sec (845 ft/sec), the shape of the bird at the gun exit was slightly egg shaped, the total recoil was 6.4 cm (2.5 in.) and the barrel did not move horizontally or vertically.

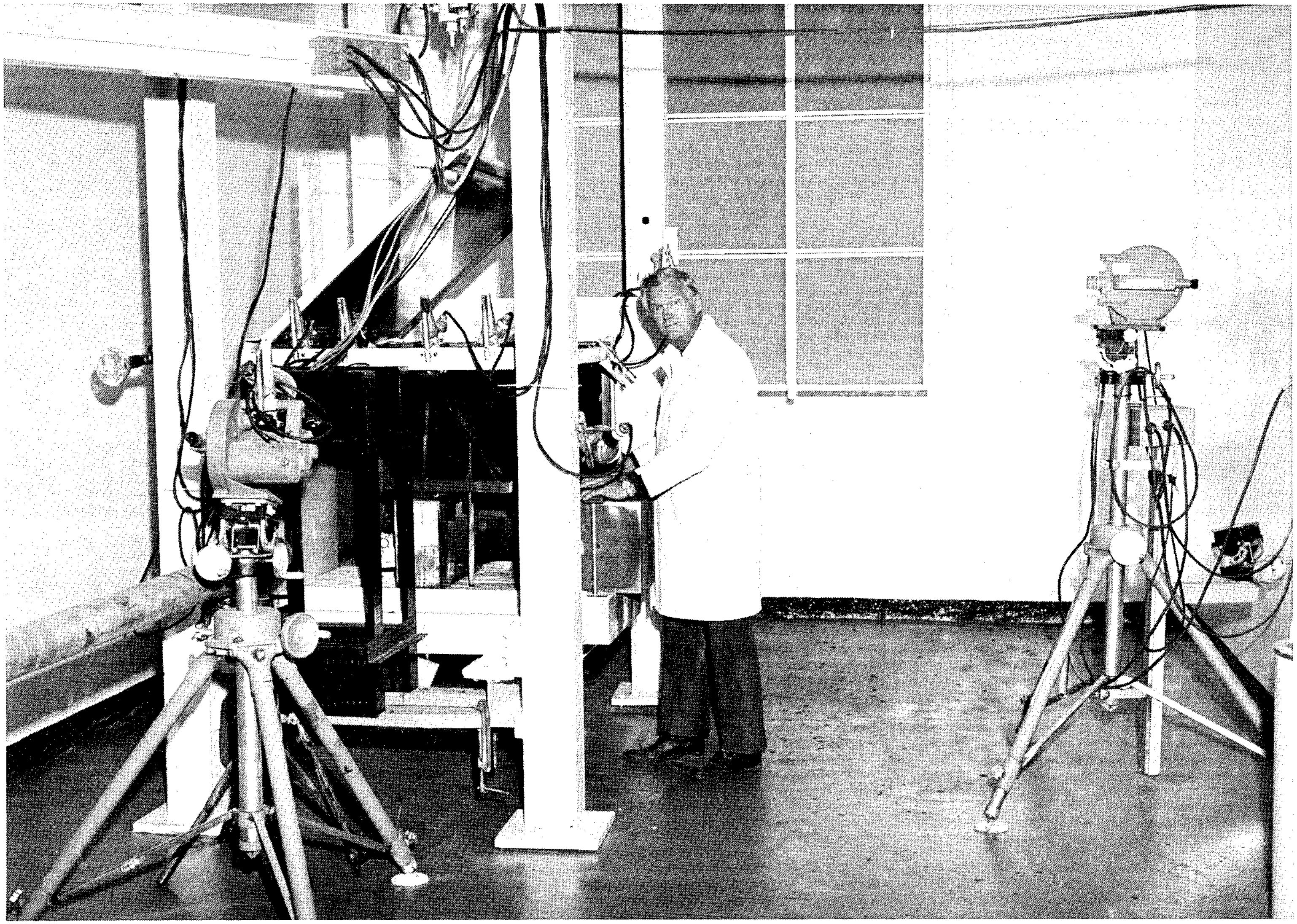


Figure 14. Static Test Facility Specimen Enclosure.

Helium gas is used to propel the bird at the desired velocity. The gas pressurization dolly is shown in Figure 15. Helium is used to prevent condensation at the barrel exit which would fog the movies.

Each impact test was monitored by high speed motion picture equipment and an instant velocity measuring device. Calibration shots were made to determine the correct pressure setting of the gas gun to achieve desired velocity and to check out the camera and facility operating conditions.

Instant velocity readout was accomplished by using a ballistic screen and velocity computing chronograph.

This device used the interruption of two light beams a given distance apart to measure the velocity of the projectile as it passed.

The velocity-computing chronograph was used with the ballistic transducers set 30.5 cm (12 in.) apart. Immediately after the round was fired, the velocity of that round was digitally calculated and instantaneously displayed on the front panel indicator tubes, Figure 16.

Two high speed cameras were used to record the impact event. One of the cameras was used to trigger the quick acting valve. When this camera reached the desired film speed, a relay closed allowing the signal to activate the valve.

One camera from the side filmed the convex side of the test panel, the other filmed the top edge of the tip. A grid scale was placed on the glass top of the enclosure so tip deflection could be accurately measured.

The camera equipment speed setting was:

- Side Camera - speed setting - 8000 frames/sec
- Top Camera - speed setting - 8000 frames/sec

Whirligig Test Facility

This facility consists of a 746,000 watt (1000 horsepower) drive motor, a variable speed output magnetic clutch, a speed increasing gearbox, and a horizontal drive spindle shaft to the rotor. The test setup is basically a standard TF39 fan package.

The structure consists of a TF39 fan frame with the No. 1 and No. 2 bearings and sump systems, the stage 2 stator case, and the slave stage 1 shrouding. The entire vehicle is soft mounted. Only one blade was installed and tested at a time.

The stage 1 disc was provided with two opposing slots, one for the composite dovetail and one for the dummy metal blade for counterbalance. The slots were machined in the closed position relative to their standard setting angle to provide an impact incidence angle consistent with the desired test

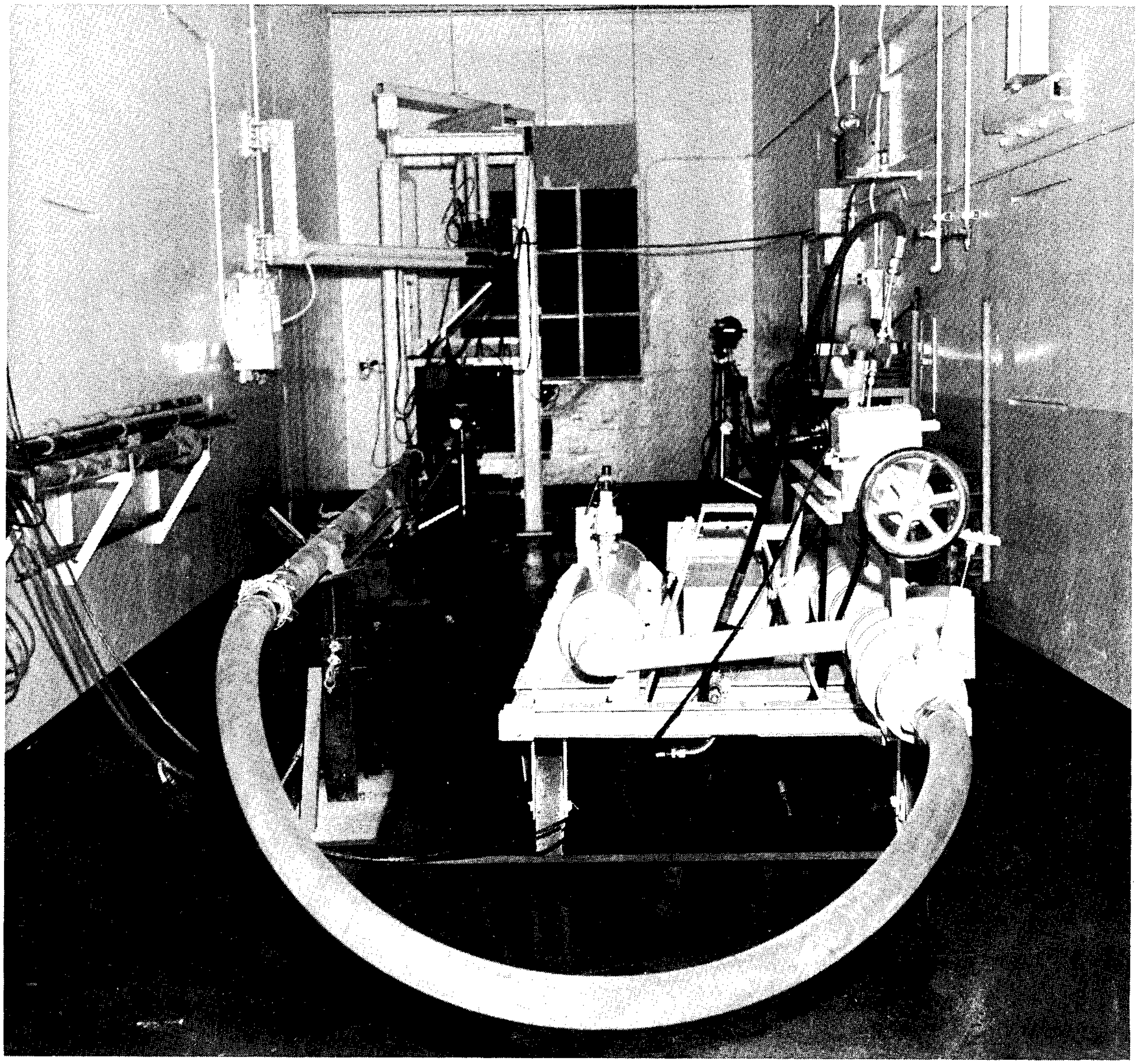


Figure 15. Static Test Facility Ballistic Gun and Gas Pressurization Dolly.

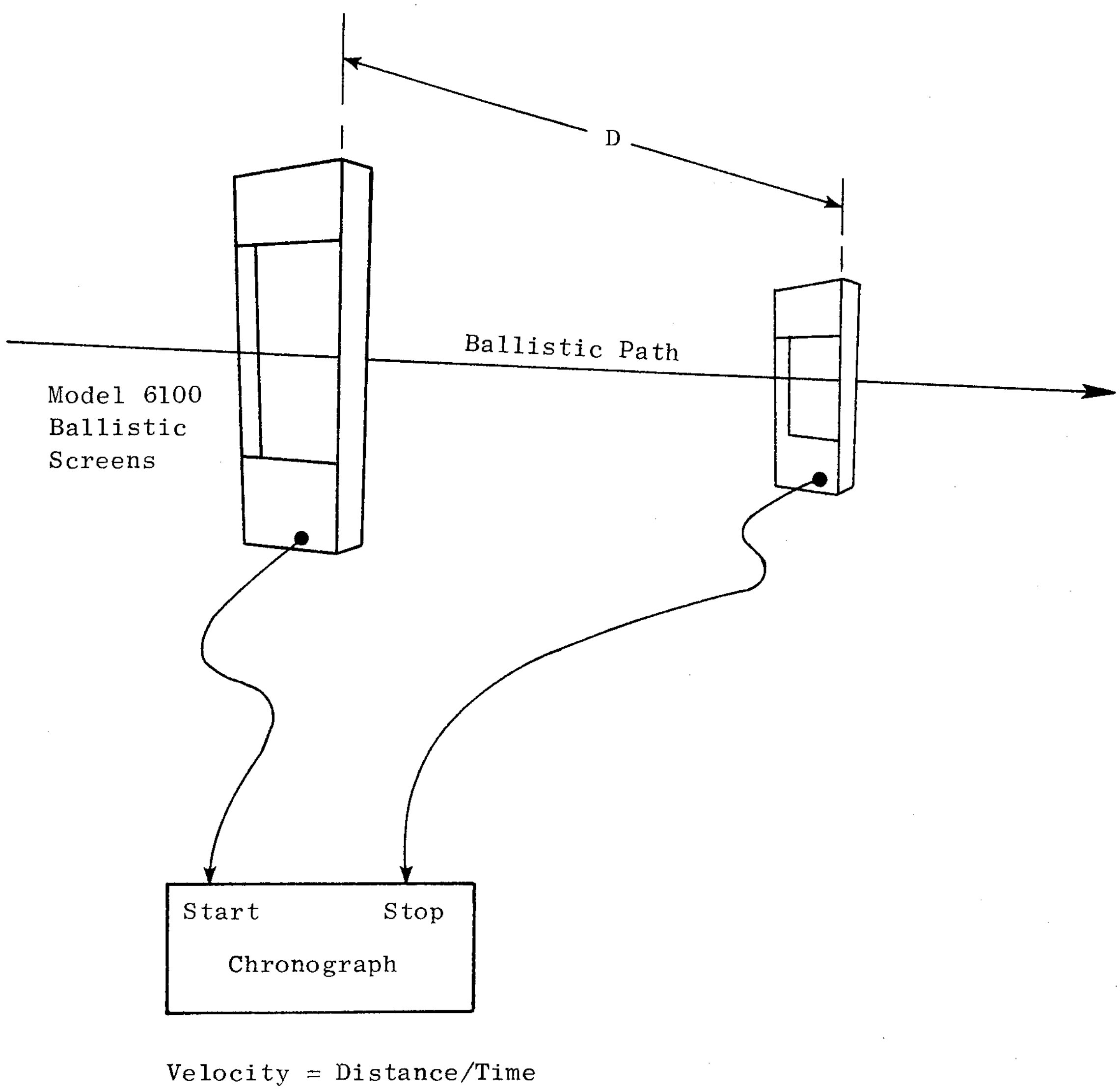


Figure 16. Velocity Measuring Device.

condition.

The slave shrouding for stage 1 was provided as containment for blade and debris as well as to protect and minimize damage to the test vehicle.

The environmental chamber, Figure 17, provided the capability to operate in a helium atmosphère in order to reduce horsepower requirements and temperature buildup.

The environmental chamber was made with three camera ports, located at the top, side and directly in front of the rotor, to permit high speed motion pictures to be taken from several angles simultaneously. Camera equipment, setup, and movie data are summarized below:

Front Camera:
Hycam 121.68 m (400 ft), Model 41-0004
Speed setting: 4500 frames/sec
Shutter: 1/2.5 (-1/12000 sec)
Lens: 10 mm
f/stop: 5.6
Film: B&W Kodak 2479, 136.89 m (450 ft) roll, ASA 800
Processing: Force processed to ASA 2000

Side Camera:
Hycam 121.68 m (400 ft), Model 41-0004
Speed setting: 4500 frames/sec
Shutter: 1/2.5 (-1/12000 sec)
Lens: 5.7 mm
f/stop: 4
Film: Color, Kodak -241, 121.68 m (400 ft) roll, ASA 160
Processing: Force processed to ASA 2000

Top Camera:
Fastax, Model WF4
Speed setting: 4500 frames/sec
Shutter: Nonvariable - effectively 3 times frame rate (1/13500 sec)
Lens: 13 mm
f/stop: 5.6
Film: B&W Kodak 2479, 136.89 m (450 ft) roll, ASA 800
Processing: Force processed to ASA 2000

The lighting was provided by thirty-two 1000 watt (GE Par 64) spotlights mounted on the outside of the environmental chamber and directed through individual glass ports. The blades and background were appropriately painted to reflect the light and provide contrast.

The gravel and iceballs were "injected" by allowing them to fall through a "j" shaped feeder tube and exit into the path of the blade. The tube was secured to the environmental chamber at approximately 12 o'clock but passed through it to permit the iceballs to be loaded from the outside just before the acceleration. The tube was equipped with a solenoid-operated gate flap which was automatically actuated when the rotor reached triggering speed. It was determined that the timing was not particularly

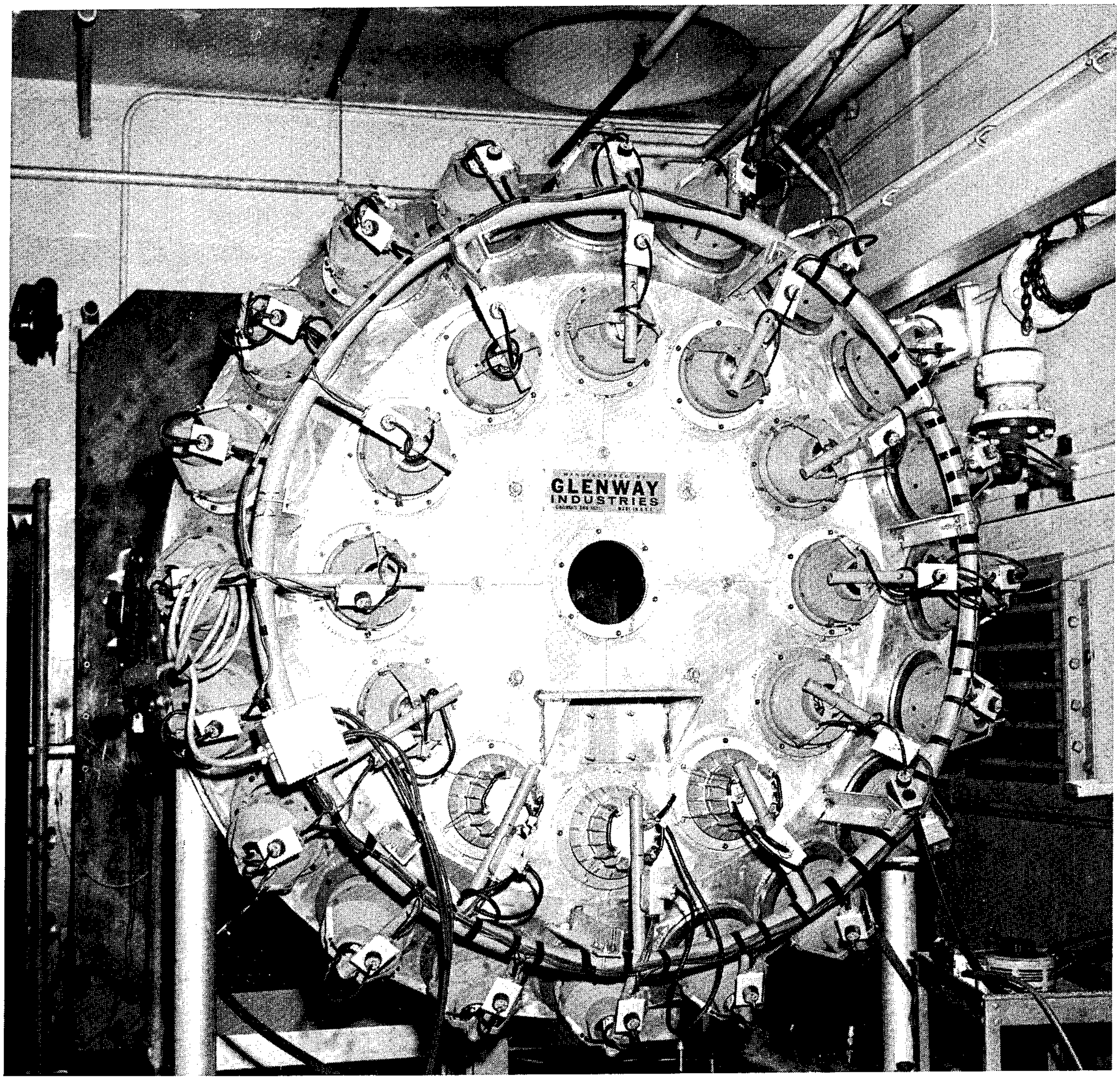


Figure 17. Whirligig Environmental Chamber.

critical because the objects would not be falling fast enough to get through the blade path in less than a revolution.

In order to obtain a consistent and reproducible impact bite when tested for bird impact, the "fixed bird" technique was used. This means that the bird was securely fixed to a mechanical injecting system which could insert (and retract) it at a set depth into the path of the rotating blade. Basically the mechanism consisted of a cup (bird carrier) attached to the end of a spring-loaded shaft which was supported and free to slide in two ball bushings. It was actuated by firing an explosive bolt which held the shaft (and spring) in the retracted (cocked) position. The particular springs that were used provided a maximum stroke of 7.62 cm (3 in.) in 10 milliseconds. This yielded a maximum bite of 6.35 cm (2.5 in.) allowing for initial clearance between blade and bird.

In order to obtain the required bite, the explosive bolt not only had to be fired when the rotor was at the required speed, but at an instant which would permit the blade to reach the impact point at the same time the bird reached the desired depth (full stroke). In addition, the camera and lights had to be activated to catch the event.

An automatic firing system was used to trigger the events and to fire the bolt at the proper time.

Inertial Head Test Facility

The Inertial Head Centrifugal Load Simulation Device was designed to produce an axial tension load on the blade so that the blade response to impact could be studied in the presence of axial tensile stresses.

The axial load is measured by means of two sets of back-to-back strain gages mounted to the major load strap. After load application, these gages are then connected via potentiometer-type circuits to monitor the changes in the axial load during the impact test.

The blades were mounted on the inertial head. The basic feature of this apparatus is that the blade is mounted to a rigid mass which is free to pivot omnidirectionally about a fixed point. The point is very close to the center of gravity of the mass. Upon impact the blade undergoes vibratory motions which cause rotational acceleration of the mass about the pivot point. These accelerations are sensed by a set of accelerometers positioned about three orthogonal axes whose origin is the pivot point (Figure 18). By this means the three components of angular momentum and, hence, the total angular momentum of the mass may be obtained. The momentum history was related to blade motions by analysis and, as a result, the basic motion of the blade itself was inferred. It has been found that quantities such as total momentum, kinetic energy, average impact force, base bending moments, tip deflection, vibration frequencies, and damping constant can be determined by this method.

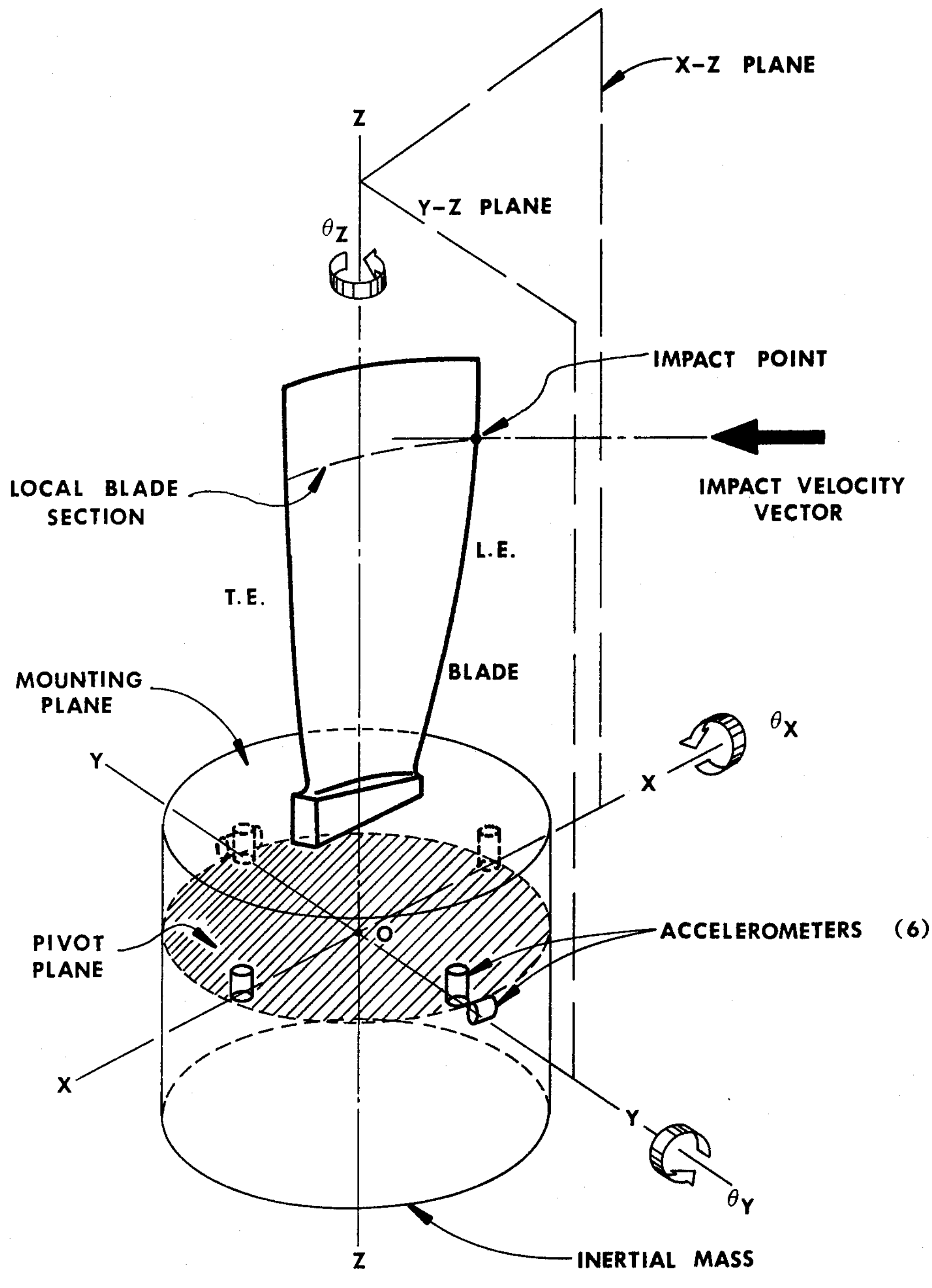


Figure 18. Instrumentation Coordinate System.

5.2.2 Foreign Objects

The following foreign objects, shown in Figure 19, were used during the program.

1. Simulated birds: Silicone foam material(RTV) was used to make up the simulated birds. They were made as either 7.6, 10.2, or 14 cm (3, 4, or 5.5 in.) diameter hollow or solid cylinders such that the required weight bite could be obtained from a 6.4 cm (2.5 in.) slice. The splicific ingredients of the mixture and preparation technique are given below:

   A. Base Mix

      4000 g RTV560
      350 g SF96-(50) silicone fluid
      50 g Al silicate fibers (Johns Manville)

      Mix 3 hours in a sigma blade mixer and remove

   B. Foaming Agent

      To foam the above base mix:

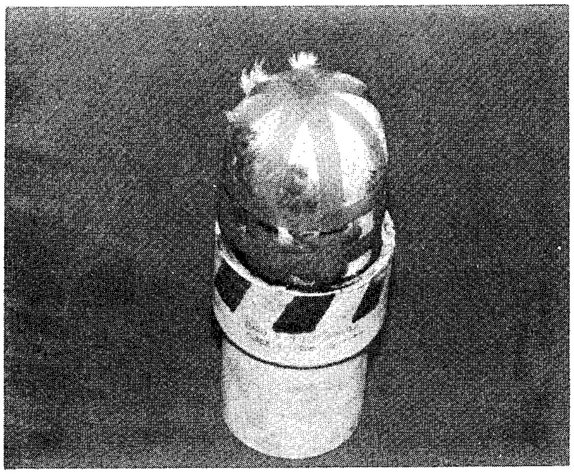
      100 g Base mix
      30 g RTV921 blowing agent
      .5 g T-12 catalyst
      4 drops Nucure 28

      Mix 3 to 4 minutes in a propeller mixer, pour in mold, and cure for 16 hours at 344.4° K (160° F).

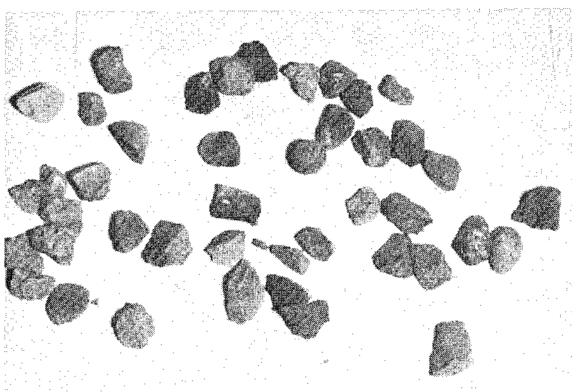
2. Real birds: Common local variety pigeons and wild mallard ducks, weighing approximately 454 g to 1134 g (16 to 40 oz.) were used to obtain the real bird impact. These birds were epoxied into the injecting cup, feet first such that 340 g to 680 g (12 to 24 oz.) would be cut off in a 6.4 cm (2.5 in.) bite. The head, wings, and feathers were maintained in a tucked-in position by narrow fiberglass strips. This was done to help hold the bird and prevent it from tearing apart due to turbulence from blade passing. The birds were allowed to thaw to room temperature before firing.

3. Gravel: Local "parking lot" type gravel was handpicked for .38 cm to .88 (0.15 to 0.38 in.) diameter size. Approximately 50 pieces were required to make 20 grams (0.7 oz.).

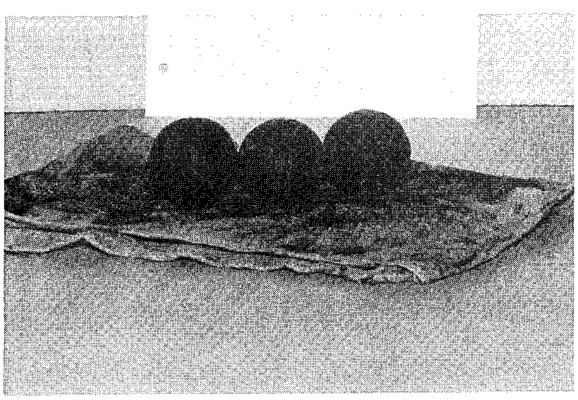
4. Iceballs: Three 5 cm (2 in.) diameter iceballs weighing approximately 68 g (2.4 oz) apiece were used for each iceball shot. They were made in rubber molds and frozen at 270.9° to 239.8° K (28° to -28° F). A small amount of washable black ink was added to color the iceballs so they would show up in the film.



Typical Real Pigeon as Used in NASA-FOD Tests. Pigeon Weight 454 g (16 oz). Held in Carrier by Glass Straps and Cement.



Stones and Gravel as Used in NASA-FOD Tests. Sized to 0.38 cm - 0.88 cm (0.15" - 0.38") Dia. Total Weight 20 Grams (0.7 oz).



Tempered Hailstones as Used in NASA-FOD Tests. Made from Distilled H_2O and Dyed Black. Total Weight of 3 Iceballs: 210 g (7.4 oz).

Figure 19. Typical Foreign Object.

5.3 TEST RESULTS

5.3.1 Single Fiber Type Composite Blades - Whirligig Tests

Four boron/epoxy and four graphite/epoxy composite blades were impacted in a rotating whirligig facility with conditions closely simulating those which might be experienced by a STOL engine impacted with various foreign objects. The tip speed of the rotating blades was 244 m (800 ft) per second. The blades were impacted with simulated birds, real birds, and iceballs and gravel.

Strain gages, accelerometers, high speed movies, TTUCS (Through-Transmission Ultrasonic C-Scan) measurements, and sonic velocity measurements provided data on the extent and mode of impact damage.

A titanium blade was also tested under identical conditions for comparison purposes.

Gross balancing to account for the weight variation of each of the three types of blades was accomplished by installing a counterweight slave blade opposite the test blade. Titanium blades, cut off at the appropriate span, were used to balance the composite test blades while a specially-made dummy weight was used to balance the titanium test blade. Fine balancing was done by adding balance weights to the forward and aft flange of the Stage 1 disc. A summary of the whirligig test results for these blades (S/N NB 1 through NB 4 and NG 1 through NG 4) is presented in Table X, which shows each blade by serial number, the type and weight of the impacting object, and the weight slice in the case of bird FOD, along with a description of visual damage which resulted. Tip deflection, as arrived at from the high speed movies, as shown in Figure 20, is given in Table XI.

All blades which were run in the whirligig were instrumented with seven dynamic gages [type EDDY-0.003 m (0.125 in.) AD-350E] and one thermocouple. Gage locations, application system, and lead-out path are shown in Figure 21.

In order to monitor the condition of the test installation for operational safety purposes, suitable instrumentation was applied. This consisted of two thermocouples and two accelerometers for each bearing to observe bearing temperature and bearing housing vibration plus four standard CEC vibration pickups to monitor casing vibration.

A 14-channel tape recorder was used to monitor and record all strain gages and accelerometers. To prevent strain gage burnout due to the poorer heat dissipation of the composite blade material, the normal strain gage excitation voltage was reduced. The blade thermocouple, some parallel strain gages, and accelerometers, were recorded using an 8-channel Sanborn Strip Chart recorder. Casing vibration and bearing temperatures were connected to standard meters for readout by the test operator.

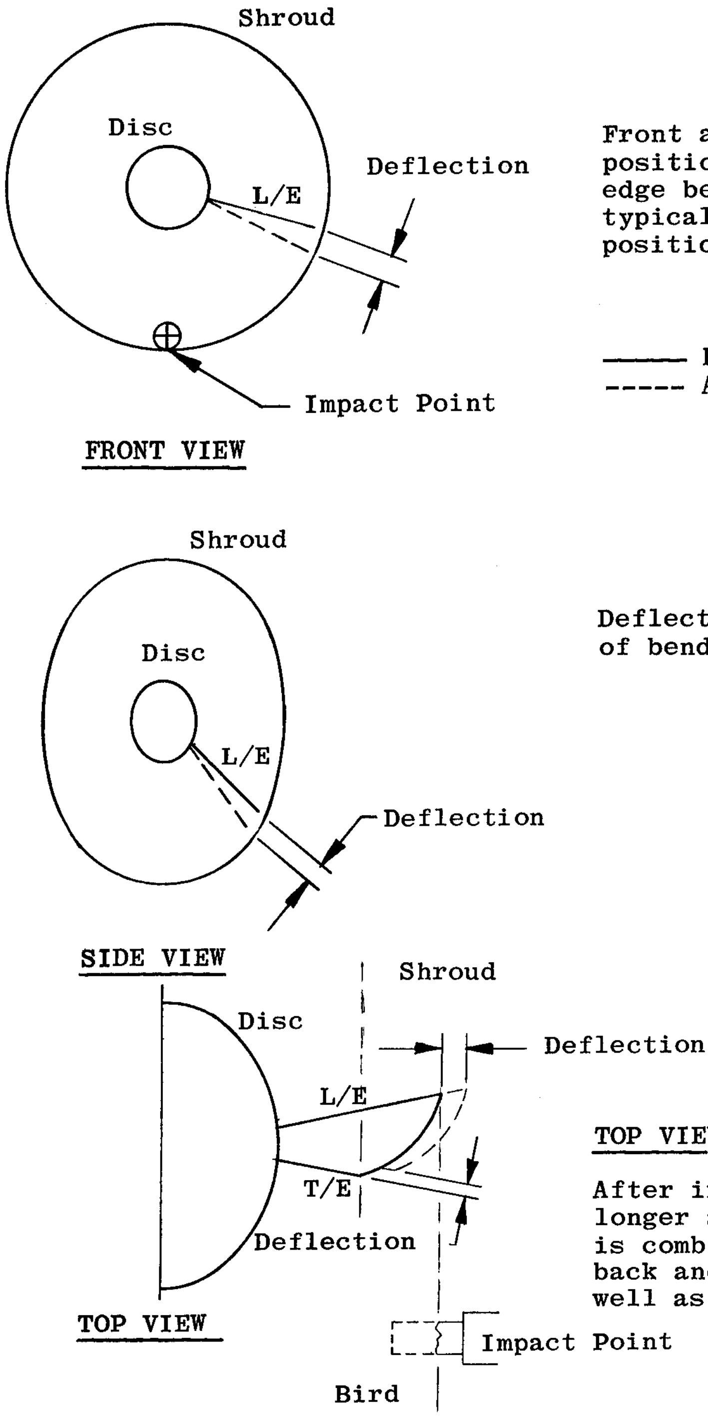
Table X. General Electric Whirligig Test Results.

Blade Tip Speed - 244 m/sec (800 ft/sec)
Impact Incidence Angle - 0.384 Radians (22°)
Impact Location - 10.2 cm (4 inches) from tip

Blade S/N	Bird Size	Bite Size	Visual Damage
NG1	340 g (12 oz) Simulated Bird	170 g (6 oz)	Loss of sliver and delamination at trailing edge of blade tip. Crack in dovetail.
NB2	340 g (12 oz) Simulated Bird	170 g (6 oz)	Radial crack in tip. Very small crack in dovetail at leading edge.
NG3	794 g (28 oz) Simulated Bird	340 g (12 oz)	Blade broke off at root.
NB4	794 g (28 oz) Simulated Bird	340 g (12 oz)	Blade broke off at root.
NG4	454 g (16 oz) Real Pigeon	312 g (11 oz)	Crack in root, as indicated by dye penetrant. Delamination in tip area.
NB3	454 g (16 oz) Real Pigeon	283 g (10 oz)	Delamination at base of leading edge, piece out of tip at leading edge. Delamination across tip.
Ti	454 g (16 oz) Real Pigeon	227 g (8 oz)	No damage.

Table X. General Electric Whirligig Test Results (Concluded).

S/N	Condition	Visual Damage
NG2	Gravel 0.38 cm (0.15") to 0.88 cm (0.38") Diameter Total Weight - 20 g (0.7 oz)	No visible damage.
NG2	Hailstones; Tempered Three, 5.08 cm (2") Diameter	No visible damage.
NB1	Gravel 0.38 cm (0.15") to 1.02 cm (0.25") Diameter Total Weight - 20 g	No visible damage.
NB1	Hailstones; Tempered Three, 5.08 cm (2") Diameter	Slight crack at trailing edge tip, large crack 15.24 cm (6") long at leading edge metal plating.



Front and side views show position of blade leading edge before and after impact typical for 5 and 3 o'clock positions.

——— Before Impact
----- After Impact

Deflections are a combination of bending and twisting.

TOP VIEW

After impact blade appears longer and narrower. Deflection is combination of blade bending back and axially forward as well as untwisting.

Figure 20. Blade Deflections from High Speed Films.

Table XI. Blade Deflections*, Boron/Epoxy and Graphite/Epoxy Blades.

Blade S/N	Bite Size g (oz)	Blade Failure	Front View Blade Deflection cm (in.) 5 o'clock	Front View Blade Deflection cm (in.) 3 o'clock	Side View Deflection cm (in.) 5 o'clock	Top View Deflection cm (in.) 5 o'clock L/E	Top View Deflection cm (in.) 5 o'clock T/E	Notes
NG1	170 (6) RTV	No	0.79 (0.31)	3.2 (1.25)	2.8 (1.1)	4.3 (1.7)	4.3 (1.7)	Hit debris 3rd & 4th rev.
NB2	170 (6) RTV	No	1.2 (0.47)	3.2 (1.25)	3.6 (1.4)	5.3 (2.1)	5.3 (2.1)	Hit debris 3rd rev.
NG3	340 (12) RTV	Yes	4.8 (1.88)	12.7 (5.0)	8.1 (3.2	No Film		Blade separated at 3 o'clock
NB4	340 (12) RTV	Yes	2.4 (0.94)	11.2 (4.4)	No Film	No Film		Blade separated at 3 o'clock
NG4	312 (11) Pigeon	No	1.0 (1.56)	10.7 (4.2)	8.9 (3.5)	10.2 (4.0)	Obscured	Hit debris 2nd, 3rd, and 4th rev.
NB3	284 (10) Pigeon	No	---	---	5.6 (2.2)	6.6 (2.6)	Obscured	Hit debris 2nd - 6th rev.
Ti	227 (8) Pigeon	No	4.8 (1.88)	12.0 (4.6)	---	6.0 (2.34)	Obscured	No visible damage
			Deflections at 12 o'clock cm (in.)					
NG2	Gravel Ice Balls	No No	None 2.0 (0.78)					Hit gravel for 4 revs. Hit 2 ice balls on 1st rev, 1 on second rev.
NB1	Gravel Ice Balls	No No	None 0.76 (0.3)					Hit gravel for 3 revs. Hit 1 ice ball on each of 3 revs.

*Objects injected at 6 o'clock position, blade rotating counterclockwise.

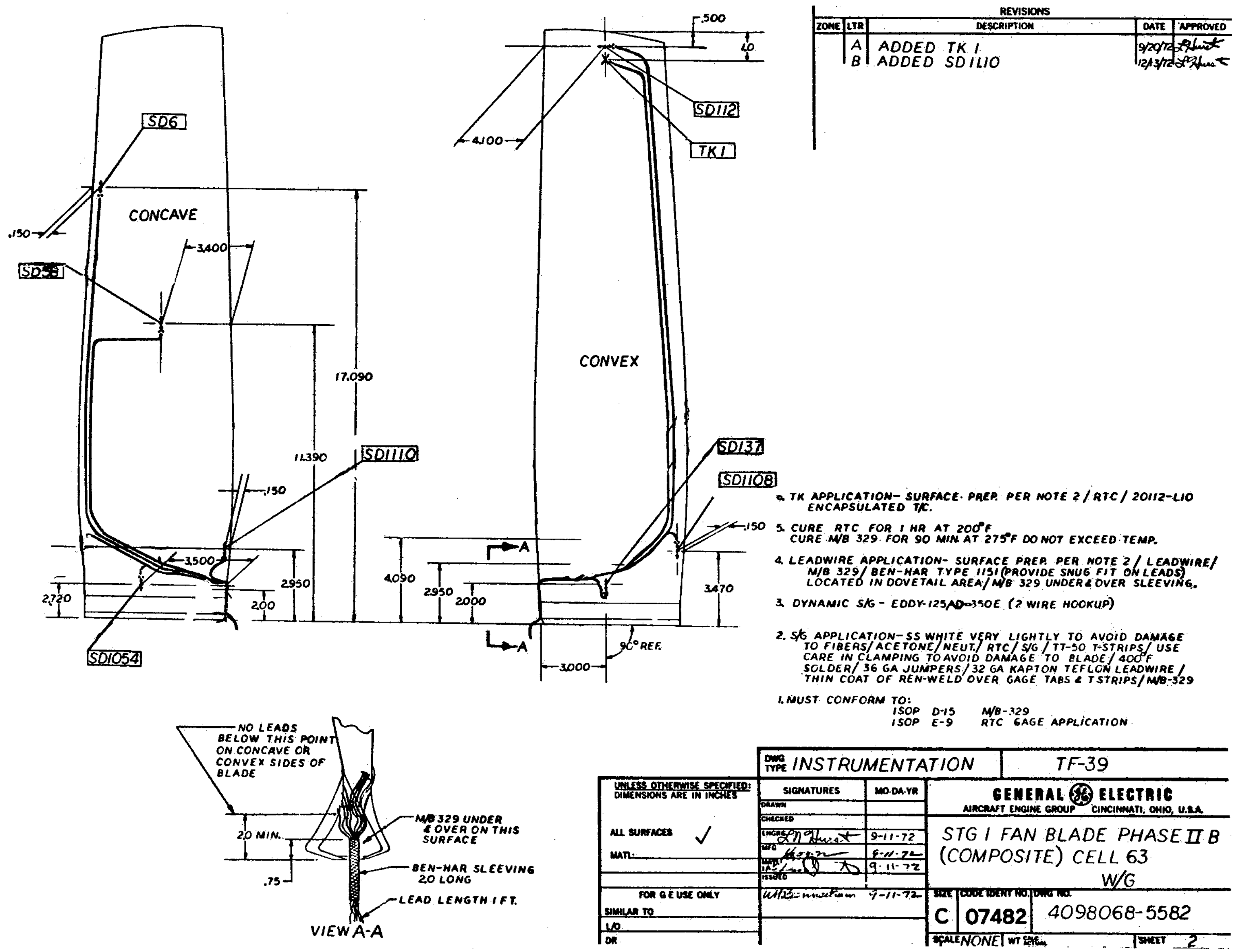


Figure 21. Composite Blade Instrumentation.

A typical taped data playback showing stresses, frequencies and time history of impact for each blade is presented in Figure 22. Table XII shows the stresses for each gage as obtained from the taped data overall level and waveform playback.

The overall level ("O/L") values listed are the response amplitudes taken from the overall level playback. In this type playback the dynamic signal is converted to an equivalent DC voltage, and the entire event (which occurs in a matter of milliseconds) shows as a very sharp spike. However, even with the short event time, the spike amplitude agrees reasonably well with the maximum peak-to-peak value shown by the waveform.

In the waveform type reduction the tape is played back at a very slow speed which in effect stretches out the event time permitting the actual dynamic signal to be printed out. This then shows the time history of the event and allows for such things as frequencies, decay times, secondary impacts, etc. to be identified. The "W/F P-P" values listed in the table are the maximum peak-to-peak responses as obtained from waveform playbacks. All recorded stresses were obtained from strain times modulus ($\sigma = \varepsilon E$) using the following values for the modulus (E):

	N/m^2	(PSI)
Graphite/Epoxy ----------	95.1×10^9	(13.8×10^6)
Boron/Epoxy -------------	155.1×10^9	(22.5×10^6)
Titanium ----------------	108.9×10^9	(15.8×10^6)

In general terms, the waveform playback shows the following:

1. At the moment of impact and during the very short duration of blade/bird interaction, the response was forced and showed a mixture of frequencies.

2. In most cases this interaction period was very short and was over in less than .52 radian (30°) of rotation (1-2 milliseconds). The gages indicated that at this point (approximately 5 o'clock) the blade had fundamentally been bent over in a first flex attitude and torsionally had already untwisted and was on its way back.

3. For the most part, after the initial interaction, the waveforms were clean showing first flex and first torsional decay. For both types of composite blades, strain gages, SD 58, 1110, 1054, and 137 showed primarily flex while SD6, 112, and 1108 showed torsion (see Figure 21). For the titanium blade only SD 1 showed torsion while the remaining gages showed flex.

4. For the blades which didn't break off or were intact enough to show this pattern, the flex response reached its peak around 1.75 radians (100°) after impact (between 2 and 3 o'clock).

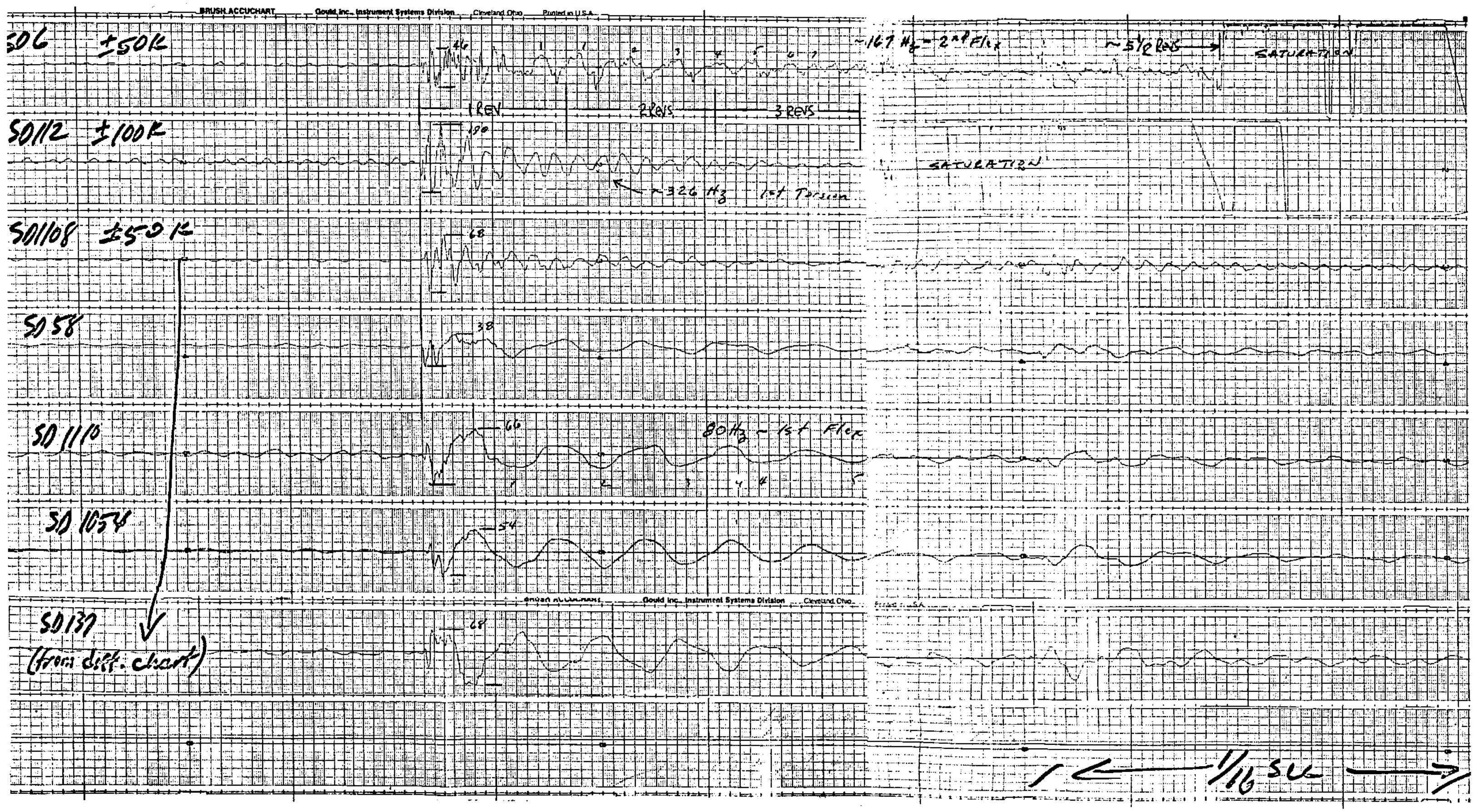


Figure 22. Typical Taped Data Playback for Composite Blade.

Table XII. Strain Gage Stress Summary of Whirligig Impact Test Results.

Blade S/N	Bite Size	SD 6 O/L DA	SD 6 W/F P-P	SD 112 O/L DA	SD 112 W/F P-P	SD 1108 O/L DA	SD 1108 W/F P-P	SD 58 O/L DA	SD 58 W/F P-P	SD 1110 O/L DA	SD 1110 W/F P-P	SD 1054 O/L DA	SD 1054 W/F P-P	SD 137 O/L DA	SD 137 W/F P-P	Blade Temperature ° K	(° F)	Results
NG1	170 g (6 oz) RTV	OD	283 (41)	OD	117 (17)	365 (53)	414 (60)	303 (44)	228 (33)	365 (53)	400 (58)	324 (47)	393 (57)	455 (66)	414 (60)	353	(175)	Broken piece at tip D/T crack.
NB2	170 g (6 oz) RTV	710 (103)	758 (110)	OD	103 (15)	462 (67)	455 (66)	386 (56)	338 (49)	586 (85)	607 (88)	310 (45)	338 (49)	420 (61)	380 (55)	344	(160)	Tip crack; small crack at D/T leading edge.
NG3	340 g (12 oz) RTV	OD	241 (35)	76 (11*)	69 (10*)	OD	455 (66)	OD	724 (105)	OD	420 (61)	OD	545 (79)	OD	662 (96)	356	(180)	Broke off at dovetail.
NB4	340 g (12 oz) RTV	OD	552 (80)	OD	97 (14)	OD	600 (87)	OD	524 (76)	OD	469 (68)	OD	262 (38)	OD	317 (46)	356	(180)	Broke off at dovetail.
NG4	312 g (11 oz) Pigeon	OD	490 (71)	OD	48 (7)	530 (77)	530 (77)	475 (69)	530 (77)	869 (126)	758 (110)	303 (44)	365 (53)	228 (33)	255 (37)			Tip cracks.
NB3	283 g (10 oz) Pigeon	627 (91)	207 (30)	69 (10)	62 (9)	400 (58)	380 (55)	OD	365 (53)	420 (61)	524 (76)	386 (56)	345 (50)	524 (76)	2000 (290*)			Broken tip piece and tip crack.
		SD 1		SD 14		SD 18		SD 58		SD 58		SD 62		SD 79				
Ti THB 02220	227 g (8 oz) Pigeon	758 (110)	965 (140)	945 (137)	414 (60)	1207 (175)	1241 (180)	552 (80)	621 (90)	Out		758 (110)	896 (130)	862 (125)	1034 (150)			No damage.

NOTES:

1. Abbreviations: O/L = Overall level (playback)
   W/F = Waveform (playback)
   OD = Amplifier overdriven - no data
   DA = Double amplitude
   P-P = Peak to peak
2. Values are X 10^6 N/m^2 (kpsi)
3. * These values are questionable:
   - For blade NG3 which broke off at the dovetail, thereby presumably severing the gage leads, the resulting signal should have overdriven the system. However, the tape chart shows what appears to be a good signal.
   - For blade NB3, this value is not typical of other values in the table and is inconsistent with its O/L. A scale or calibration error may be at fault.
4. See Figure 21 for Strain Gage Locations.

5. For the blades which did break off, amplifier saturation occurred less than 1.57 radians (90°) after impact resulting in no meaningful stress data from playback tapes.

6. In cases where only a small piece of blade broke off, the gages indicated that the separation or crack didn't happen immediately, but after several revolutions, and sometimes apparently as a result of secondary impact.

7. Many of the gages showed minor secondary impacts which correlated time-wise to integral revolutions. For the most part, the torsional response gages had the biggest effect.

8. Generally the response, without secondary impacts, decays out anywhere from 3 to 10 revolutions after impact.

In addition, all blades were checked for frequency, both before and after test. The bench frequencies for the first three modes of all blades are shown in Table XIII. In addition, the after test frequencies for the first flex only are presented due to the extent of damage. These data show that 1F frequencies basically remain the same. The biggest change in frequency occurred on graphite blade NG4 which was impacted with a 312 g (11 oz) slice of a 454 g (16 oz) pigeon.

Each blade was also subjected to Through-Transmission Ultrasonic C-Scan (TTUCS) after impact. This method of nondestructive evaluation revealed damage not seen with the naked eye and is reported as follows:

<u>Boron/Epoxy Blades</u>

S/N NB1 - (gravel, iceballs) - Crack along LE protection. Delamination area at base of the blade after impact (Figure 23). Dye penetrant inspection of the dovetail revealed a crack along the LE (Figure 24). Reduced velocity values at base of blade also indicate delamination.

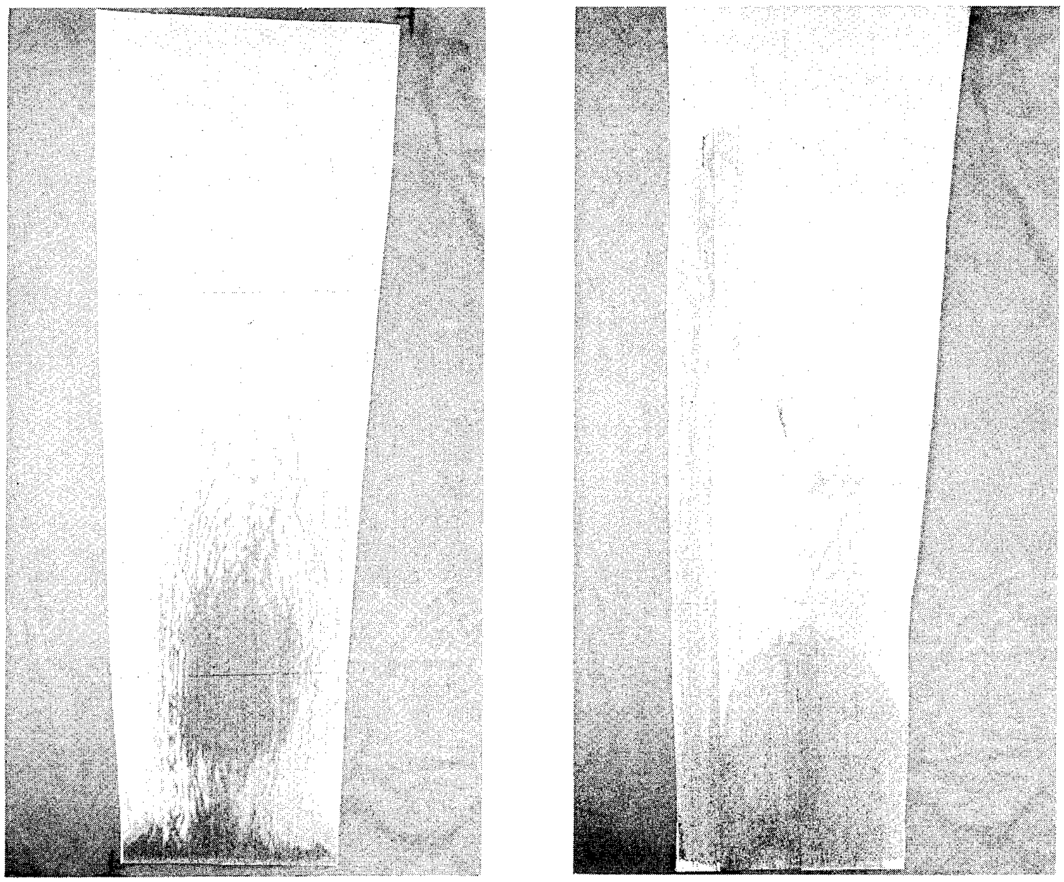
S/N NB2 - [340 g (12oz) RTV bird, Figure 25] - LE delamination at base - concave side. Delamination at base of blade after impact. Velocity decrease at base of blade indicating unbonded area.

S/N NB3 - [454 g (16 oz) Pigeon, Figure 26] - Delamination at base of LE. TTUCS after impact indicates blade has internal damage throughout (Figure 27). The dovetail had cracks in both LE and TE as shown by dye penetrant checks (Figure 28). Reduced velocity measurements made over the entire blade surface after impact confirmed the TTUCS data.

S/N NB4 - [794 g (28 oz) RTV bird, Figure 29] - No NDE performed after impact. Blade broke off at root.

Table XIII. TF39 Composite Blade Frequency Results

S/N	Before 1F (cps)	After 1F (cps)	2F (cps)	1T (cps)
NG1	62	60	168	310
NG2	60	62	170	314
NG3	62	--	162	308
NG4	62	47	170	308
NG5	60	60	162	304
NB1	74	71	200	368
NB2	77	71	180	364
NB3	75	79	195	368
NB4	77	--	200	375
NB5	76	67	197	371



Before Impact After Impact

Figure 23. TTUCS of Boron/Epoxy Blade S/N NB1.

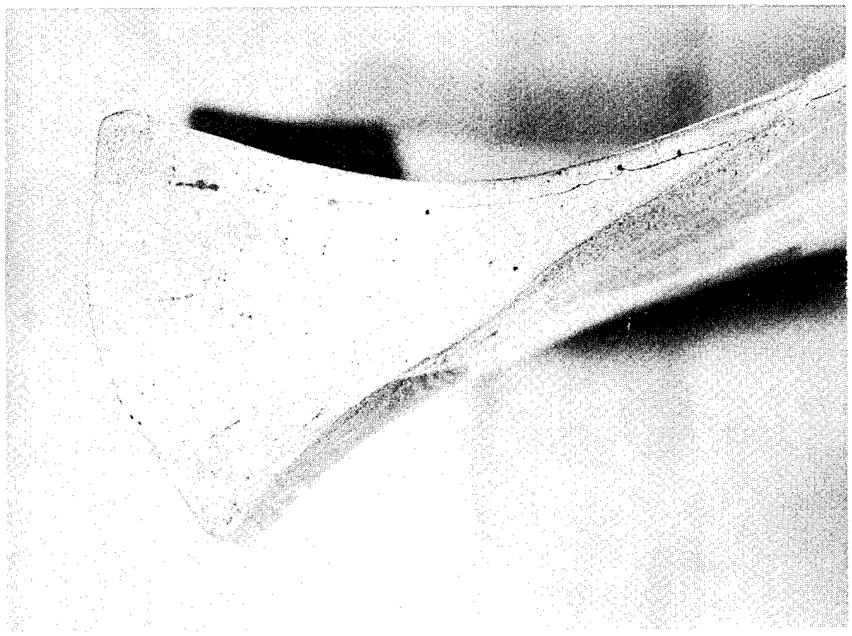
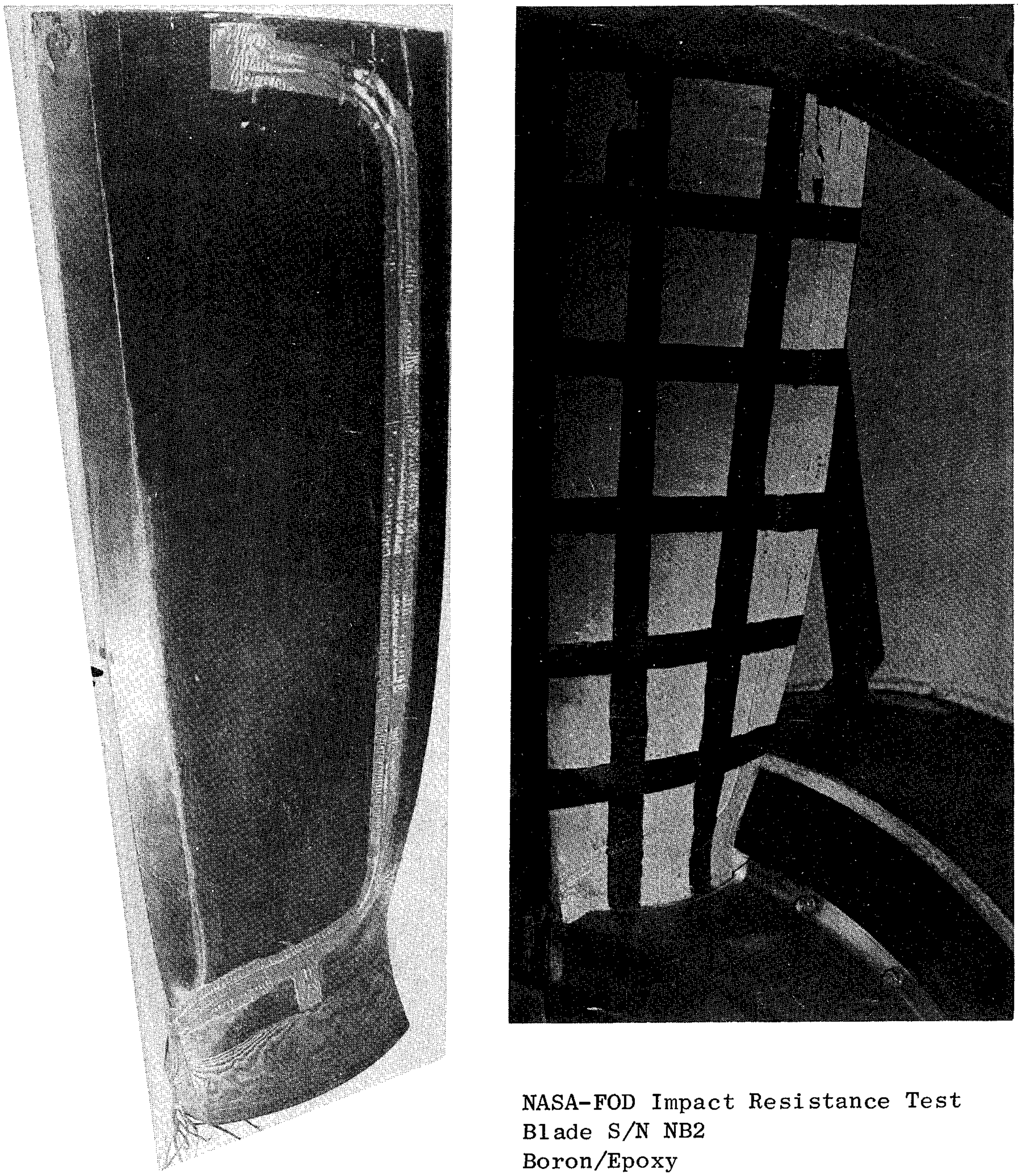


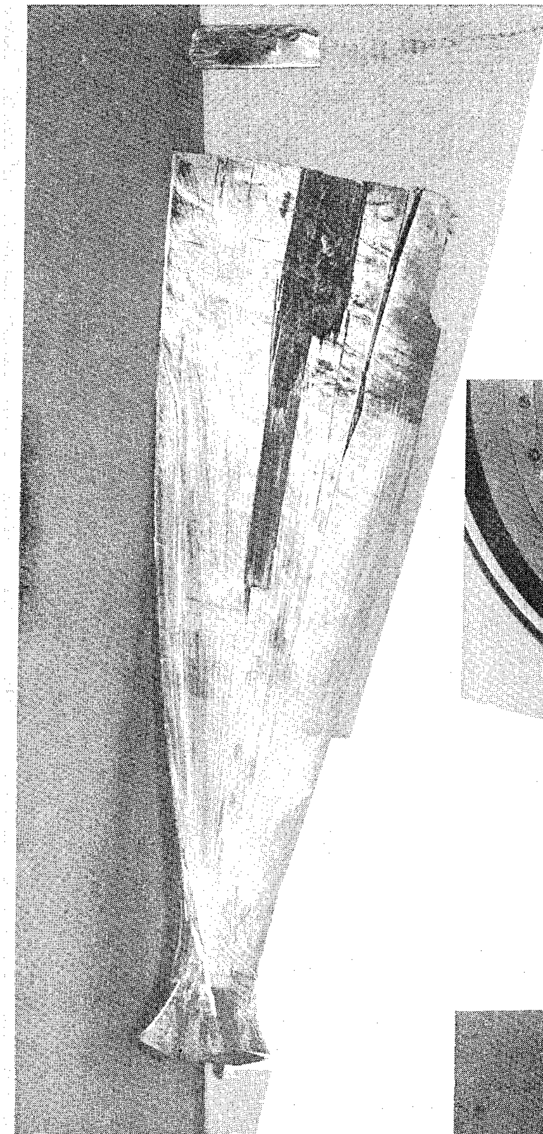
Figure 24. Dye Penetrant Inspection of Dovetail Leading Edge After Impact, Blade S/N NB1.



NASA-FOD Impact Resistance Test
Blade S/N NB2
Boron/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
340 g (12 oz) RTV Bird
170 g (6 oz) Slice
0.384 Radians (22°) Incidence Angle

Figure 25. Blade S/N NB2 after Impact.

NASA-FOD Impact Resistance Test
Blade S/N NB3
Boron/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
454 g (16 oz) Real Pigeon
283 g (10 oz) Slice
0.384 Radians (22°) Incidence Angle



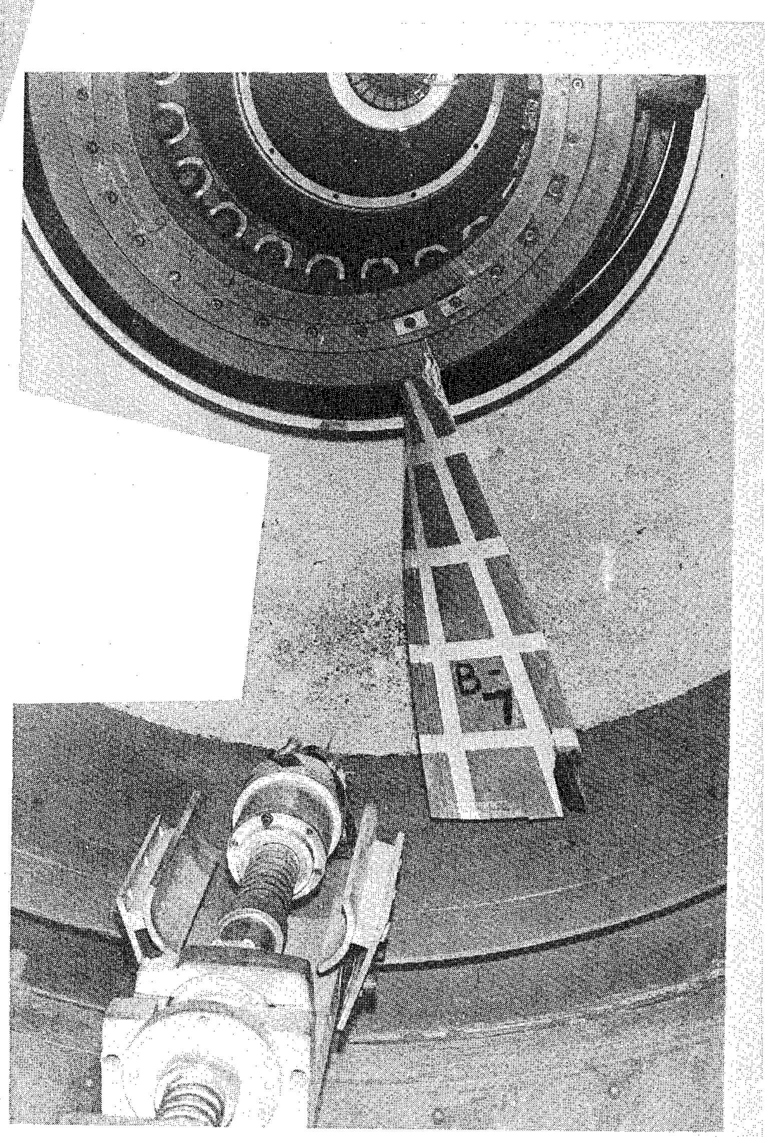
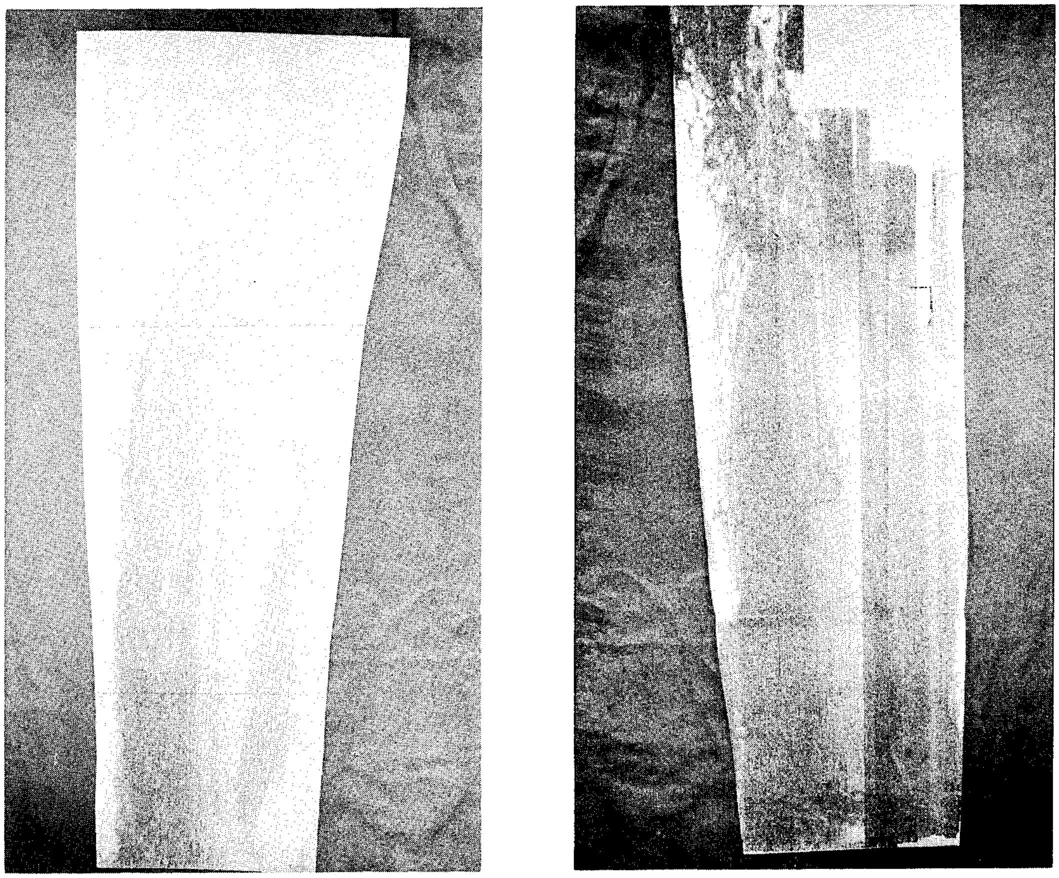


Figure 26. Blade S/N NB3 after Impact.



Before Impact After Impact

Figure 27. TTUCS of Boron/Epoxy Blade S/N NB3.

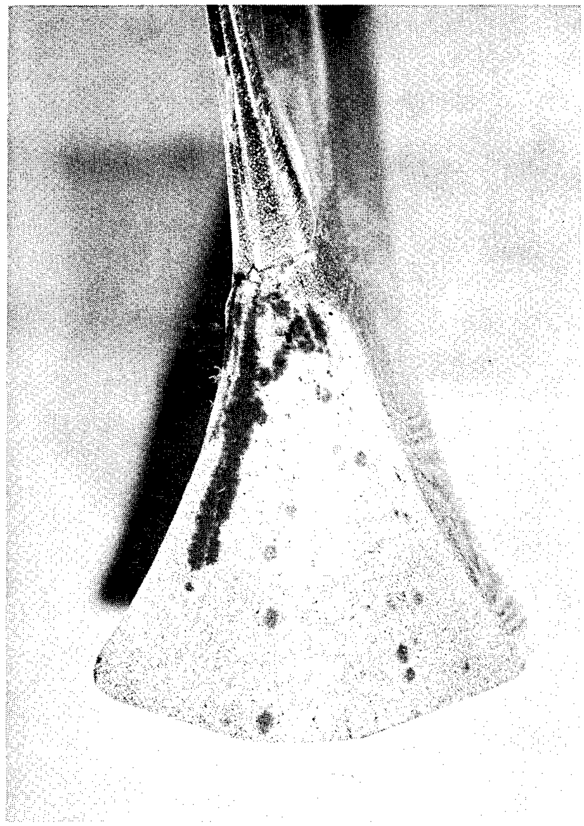
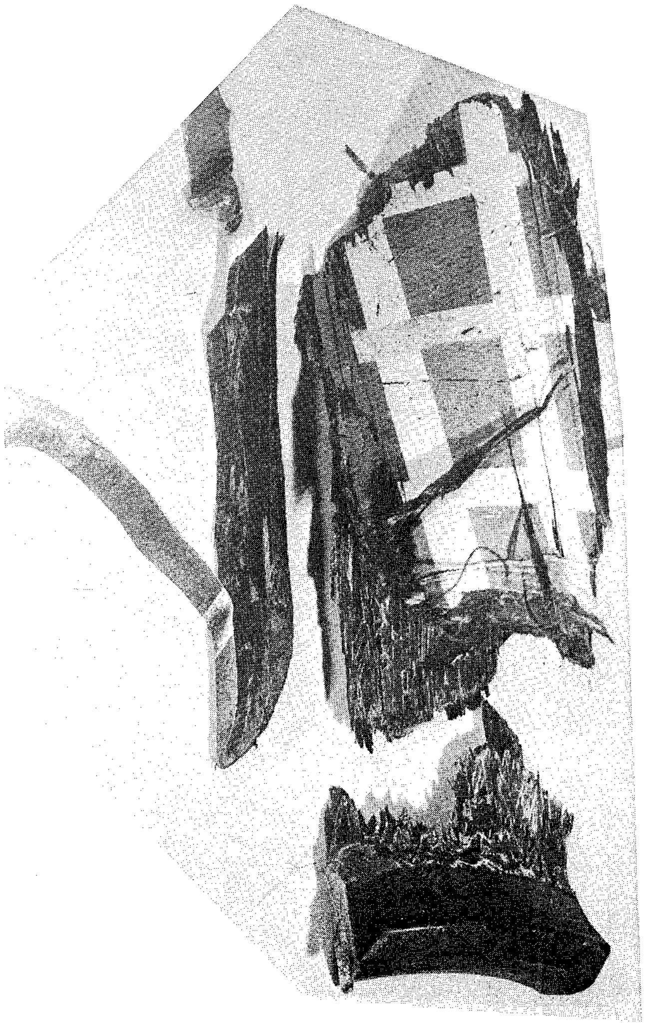
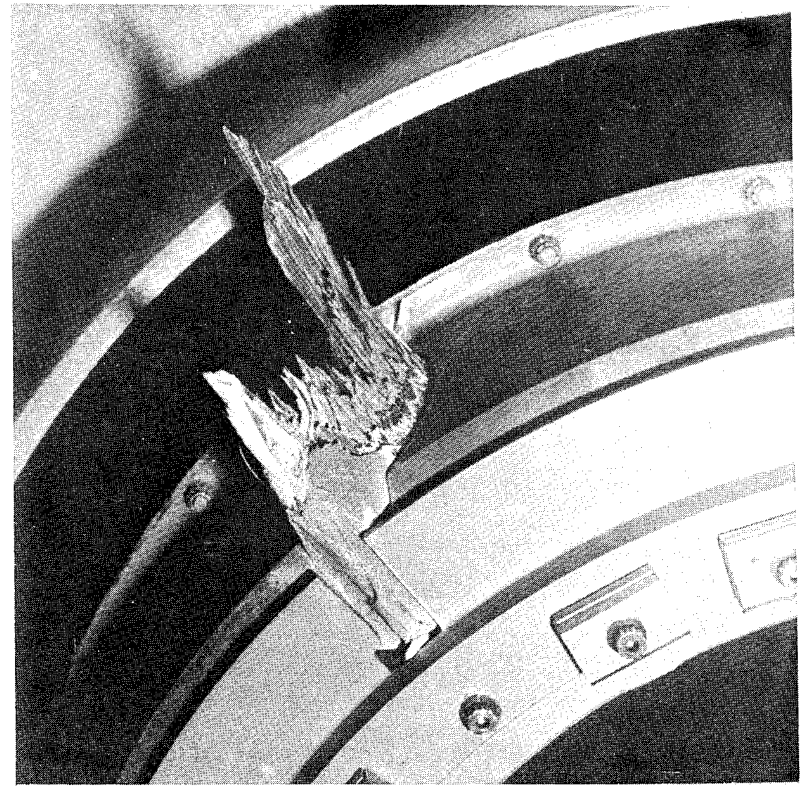


Figure 28. Dye Penetrant Inspection of Dovetail Leading Edge After Impact, Blade S/N NB3.





NASA-FOD Impact Resitance Test
Blade S/N NB4
Boron/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
794 g (28 oz) RTV Bird
340 g (12 oz) Slice
0.384 Radians (22°) Incidence Angle

Figure 29. Blade S/N NB4 after Impact

Graphite/Epoxy Blades

S/N NG1 - [340 g (12 oz) RTV bird, Figure 30] - Crack in dovetail, slight separation of nickel from LE. TTUCS revealed delamination area at base plus damage at TE tip (Figure 31). Delamination in dovetail can be seen in photographs of dye penetrant check (Figure 32). Low velocity measurements were recorded at base of blade, TE side, indicating internal damage.

S/N NG2 - (Gravel, iceballs - Figure 33) - TTUCS indicated small debonded area along LE protection. Remaining airfoil undamaged. Dye penetrant inspection did not reveal any cracks or delaminations in the dovetail after impact.

S/N NG3 - [794 g (28 oz) RTV bird, Figure 34] - No NDE after test - too severely damaged.

S/N NG4 - [454 g (16 oz) pigeon, Figure 35] - Severe root damage. TTUCS shows large delamination area running from dovetail to midway up the blade (Figure 36). Tip badly delaminated also. Dye penetrant inspection showed crack running around entire dovetail (Figure 37).

5.3.2 Single Fiber Type Composite Blades - Inertial Head Tests

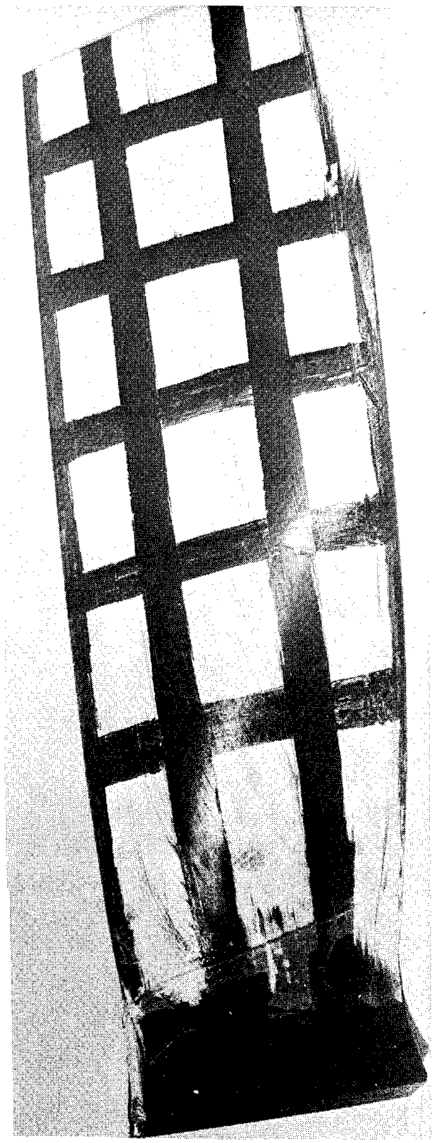
Two full-scale TF39 composite blades, one made of graphite/epoxy and one of boron/epoxy, were tested in the inertial head facility described in Section 5.2.1. A titanium blade was also tested to provide a reference point.

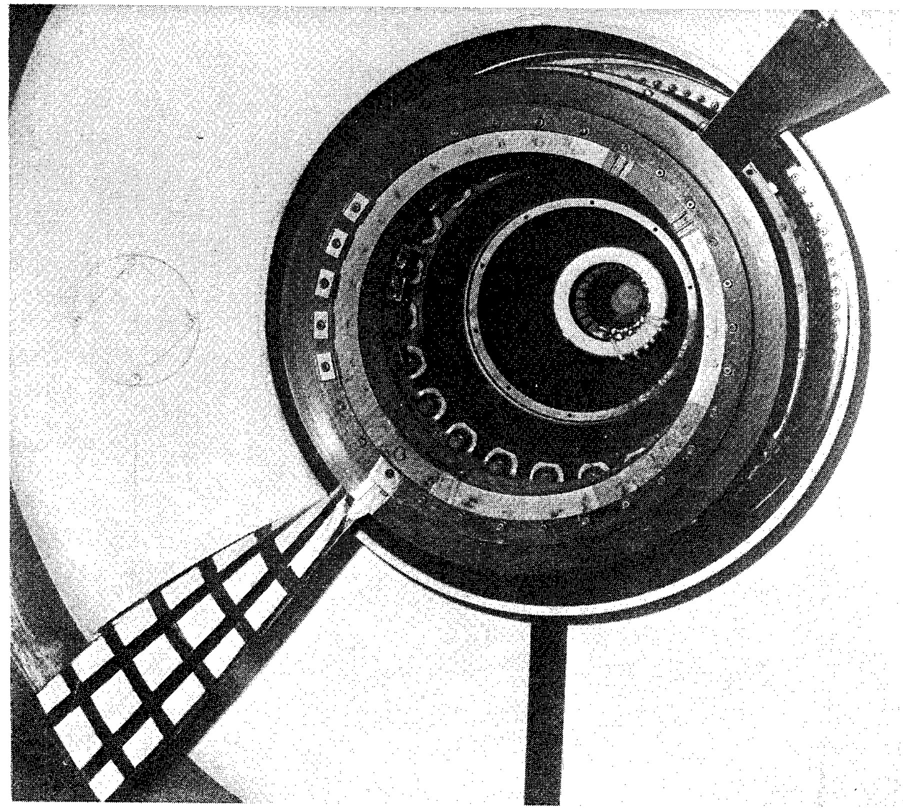
Simulated bird-carcass projectiles were impacted against these blades while they were mounted on the inertial head apparatus. The projectiles were in the form of a solid circular cylinder and were made of RTV plastic foam.

During impact, a portion of the projectile is sliced off and deflected by the blade and this portion travels along the concave surface of the blade, exerting force on it, due principally to its inertia. The sliced-off portion is grossly broken apart as it engages the blade, but the remainder of the projectile remains remarkably intact and passes by the blade relatively undisturbed.

The composite blades were placed under an axial tensile load in order to provide some simulation of the centrifugal force present under engine operating conditions.

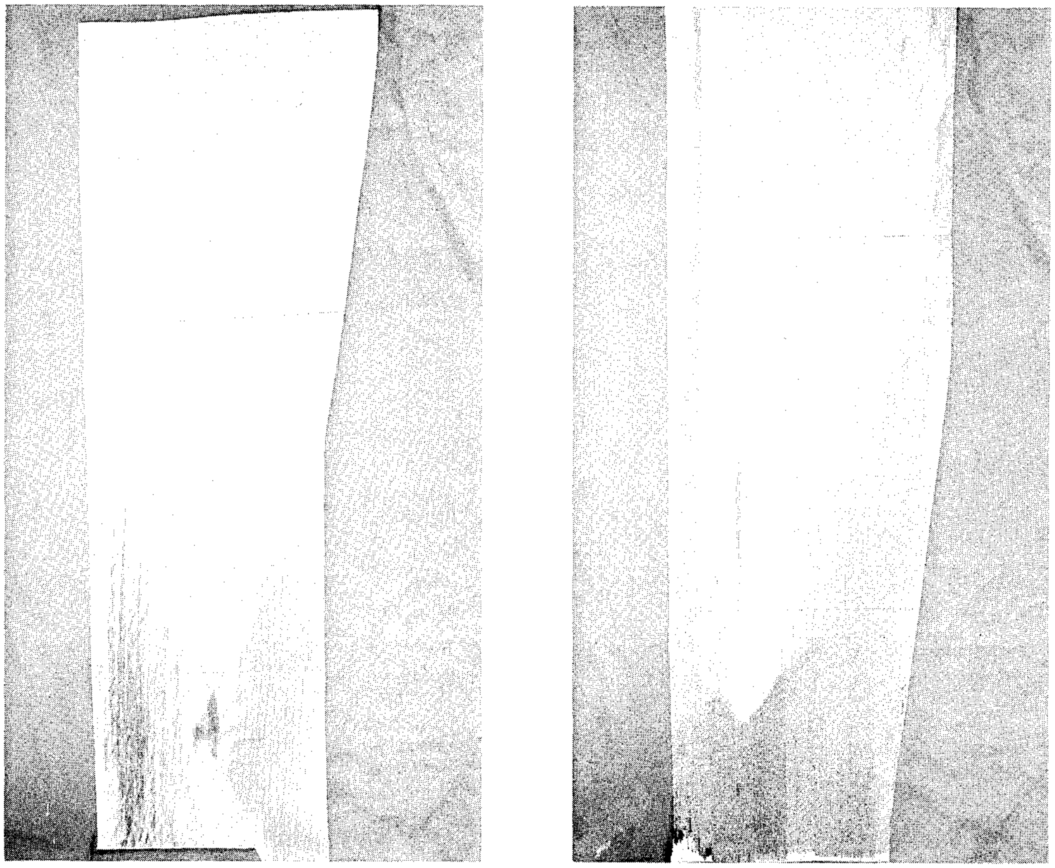
The values of axial loading were set approximately equal to centrifugal loading imposed on the blade section located four inches below the blade tip. This section lies along the central line of projectile impact. The loads imposed are as follows:





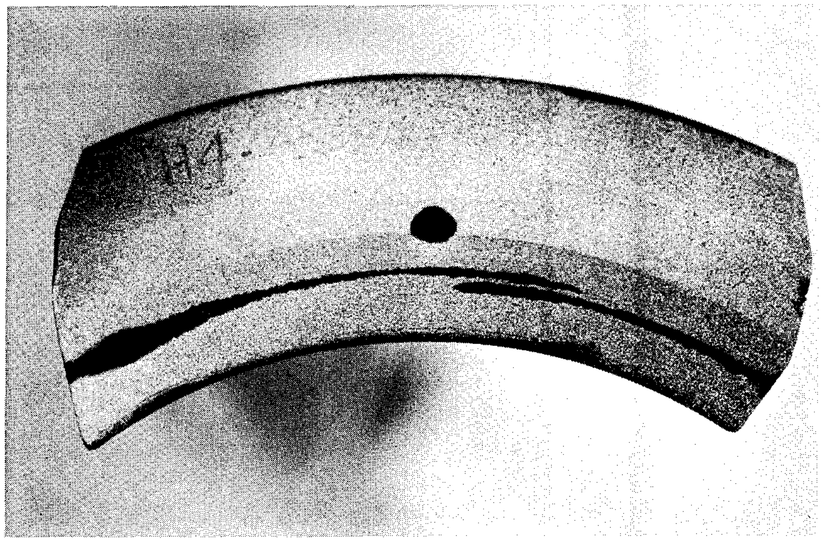
NASA-FOD Impact Resistance Test
Blade S/N NG1
Graphite/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
340 g (12 oz) RTV Bird
170 g (6 oz) Slice
0.384 Radians (22°) Incidence Angle

Figure 30. Blade S/N NG1 after Impact.

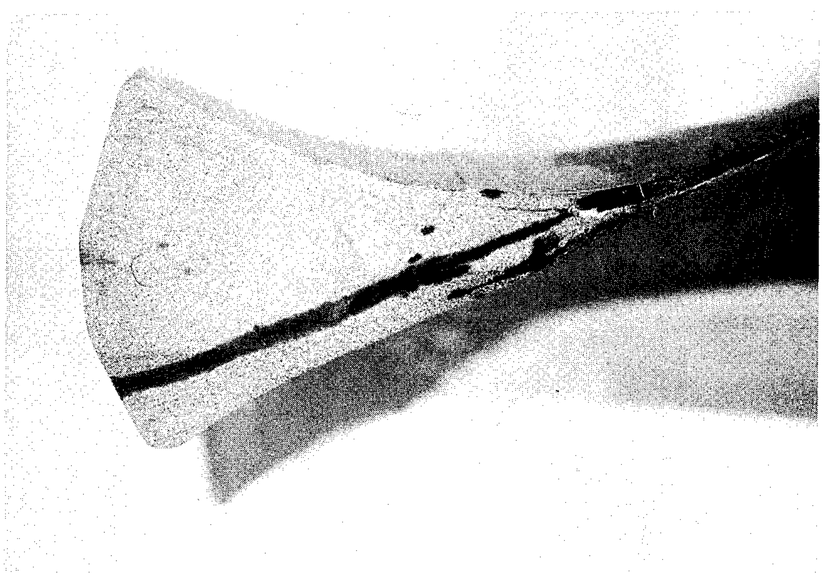


Before Impact After Impact

Figure 31. TTUCS of Graphite/Epoxy Blade S/N NG1.

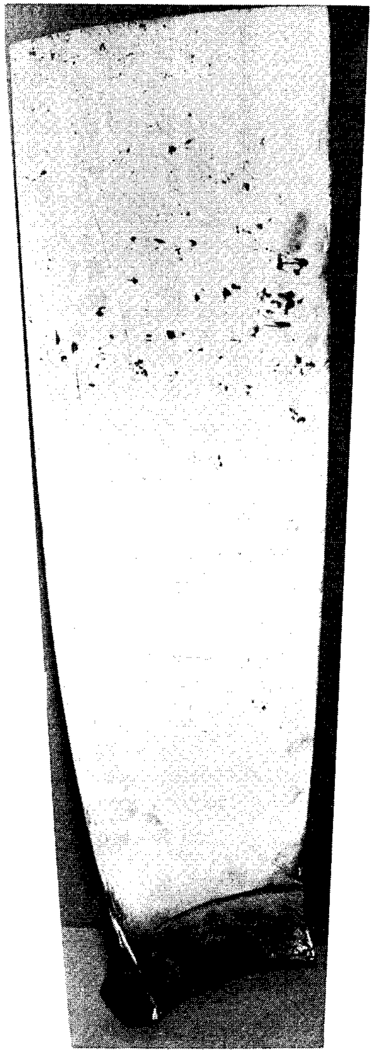


(a) Base of Blade

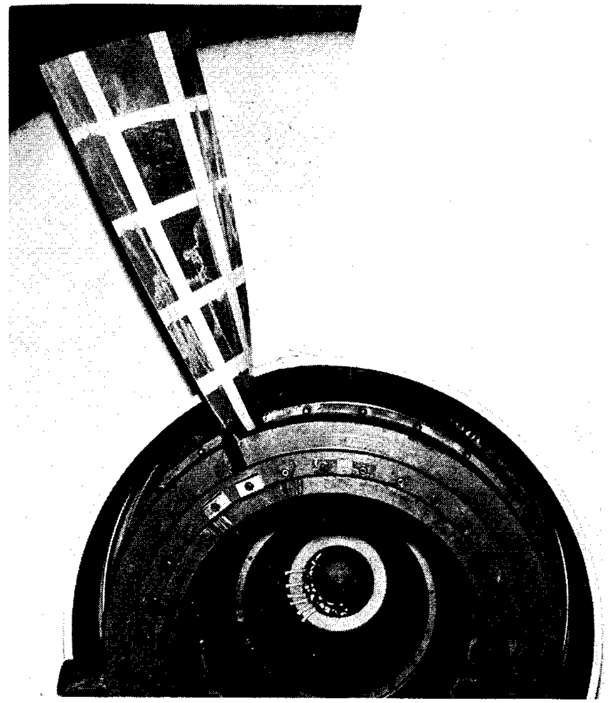


(b) Blade Dovetail Trailing Edge

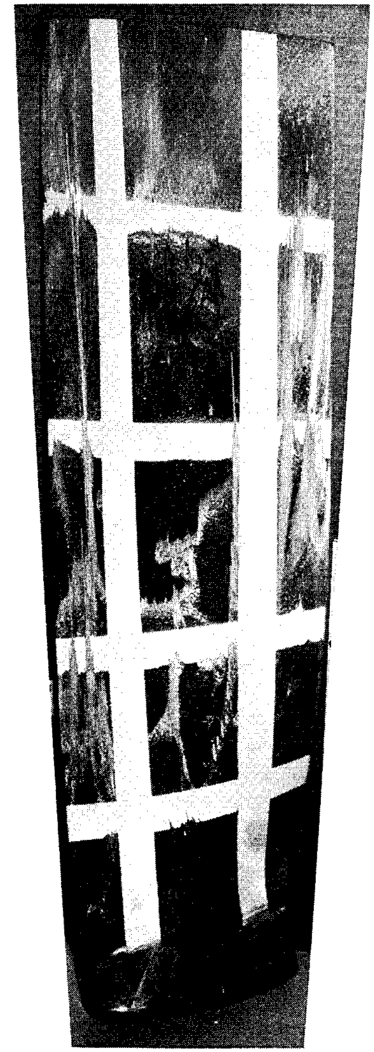
Figure 32. Dye Penetrant Inspection of Dovetail After Impact, Blade S/N NG1.



Following Impact with
20 grams Stones and
Gravel, 0.38 to 0.88
cm Diameter

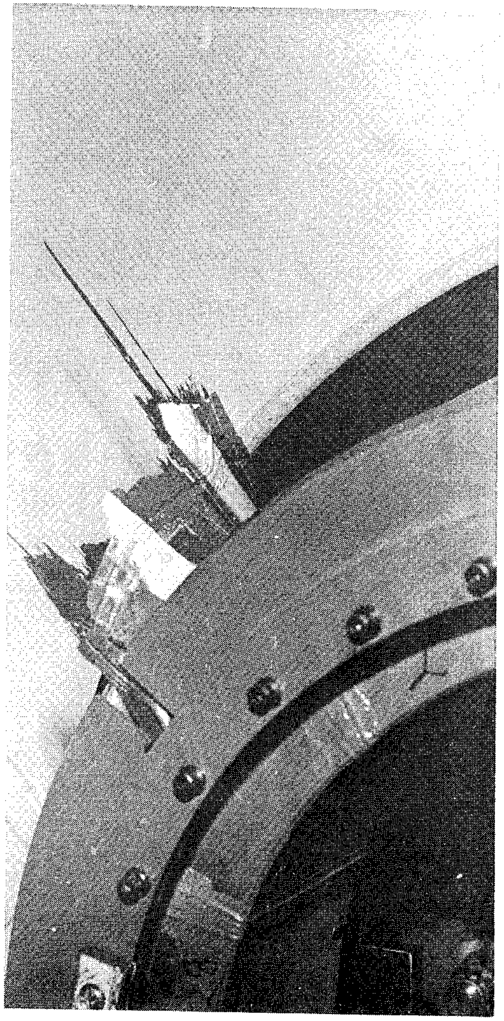


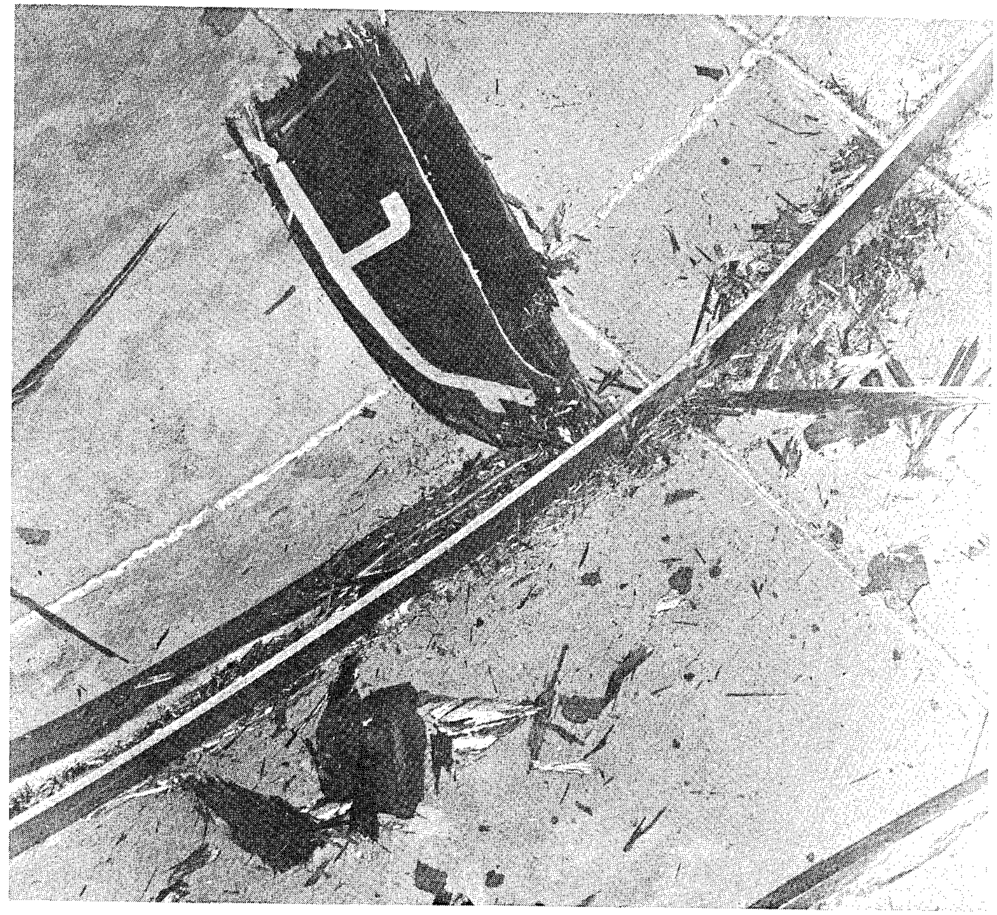
NASA-FOD Impact Resistance Test
Blade S/N NG2
Graphite/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)



Following Impact with
3 Each 5.08 cm Diameter
Tempered Hailstones.
Total Weight, 210 g (7.4 oz).

Figure 33. Blade S/N NG2 After Impact.

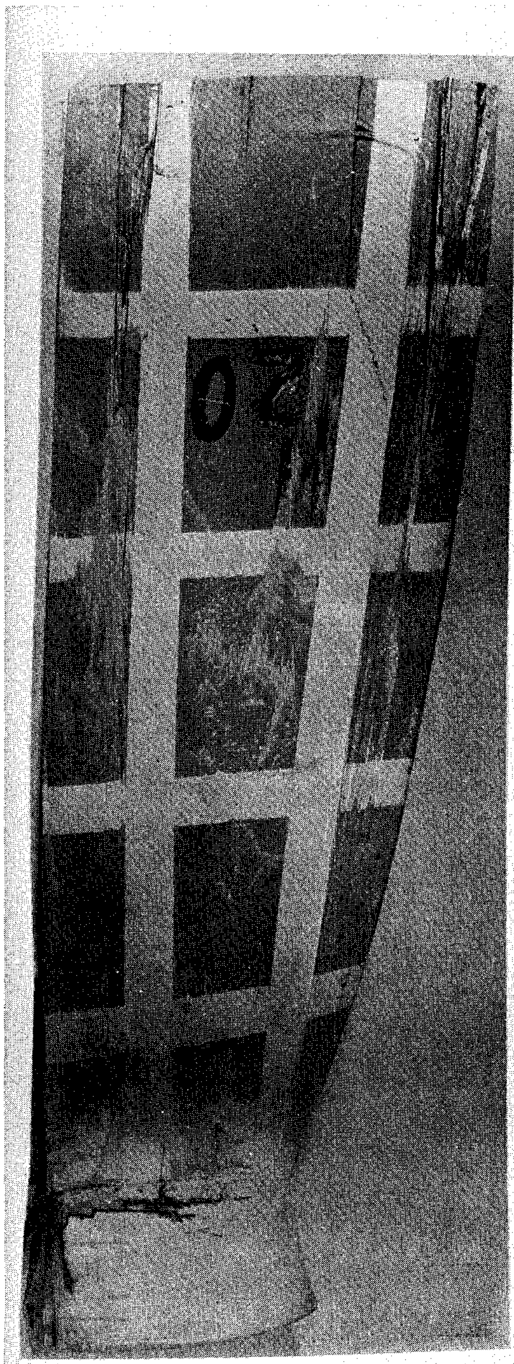




NASA-FOD Impact Resitance Test
Blade S/N NG3
Graphite/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
794 g (28 oz) RTV Bird
340 g (12 oz) Slice
0.384 Radians (22°) Incidence Angle

Figure 34. Blade S/N NG3 after Impact.

NASA-FOD Impact Resistance Test
Blade S/N NG4
Graphite/Epoxy
Tip Speed: 244 m/sec (800 ft/sec)
454 g (16 oz) Real Pigeon
312 g (11 oz) Slice
0.384 Radians (22°) Incidence Angle



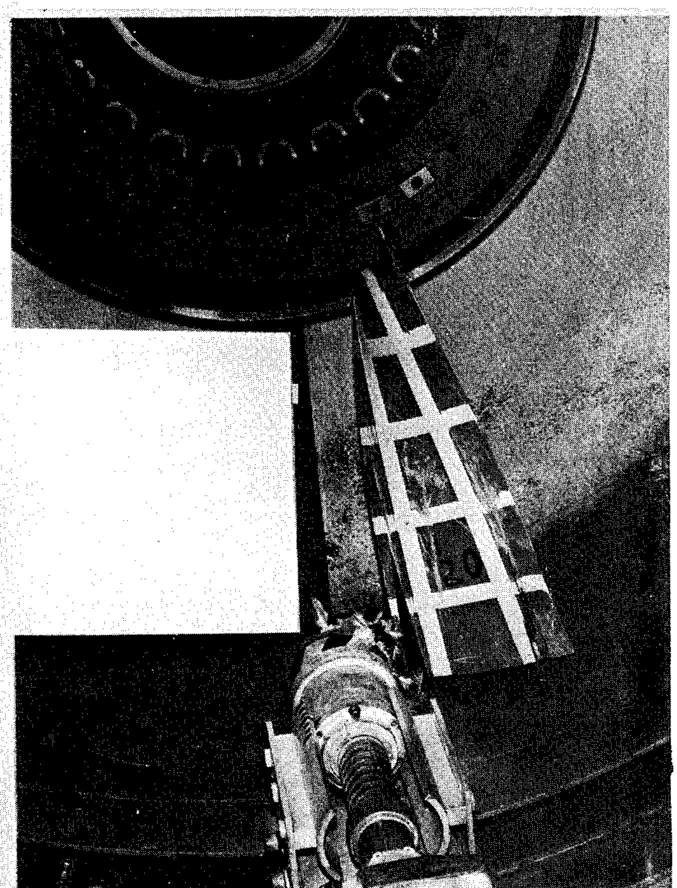
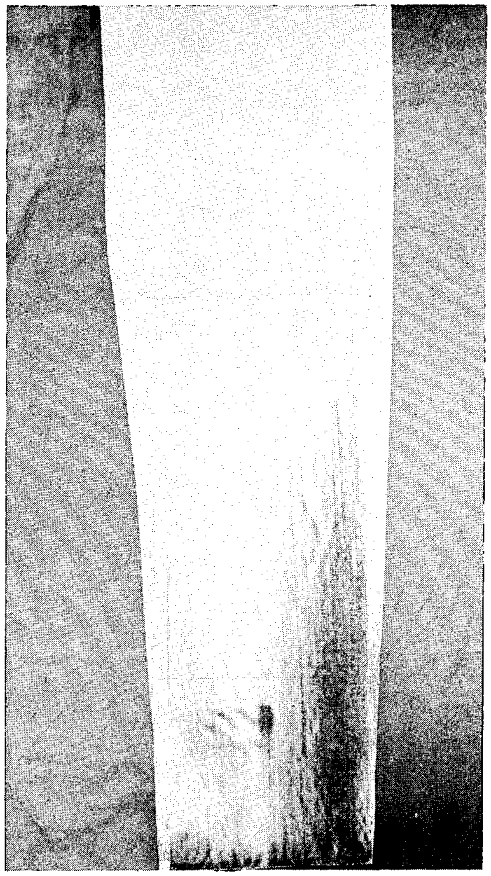
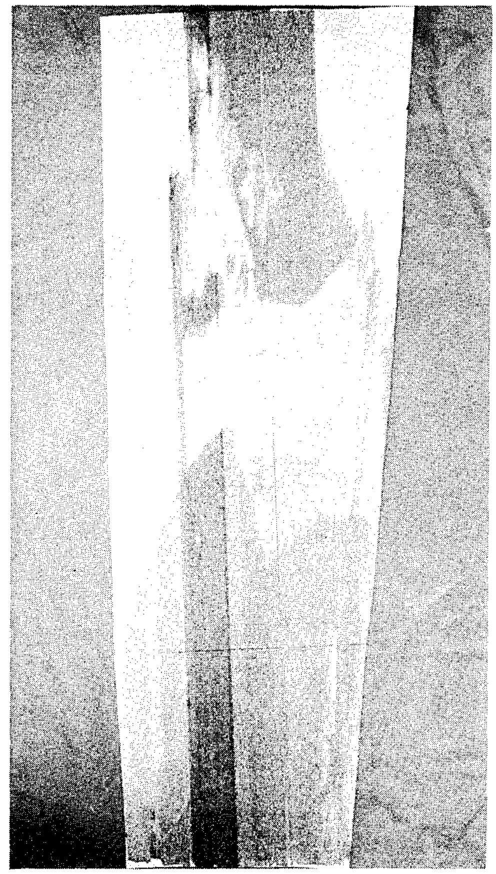


Figure 35. Blade S/N NG4 after Impact.



Before Impact



After Impact

Figure 36. TTUCS of Graphite/Epoxy Blade S/N NG4.

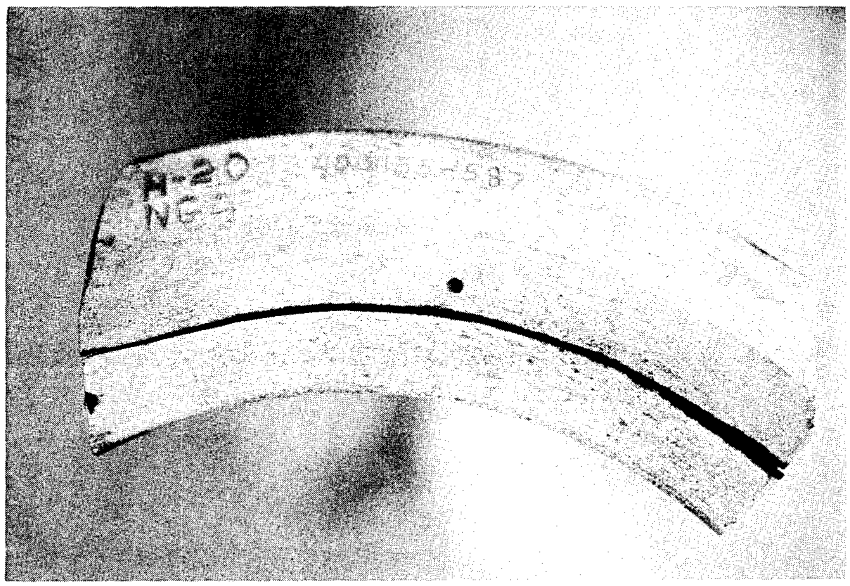


Figure 37. Dye Penetrant Inspection of Dovetail After Impact, Blade S/N NG4.

Test No.	Blade Type	Axial Load	
NG5	Graphite/Epoxy	24.5 KN	(5500 lbs)
NB5	Boron/Epoxy	30.5 KN	(6850 lbs)

The titanium blade was not tested under an axial load. The apparatus providing axial load was designed to test composite blades only, the motivation being the belief that such materials may be more affected by tensile loading than ductile materials. The apparatus, therefore, was not designed to accommodate the relatively large blade deflection response of the titanium blades to impact. It was obviously desirable to minimize blade interactions with the apparatus.

Measurement and analysis of triaxial inertial head acceleration histories as well as blade strains were carried out. High speed motion picture records of the tests were also studied and integrated with inertial head data.

The most striking feature of these tests is the generally good appearance of the composite blades after impact. The graphite/epoxy blade (NG5) is shown in Figures 38 (convex view) and 39 (concave view). The only visible damage to the blade was a rather clean crack extending down from the tip section a distance of less than 7.62 cm (3 in.). The chalk coating can still be seen adjacent to the projectile part (Figure 39) which extended across the entire blade chord. The convex surface of the blade was marked only with short line segments extending back from the leading edge. The lines can be seen clearly to the leading edge, demonstrating, thereby, that no projectile interaction has taken place on the convex surface. The axial load measured after the test showed the same level as set up before the test.

The boron/epoxy blade is shown after impact in Figures 40 (convex) and 41 (concave). This blade was damaged much more severely than the previous one, although it too tolerated the impact well. The principal damage consisted of cracks and multiple delaminations extending down from the tip section and situated again between the loading straps. The damage is especially clear in Figure 41. Similar indications of projectile interaction can be seen here as well.

The strap load after the test was measured as being 25.9 KN (5820 lbs) representing a drop off of only 15%. Thus, the strap loads were essentially maintained during impact.

The titanium blade impacted in the third test is shown in Figures 42 (convex) and 43 (concave). The blade was not fractured but was perceptibly deformed at the leading and trailing edges along the projectile path.

Data obtained by integration of inertial head acceleration records are shown in Table XIV.

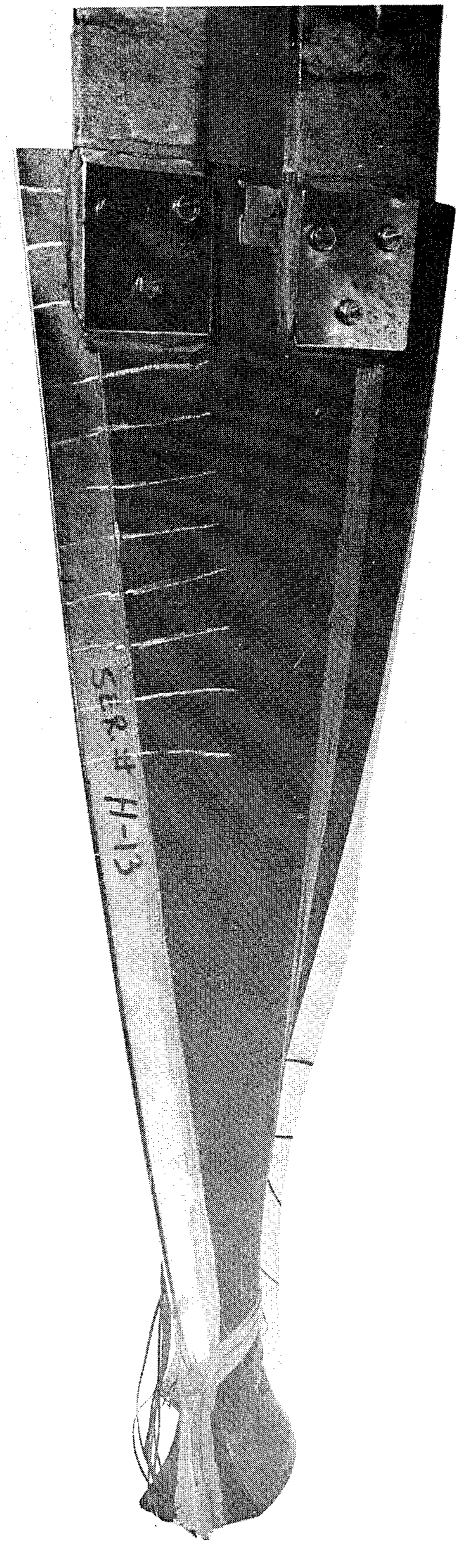


Figure 38. NG5 Graphite/Epoxy Blade after Impact (Convex Surface), Test No. STOL 1.

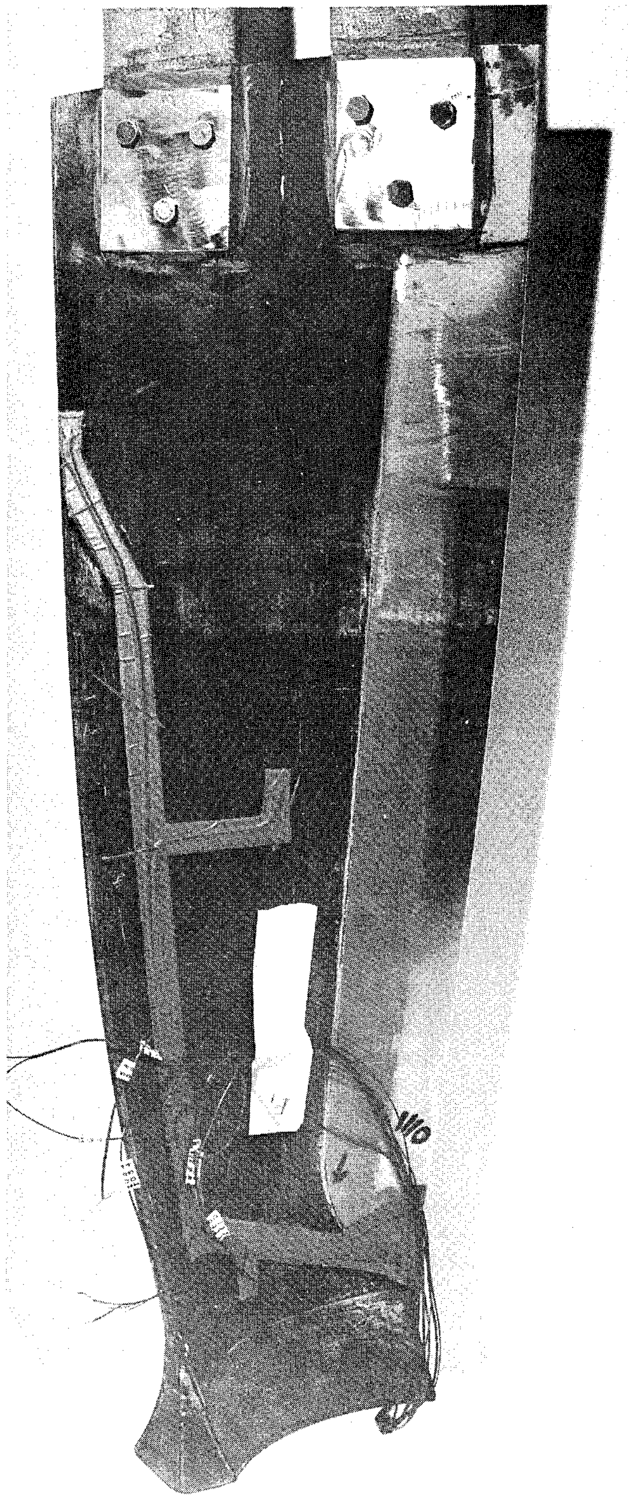


Figure 39. NG5 Graphite/Epoxy Blade after Impact (Concave Surface), Test No. STOL 1.

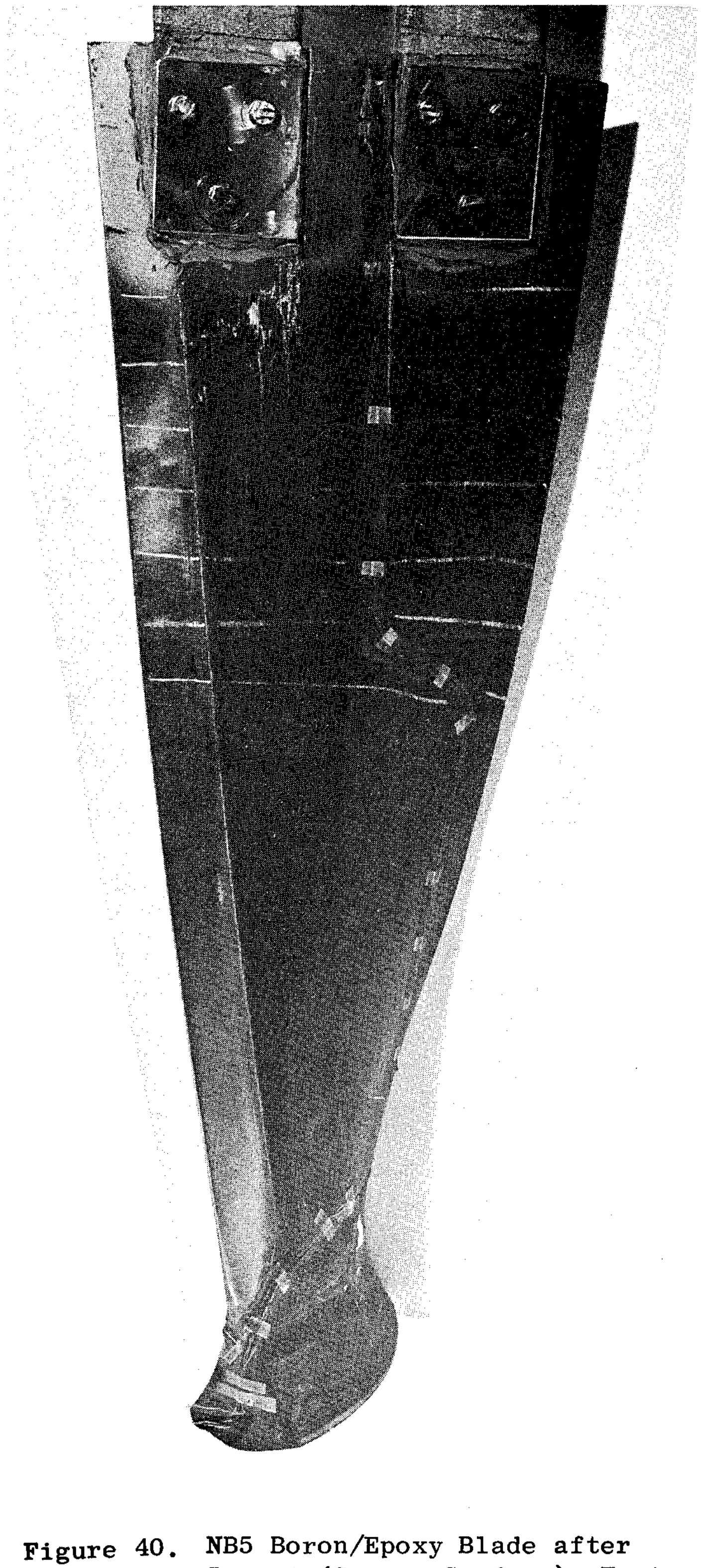


Figure 40. NB5 Boron/Epoxy Blade after Impact (Convex Surface), Test No. STOL 2.

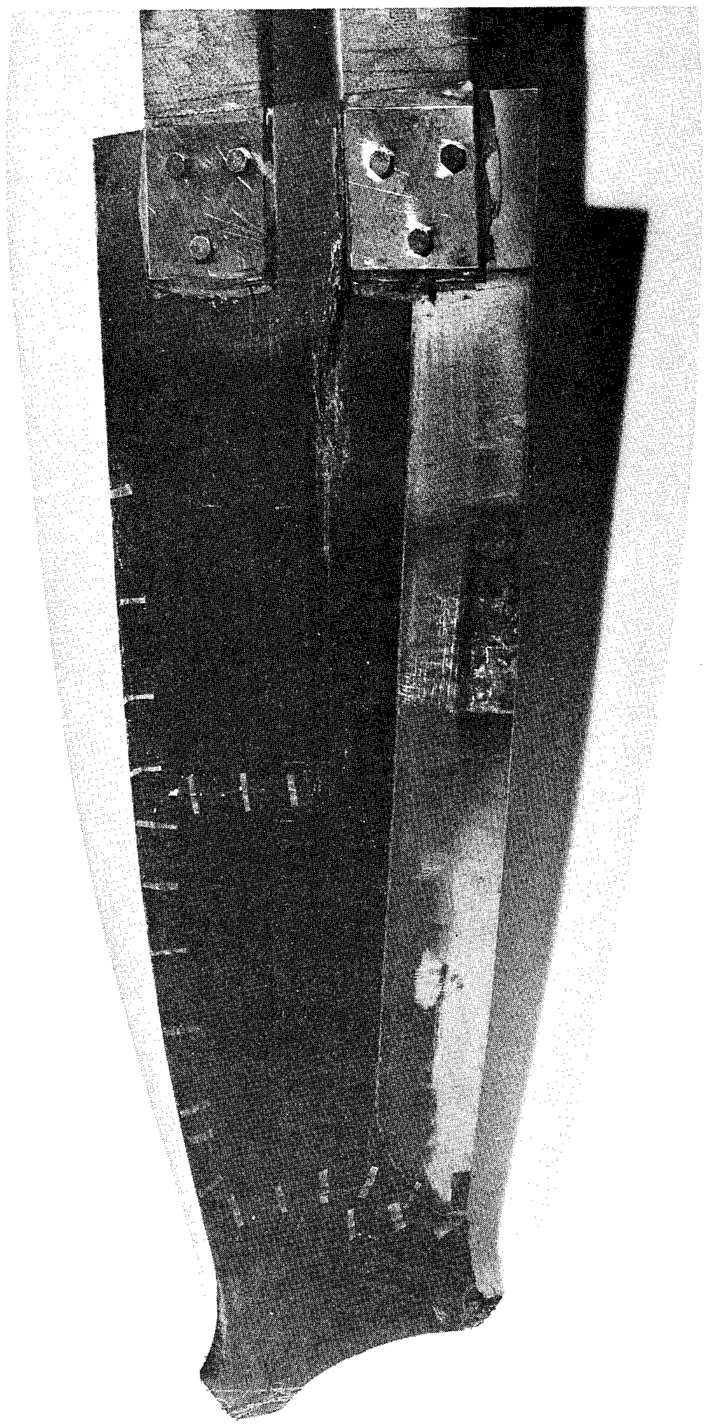


Figure 41. NB5 Boron/Epoxy Blade after Impact (Concave Surface), Test No. STOL 2.

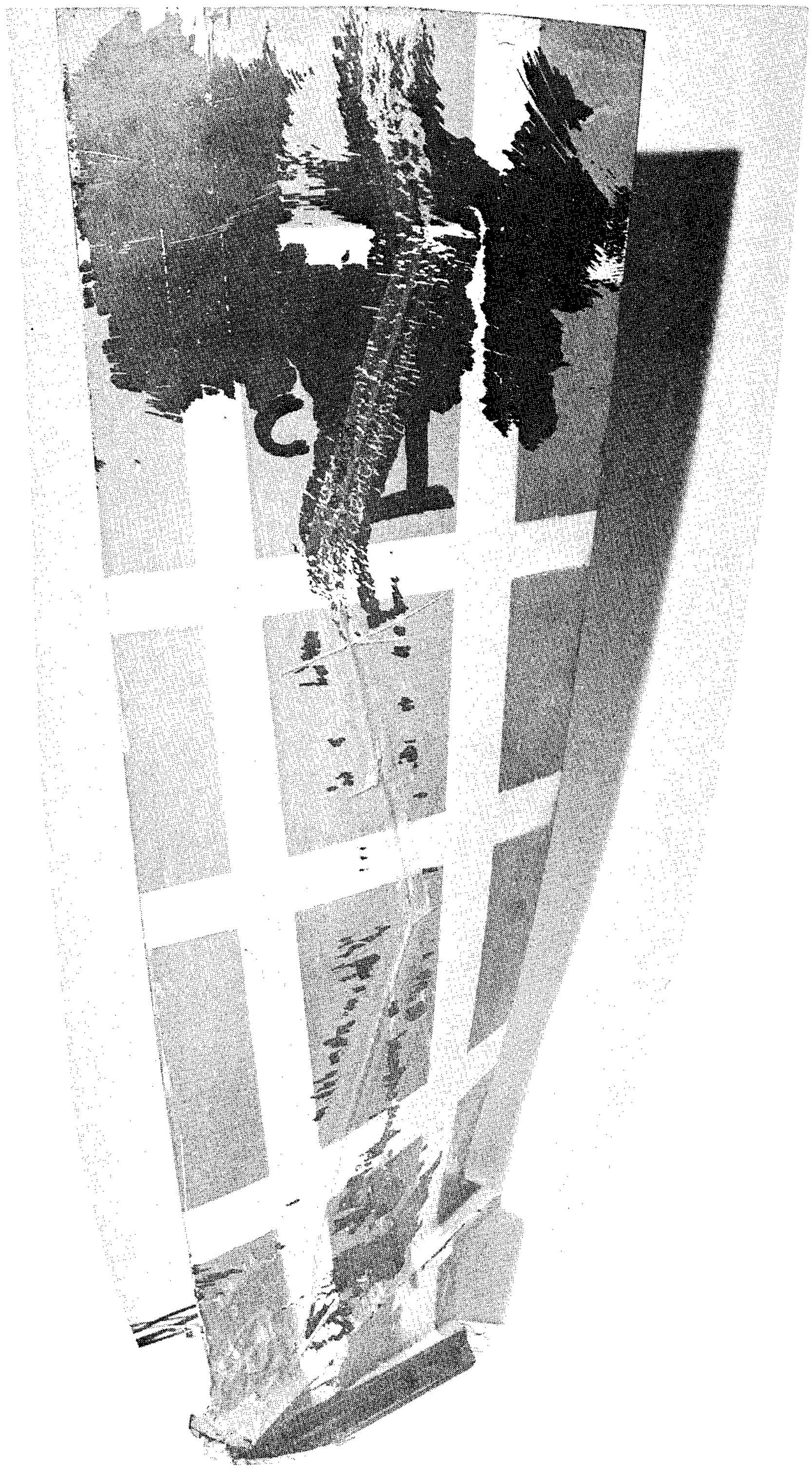


Figure 42. Titanium Blade after Impact (Convex Surface), Test No. STOL 3.

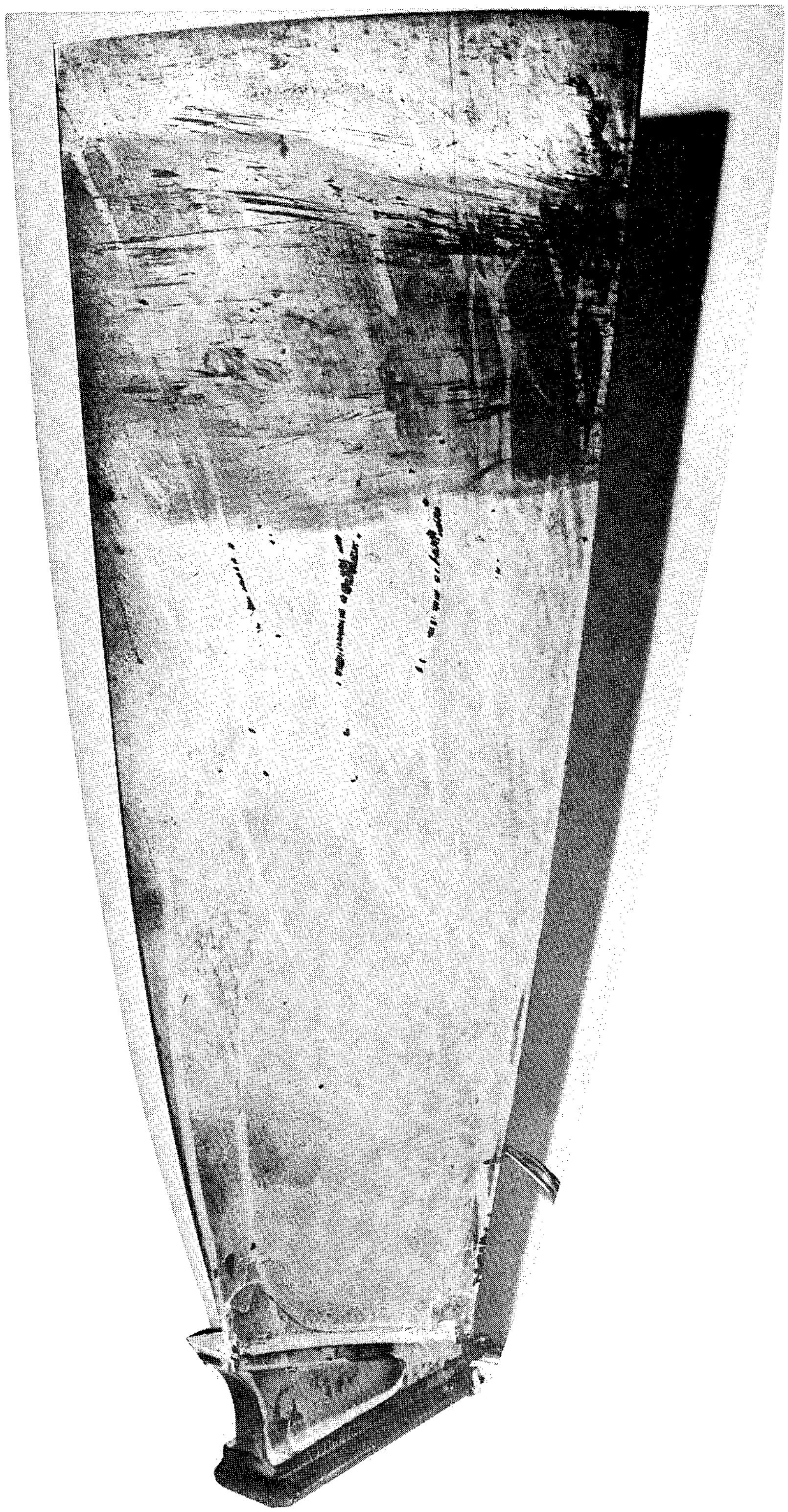


Figure 43. Titanium Blade after Impact (Concave Surface), Test No. STOL 3.

Table XIV. Inertial Head Data

Test No.	W_h Kilogram (lb)	$J_x = J_y$ Kilogram-Meter^2 (lb-ft-sec^2)	J_z Kilogram-Meter^2 (lb-ft-sec^2)	$\dot{\theta}_m$ Rad/sec	H kg-meter^2/sec (lb-ft-sec)
NG5	300 (662)	14.29 (10.54)	12.87 (9.49)	1.227	17.53 (12.93)
NB5	300 (662)	14.29 (10.54)	12.87 (9.49)	1.307	18.68 (13.78)
Ti2	103 (228)	2.66 (1.96)	1.63 (1.20)	10.32	27.42 (20.23)

W_h - Weight of rigid mass section of inertial head apparatus

J_x, J_y, J_z - Mass moments of inertia of corresponding inertial head section about x, y, z axes

$\dot{\theta}_m$ - Maximum measured value of angular velocity of the inertial head

H - Angular momentum corresponding to $\dot{\theta}_m$

The angular velocity of the inertial head was obtained by direct integration of the accelerometer records. A typical example of these records is shown in Figure 44.

Once the angular velocity of the inertial head was obtained, the value of the initial velocity of the blade center of gravity was found. For this the inertial properties of the system, listed in Table XV, were used. The value of V was found by equating the theoretical value of the inertial head angular velocity, expressed in terms of V, to the measured value. These values are shown respectively in columns 1 and 2 Table XVI. Once V was known, the kinetic energy and momentum of the blade produced by the impact were obtained,

$$E = \frac{1}{2}\left(\frac{J_b}{\ell^2} + M\right)V^2$$

$$I = \left(\frac{J_b}{\ell^2} + M\right)V$$

the values for V, I, and E are also listed in Table XVI.

The mode of failure observed during inertial head testing is different from whirligig results with damage taking place in between the straps. The blade stiffness in the tip region is unnatural due to the strap attachment and reinforcement method used.

5.3.3 Hybrid Composite Laminate Panel Tests

Panel specimens representing the outer 31 cm (12 in.) of the TF39 blade were designed as outlined in Section 3.2. These designs were selected as being the most likely FOD resistant specimens with which to conduct screening tests.

In each test case the simulated RTV bird was targeted so the leading edge of the panel would split the projectile in half. The panel was positioned at .384 radian (22°) incidence relative to the gun barrel. The impact location was 10.2 cm (4 in.) from the tip and the projectile desired velocity was 226 m/sec (740 ft/sec) which represents a 244 m/sec (800 ft/sec) tip speed of a full-size rotating composite blade. A typical before-test FOD panel is shown in Figure 45.

A total of 16 test shots was made on 10 panels. Each panel was tested with an 85 g (3 oz) RTV bird, 6 panels passed this size with little damage and were tested again with a 227 g (8 oz) bird.

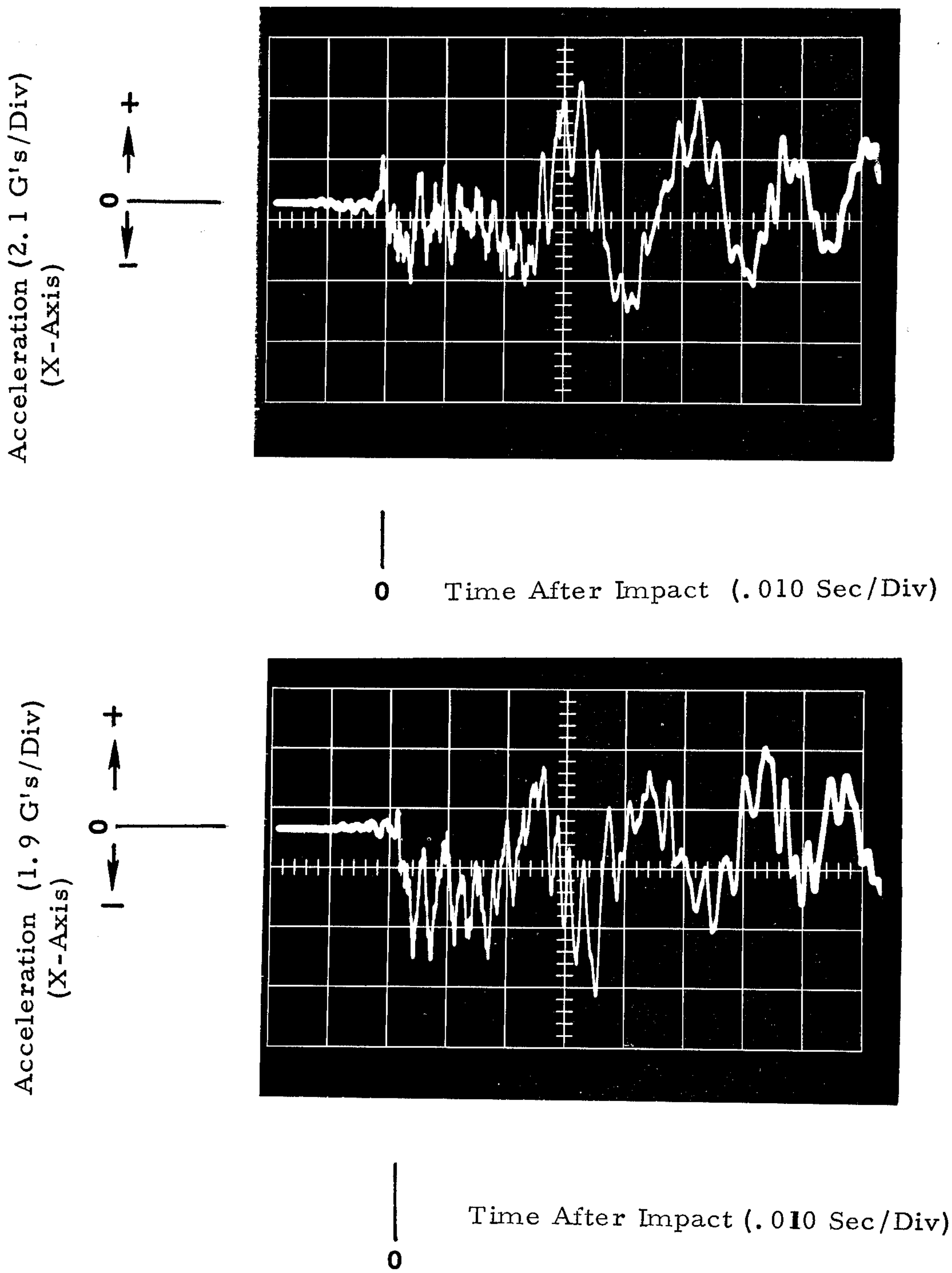


Figure 44. First Cycles of First Flexural Blade. Test Vibration after Beginning of Impact (Boron/Epoxy).

Table XV. Blade and System Properties.

Test No.	W_b Kilogram (lb)	ℓ Meter (ft)	h Meter (ft)	K	$J_b + M_b\ell^2$ Kilogram-Meter^2 (lb-ft-sec^2)
STOL 1	1.12 (2.466)	0.2196 (0.7208)	0.1765 (0.5792)	0.008673	0.0812 (0.05991)
STOL 2	1.39 (3.063)	0.2196 (0.7208)	0.1765 (0.5792)	0.01076	0.1008 (0.07442)
STOL 3	2.98 (6.57)	0.2103 (0.6900)	0.1475 (0.4842)	0.10550	0.2044 (0.1508)

W_b - Weight of blade airfoil section above reference plane PA, as used in GE/AEG drawings

ℓ - Distance between plane PA and blade center of gravity

h - Distance between plane PA and inertial head pivot point 0

K - Ratio of the head/blade inertial stiffness about the pivot point

$J_b + M\ell^2$ - Mass moment of inertia of blade about axis parallel to dovetail axis at plane PA

Table XVI. Kinetic Energy and Momentum Transferred to Blade.

Test No.	$\dot{\theta}/\frac{V}{\ell}$	$\dot{\theta}_m$ rad/sec	V meter/sec (ft/sec)	I kg-meter/sec (lb-sec)	E kg-meter^2/sec^2 (lb-ft)
NG5	0.01720	1.227	15.7 (51.4)	26.4 (5.93)	206.6 (152.4)
NB5	0.02129	1.307	13.5 (44.2)	28.2 (6.34)	190.0 (140.2)
Ti	0.19086	10.32	11.4 (37.3)	52.5 (11.81)	298.7 (220.4)

$\left(\dot{\theta}/\frac{V}{\ell}\right)$ – Theoretical value of dimensionless inertial head angular velocity at:

time $t = \frac{T}{2}$ where T is the period of first flexural blade vibration

$\dot{\theta}_m$ – Maximum integrated (measured) value of head velocity

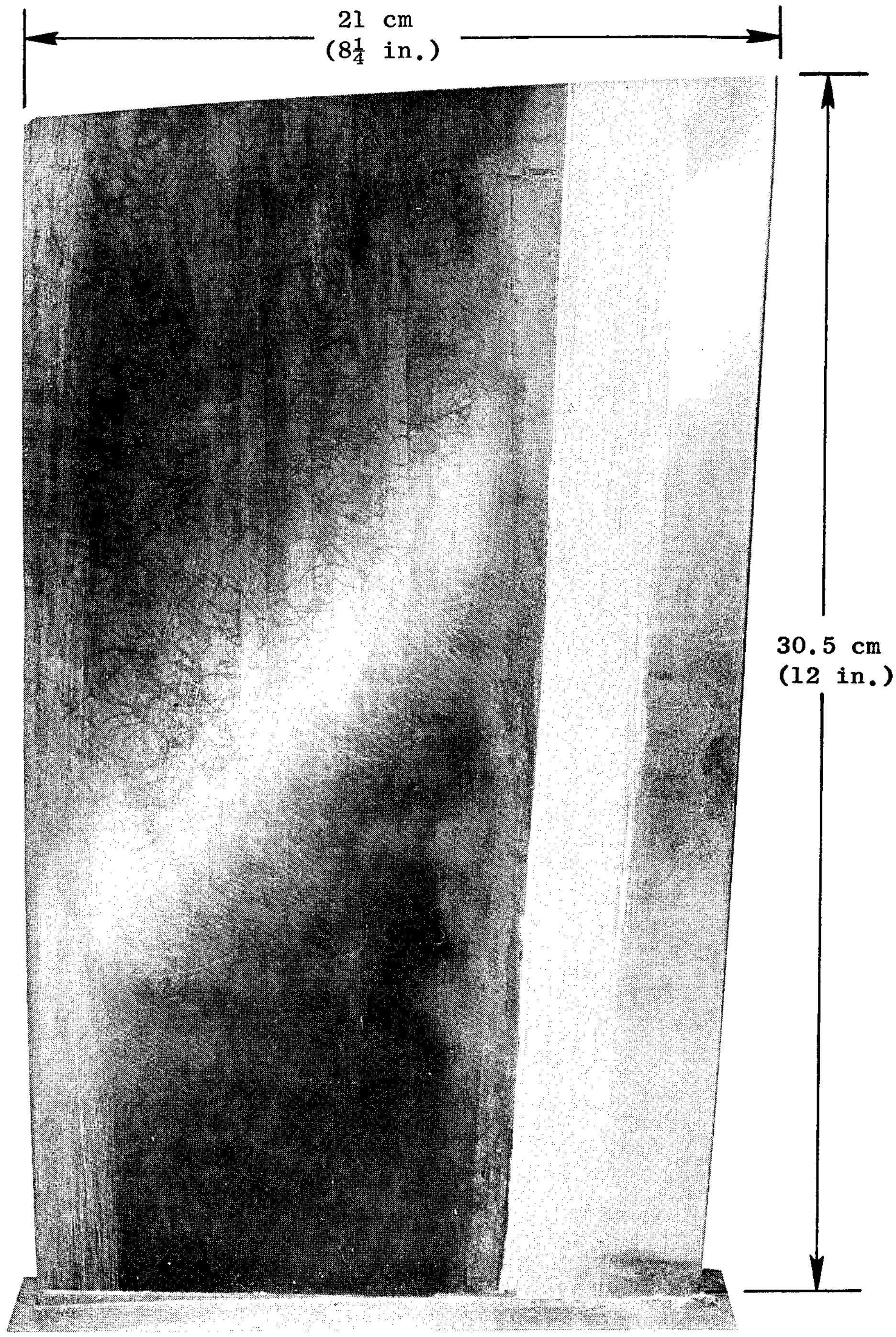


Figure 45. Typical NASA-FOD Hybrid Test Panel Before Impact.

Two panels were damaged after the initial 3-oz impact and were rejected when it was found that the nickel plate FOD leading edge protection was manufactured incorrectly. Two additional panels were made and withstood the 85 g (3 oz) impact. A complete summary of all the panels tested is shown in Table XVII.

The four panels which showed the least resistance to impact damage when impacted with an 85 g (3-oz) simulated bird were discarded. Those discarded were:

- S/N 1. PR 288/80% AUG/20% Kevlar 49. Lay-up: Standard TF39 (0/22/0/-22)

- S/N 3. Shell PR 288/80% AU/20% S-Glass. Core: PR 288/AU. Lay-up: Standard TF39 (0/22/0/-22). Shell consisted on outer 14 layers (17.78 cm, 0.07 in.)

- S/N 4. Shell PR 288/80% AU/20% S-Glass. Core: PR 288/Kevlar 49. Lay-up: Standard TF39 (0/22/0/-22). Shell consisted of outer 14 layers (17.78 cm, 0.07 in.)

- S/N 6. PR 288/AU. Lay-up: Standard TF39 (0/22/0/-22).

The primary damage to these panels occurred in the area of the nickel-plated leading edge. In each, the plating separated from the composite material, the composite split radially, and the plies separated under the plating. The high speed movies show the leading edge buckling under the force of impact and splitting at the tip. As the bird passes by the nickel-plated area, the leading edge is bent over several degrees before the composite material starts to move.

As part of the posttest evaluation, it was found that panels S/N 1 and 4 had a thicker plating of nickel than desired, and it was thought this could account for the leading edge being stiffer than it should be, thus causing the type of failure seen. It was decided to remake these two panels with the proper leading edge thickness and retest them with 85 g (3 oz) birds.

A remade panel did withstand 85 g (3 oz) FOD better than the original specimens, so these two panels (S/N 9 and 10) were included with those to be tested with larger birds.

Panel S/N 6 confirmed previous test results that an all-graphite/epoxy material tested under those conditions cannot withstand the higher shear loading induced in the shorter panel, while a full-size blade at the same conditions would be relatively undamaged. It was tested as a control specimen to establish a baseline for comparison of hybrid materials and the expected increase in threshold of moderate damage in full-scale blades.

Table XVII. Summary of FOD Panel Testing.

Panel S/N	Material Composition	Bird Weight g (oz)	Bite	Impact Angle, Radian (degrees)	Velocity m/sec (ft/sec)	Bench Frequencies (Hertz) Before Test 1F	Before Test 1T	Before Test 2F	After Test 1F	After Test 1T	After Test 2F
1	PR 288/80% AU/ 20% Kevlar 49	85, (3)	Half	.384, (22)	236, (737)	96	318	382	Not Determined		
2	PR 288/80% AU 20% S-Glass	85, (3)	Half	.384, (22)	236, (773)	96	320	380	96	302	375
	Second Shot	227, (8)	Half	.384, (22)	216, (707)	96	302	375	96	218	---
3	Shell: PR 288/ 80% AU/20% S-Glass Core: PR 288/AU	85, (3)	Half	.384, (22)	233, (764)	97	324	388	Not Determined		
4	Shell: PR 288/ 80% AU/20% S-Glass Core: PR 288/ Kevlar 29	85, (3)	Half	.384, (22)	227, (746)	95	312	384	Not Determined		
5	Shell: PR 288/ 50% AU/50% Kevlar 49 Core: PR 288/AU	85, (3)	Half	.384, (22)	242, (793)	92	308	372	93	270	366
	Second Shot	227, (8)	Half	.384, (22)	234, (768)	93	270	368	Not Determined		
6	Standard PR 288/AU	85, (3)	Half	.384, (22)	233, (764)	106	338	418	Not Determined		
7	Shell: PR 288/ 50% AU/50% Kevlar 49 Core: PR 288/ Kevlar 49	85, (3)	Half	.384, (22)	234, (768)	92	296	370	91	282	360
	Second Shot	227, (8)	Half	.384, (22)	152, (500)	91	282	360	Not Determined		
8	PR 288/AU with Kevlar 49; 4 Plies at ± 80° at 45° at Tip	85, (3)	Half	.384, (22)	231, (758)	102	328	392	95	318	363
	Second Shot	227, (8)	Half	.384, (22)	223, (732)	95	318	363	80	292	355
9	Remake of No. 1	85, (3)	Half	.384, (22)	238, (782)	95	318	363	80	292	355
	Second Shot	227, (8)	Half	.384,	214, (701)	100	318	384	Not Determined		
10	Remake of No. 4	85, (3)	Half	.384, (22)	229, (750)	100	322	380	96	300	376
	Second Shot	227, (8)	Half	.384, (22)	218, (715)	96	300	376	Not Determined		

Panel S/N 3 sustained local damage at the leading edge. However, to impact this specimen with a larger bird would most surely have caused leading edge total failure so it was rejected.

Six of the panel specimens were selected for continued testing with larger size simulated RTV birds. The test conditions remained the same with only the bird weight increased to 227 g (8 oz).

The specimens selected in this testing were based on results of visual examination, frequency data, ultrasonic C-scan results, and review of high speed movies.

Those panels tested with the 8 oz. simulated bird were:

- S/N 2. PR 288/80% AU/20% S-Glass. Lay-up: Standard TF39 (0/22/0/-22)
- S/N 5. Shell: PR 288/50% AU/50% Kevlar 49. Core: PR 288/AU. Lay-up: Standard TF39 (0/22/0/-22); shell consists of 7 plies each of PR 288/AU and PR 288/Kevlar 49
- S/N 7. Shell: PR 288/50% AU/50% Kevlar 49. Core: PR 288/Kevlar 49. Lay-up: Standard TF39 (0/22/0/-22); shell consists of 7 plies each of PR 288/AU and PR 288/Kevlar 49
- S/N 8. PR 288/AU and PR 288/Kevlar 49. Lay-up: Standard TF39 (0/22/0/-22) with 4 plies of Kevlar 49 at ± 80° and ± 45°
- S/N 9. PR 288/80% AU/20% Kevlar 49 (Remake of S/N 1). Lay-up: Standard TF39 (0/22/0/-22)
- S/N 10. Shell: PR 288/80% AU/20% S-Glass (Remake of S/N 4). Core: PR 288/Kevlar 49. Lay-up: Standard TF39 (0/22/0/-22). Shell consists of outer 14 layers (17.78 cm, 0.07 in.)

The results of the 227 g (8-oz) impact test were quite clear after visual examination. The remade panels (S/N 9 and S/N 10) did not hold up at all under the impact. The plies separated across the entire chord down to the devcon base. On S/N 10 the nickel leading edge cracked at the point of impact.

Panel S/N 5 was also totally damaged. The leading edge was at 1.57 radians (90°) to the rest of the panels after impact. The composite material was completely delaminated and split.

Panel S/N 7 did exhibit some resistance to the 227 g (8-oz) FOD. The leading edge bond separated over 2/3 of the length, and there was minor damage at the trailing edge tip.

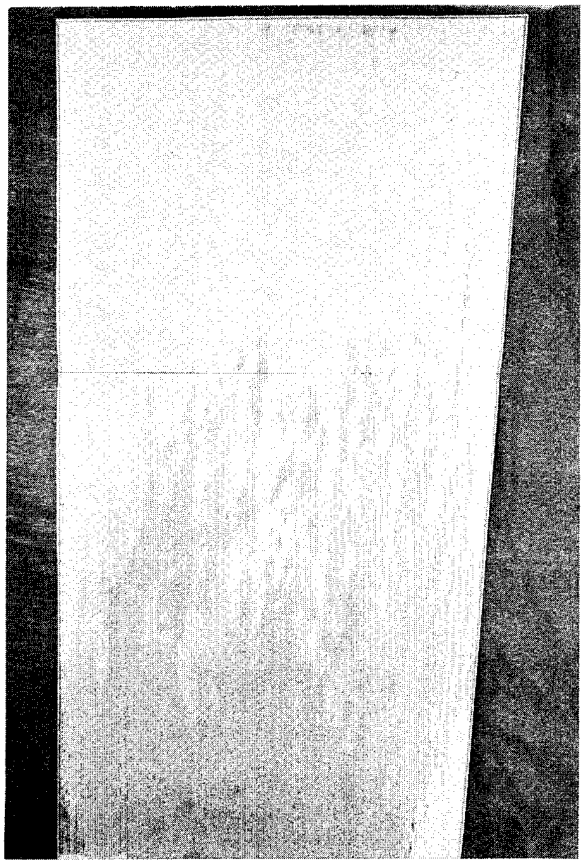
Figures 46 through 50 show the TTUCS pictures of FOD specimens S/N 1 through S/N 8. C-scans, before test, were not obtained on specimens S/N 4, S/N 5, and S/N 6 due to equipment problems at the time. After impact, C-scans are shown for specimens S/N 5, S/N 7 and S/N 8. All scans before test show acceptable levels of grayness. Specimens S/N 5, S/N 7, and S/N 8 all sustained hits by an 85 g (3-oz) bird followed by a 227 g (8-oz) bird. Figure 48 shows S/N 5 after impact with an 85 g (3-oz) bird. Visual inspection revealed slight separation between the LE protection and the specimen at the tip. The specimen was not scanned after impact with the 227 g (8-oz) bird, which resulted in severe delamination and the LE being torn away. C-scans are shown for S/N 7 and S/N 8 after impact with the 227 g (8-oz) bird in Figures 49 and 50, respectively. Only moderate damage occurred to S/N 7 while S/N 8 had severe localized damage at the TE tip.

The most resistant material/lay-up configurations to the 227 g (8-oz) FOD were S/N 2 (Figure 51) and S/N 8 (Figure 52). The panels sustained moderate local damage but posttest investigation supported the selection of these panels as the best of those tested.

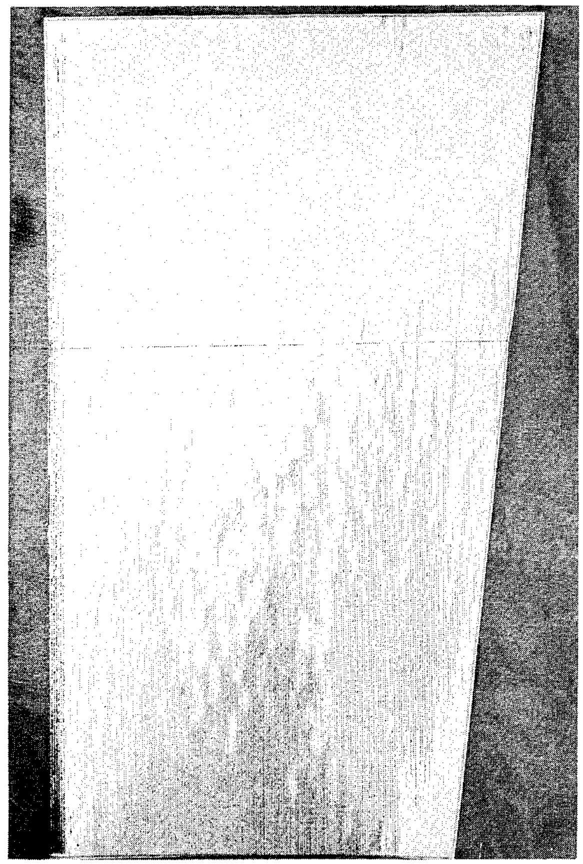
The test results indicate that static FOD panel test conditions are much more severe than anticipated in comparison with dynamic whirligig blade FOD testing. This is due primarily to the higher shear loading induced in the shorter panels as compared to a full-size blade. However, material screening results using panels show good correlations when comparing relative merits of material on an absolute basis, but the results should not be used to compare expected damage under similar test conditions in a whirligig or an engine.

5.3.4 Hybrid/Composite Blade Tests

Based on the hybrid panel tests, six blades of the two selected designs (Panels S/N 2 and S/N 8) of hybrid/epoxy composite were tested under the same conditions as the previous blades. However, much larger birds were used because of the expected increase in blade impact strength. In these tests 794 g (28-oz) and 1350 g (48-oz) RTV simulated birds were used, so effective slices of 227 g (8-oz) and 700 g (24-oz), respectively, were impacted by the blades. This represented a 25% increase in the size for expected moderate damage and a 100% increase in the size for expected heavy damage over previously tested full-size blades. One blade of each design was then tested with a 1130 g (2.5 lb) real mallard duck. A summary of the tests for the hybrid/epoxy blades is given in Tables XVIII and XIX, along with a description of the resultant damage. The Design 1 blades (S/N HE 4, 5, and 6) were based on the panel S/N 2 configuration, and the Design 2 blades (S/N HE 1, 2, and 3) were based on the panel S/N 8 configuration.



S/N 1



S/N 2

Figure 46. TTUCS of FOD Panel S/N i and 2, Before Impact.

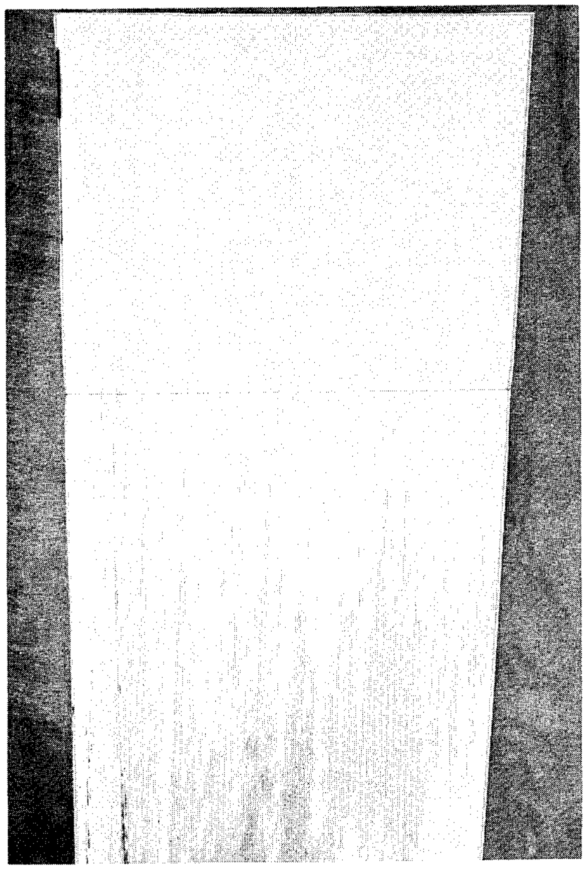


Figure 47. TTUCS of FOD Panel S/N 3, Before Impact.

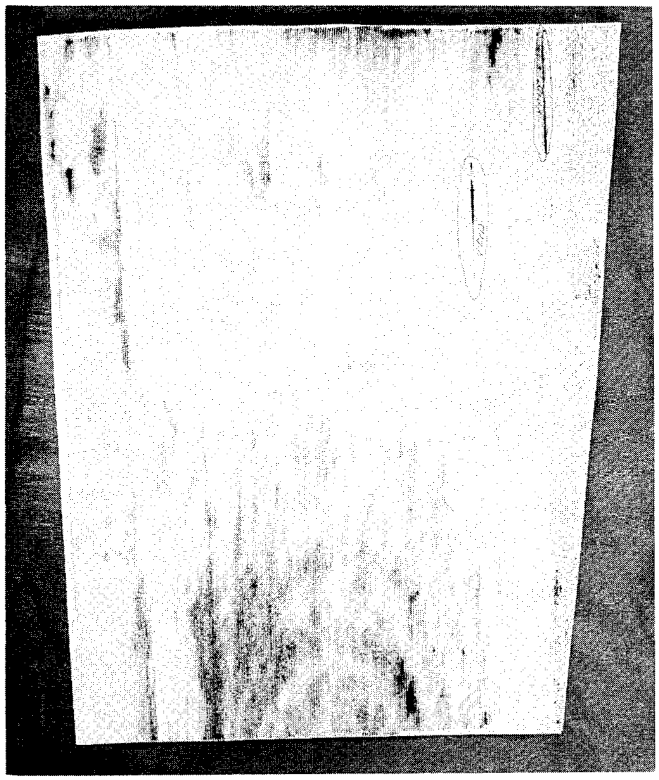
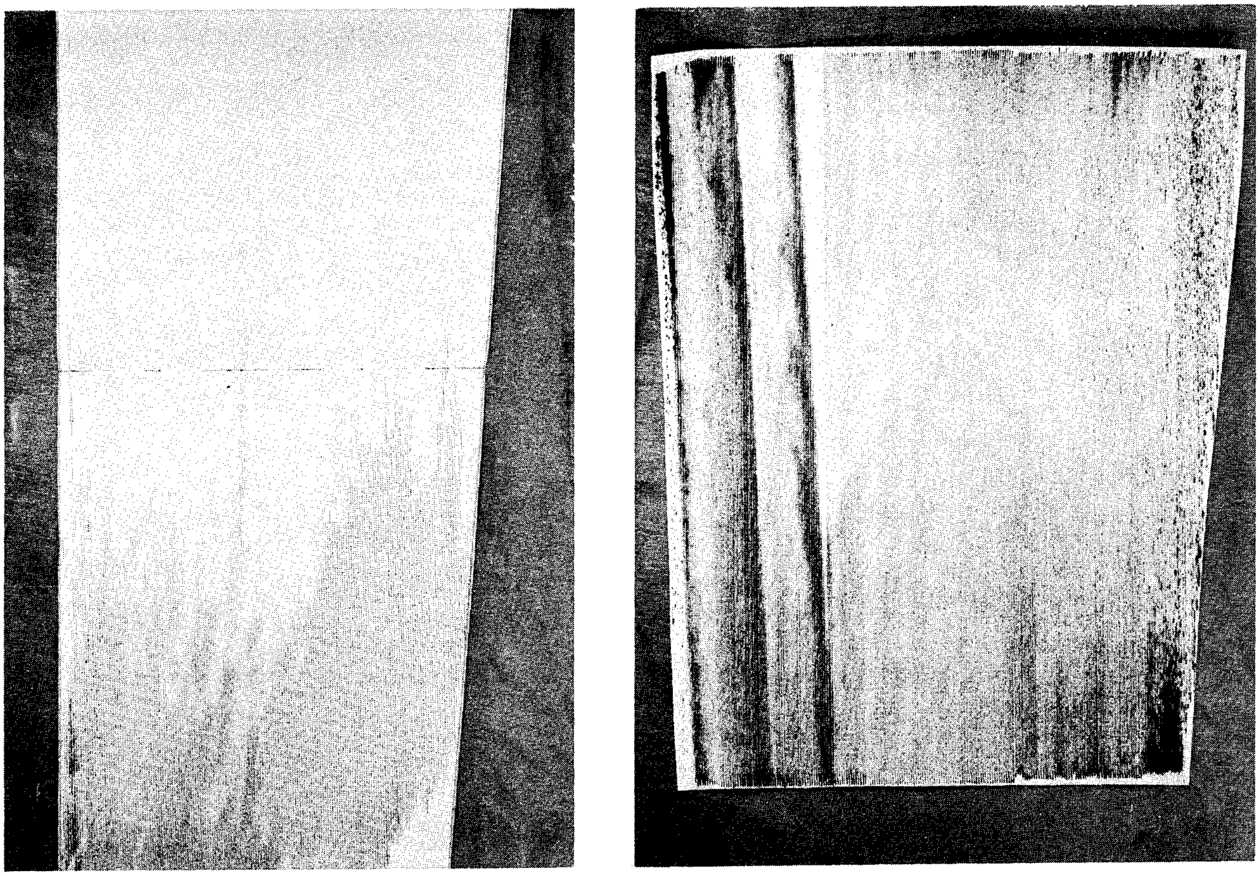


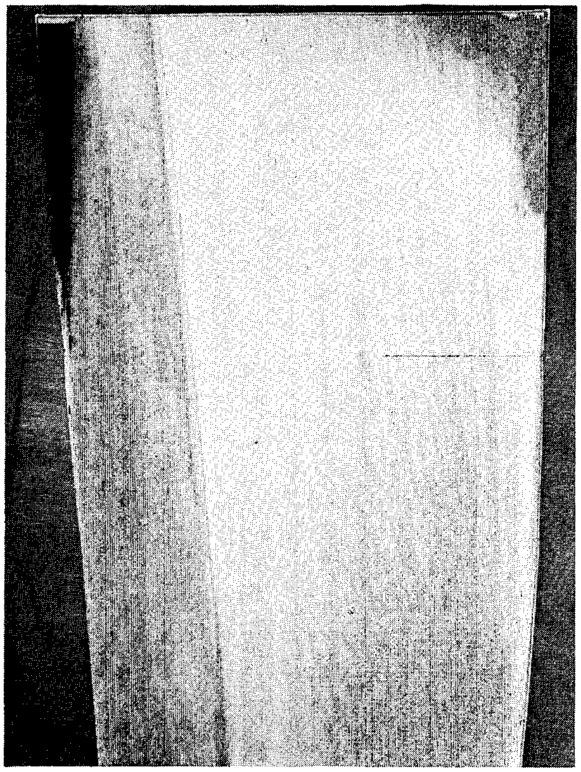
Figure 48. TTUCS of FOD Panel S/N 5, After Impact.



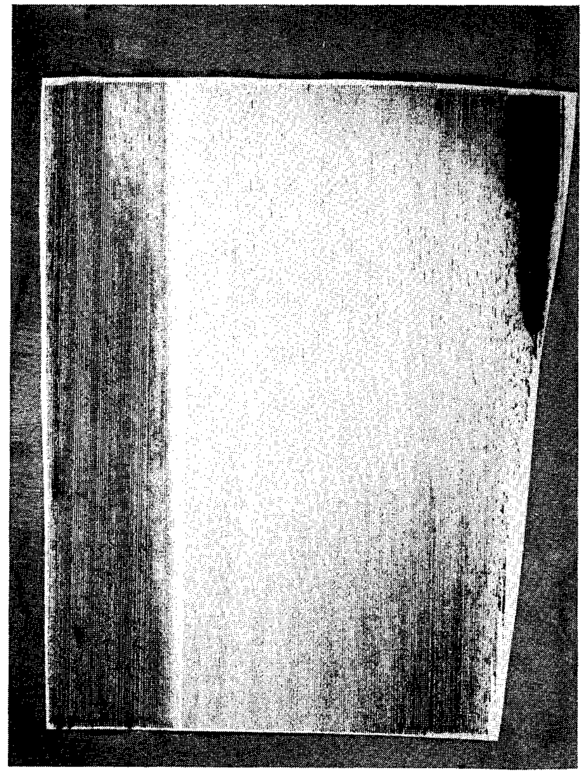
Before Impact

After Impact

Figure 49. TTUCS of FOD Panel S/N 7, Before and After Impact.



Before Impact

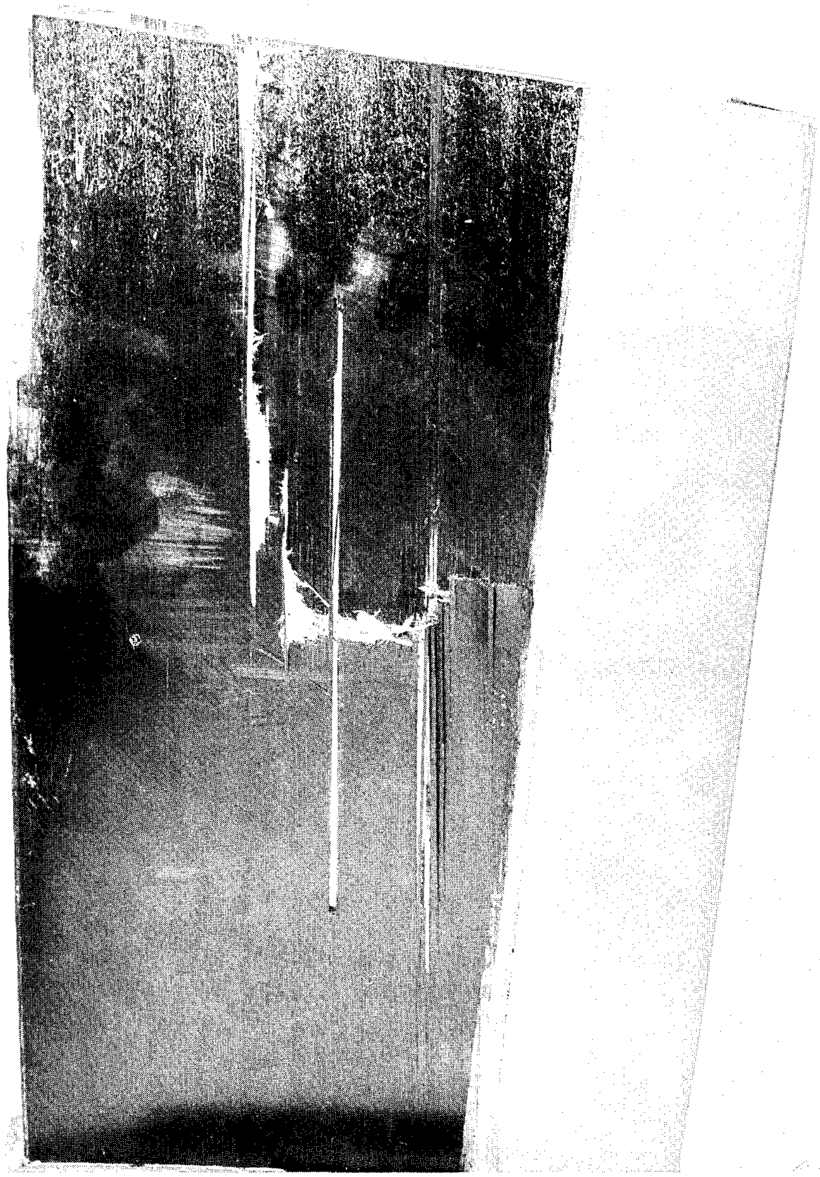


After Impact

Figure 50. TTUCS of FOD Panel S/N 8, Before and After Impact.

NASA-FOD Program
Panel S/N 2
PR 288/80% AU/20% S-Glass
RTV Simulated Bird
Bird Size: 227 g (8 oz)
Half Bite
Impact Velocity: 215 m/sec (707 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 51. Panel S/N 2 After Impact.



NASA-FOD Program
Panel S/N 8
PR 288/AU with Kevlar 49
4 Plys @ ± 80° At Tip
4 Plys @ ± 45°
RTV Simulated Bird
Bird Size: 227 g (8 oz)
Half Bite
Impact Velocity: 223 m/sec (732 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 52. Panel S/N 8 After Impact.

Table XVIII. Impact Results Summary.

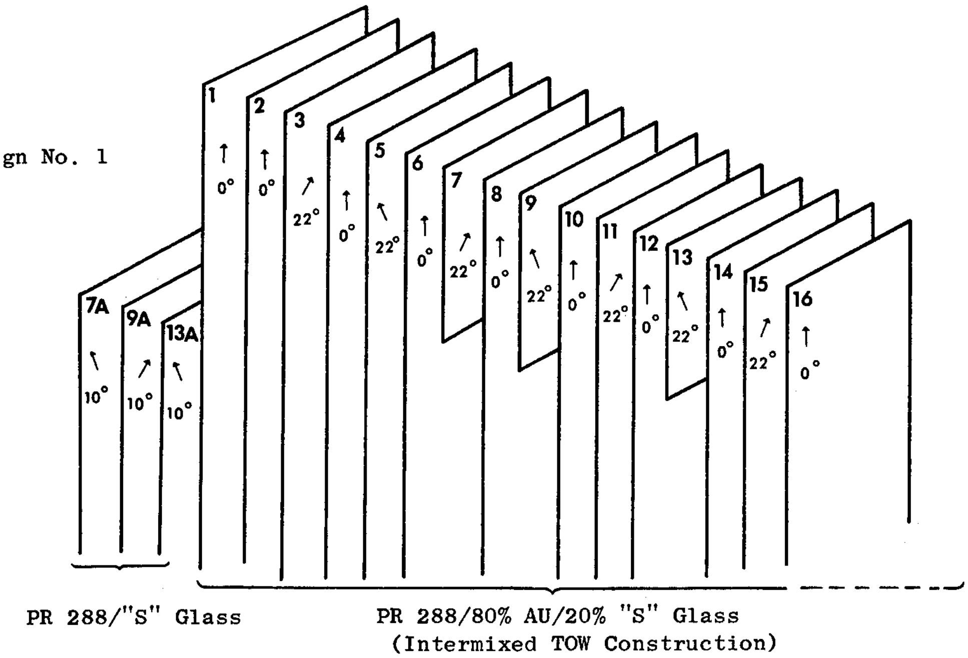
Shot No.	Blade S/N	Blade** Design	Bird Size	Bite Size	Blade Failure	Max. Tip Defl.	Angle of Rotation	Comments
1	H/E 1	2	794 g, (28 oz)	200 g, (7 oz)	No	6.53 cm, (2.57 in.)	39°	Axial crack entire length of dovetail extending up TE* approximately 10 cm (4 in.) and up LE to nickel plating. Slight laminar separation at TE tip. Slight unbonding of nickel plating at LE tip.
2	H/E 2	2	1360 g, (48 oz)	680 g, (24 oz)	No	16.7 cm, (6.58 in.)	53°	Two large axial cracks entire length of the dovetail extending up LE and TE. Axial crack across blade root. 28 cm (11 in.) of nickel plating torn off down from tip. Delamination of entire airfoil.
3	H/E 4	1	794 g, (28 oz)	229 g, (8 oz)	No	N/A (No Film)	N/A (No Film)	Axial crack entire length of dovetail extending up LE and TE to airfoil. Small loss of material and delamination at TE tip. Unbonding of nickel plating 25% down LE from tip.
4	H/E 5	1	1360 g, (48 oz)	765 g, (27 oz)	Yes	24.6 cm, (9.69 in.)	84°	Airfoil separated at root from dovetail. Separation occurred approximately 200° after impact point.
5	H/E 6	1	1134 g, (2.5 lbs)	570 g, (20 oz)	No	16.5 cm, (6.48 in.)	50°	Leading edge protection (nickel plating) knocked off. Laminate separation in airfoil. Material loss at blade LE tip. Short axial crack in root. Most visible damage occurred during secondary hits (2nd - 5th revolutions after first impact).
6	H/E 3	2	1134 g, (2.5 lbs)	680 g, (24 oz)	No	22.3 cm, (8.77 in.)	68°	Axial crack entire length of dovetail extending up the LE and TE. Laminate separation in airfoil. Material loss at blade tip. Most visible damage occurred during secondary hits (2nd through 5th revolutions after first impact).

* LE - Leading Edge

TE - Trailing Edge

** See Figure 53

• Design No. 1



• Design No. 2

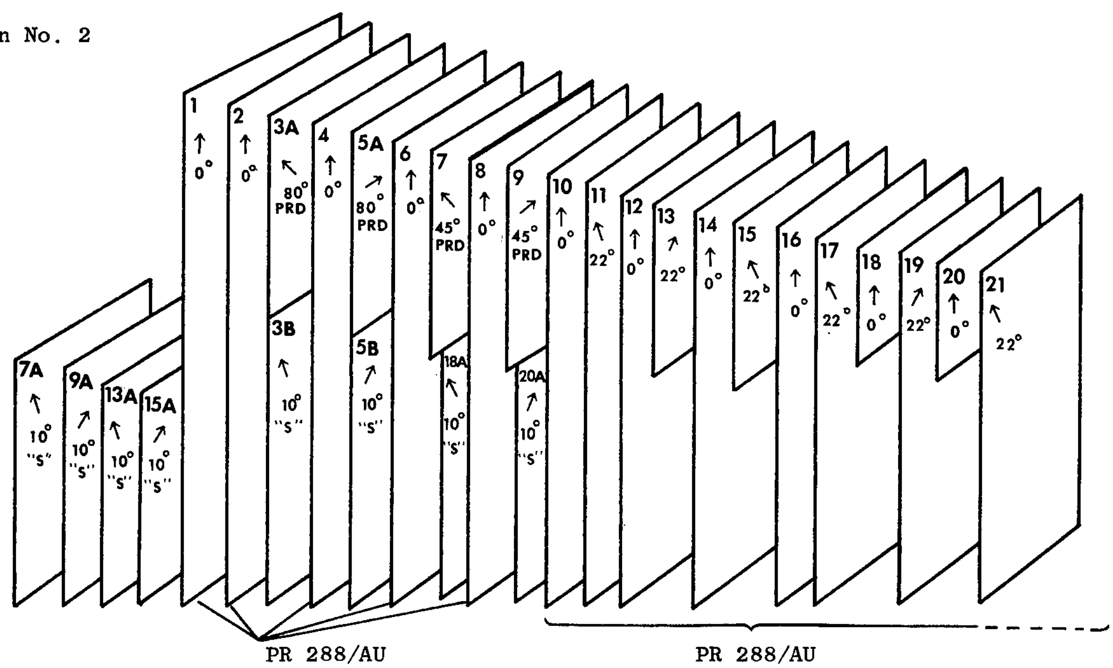


Figure 53. Manufacturing Layup of Selected Design Whiriligig Test Blades.

Table XIX. Summary of Whirligig Test.

Blade Material/Lay-up	Ser. No.	Bird Size	Slice Size	Before Test Frequency (Hertz)			After Test Frequency (Hertz)			Δ in Freq.	% Loss in Weight	% Loss in Area
				1F	2F	1T	1F	2F	1T			
Design 2*	H/E 1	794 g (28 oz)	200 g (7 oz)	58	163	300	58	152	292	7%	1%	1%
Design 2	H/E 2	1360 g (48 oz)	680 g (24 oz)	58	156	300	Not able to determine			---	5%	5%
Design 2	H/E 3	1134 g (40 oz)	680 g (24 oz)	58	156	300	Not able to determine			NA	9%	10%
Design 1*	H/E 4	794 g (28 oz)	227 g (8 oz)	59	160	306	59	140	264	15%	1%	1%
Design 1	H/E 5	1360 g (48 oz)	765 g (27 oz)	57	159	300	Blade failed			---	---	---
Design 1	H/E 6	1134 g (40 oz)	570 g (20 oz)	58	158	301	Not able to determine			NA	9%	10%

* See Figure 53

Also shown in the same table are tip deflections as taken from the high speed movies.

Figure 54 shows the RTV simulated bird before test, and Figure 55 shows the mallard duck. The duck is positioned for impact in Figure 56.

Posttest photographs of the blades are shown in Figure 57 through 62.

The six hybrid/epoxy blades were also subjected to evaluation using nondestructive means. Figures 63 through 67 show the TTUCS taken on blade specimens H/E 1 through H/E 6.

S/N H/E 1 - H.E 1 displayed nickel LE unbond down the entire blade length after impact with a 198 g (7-oz) slice of a simulated bird in addition to local delamination at the TE tip. There was also a single crack running across the dovetail. See Figure 63.

S/N H/E 2 - Hybrid blade H/E 2 was impacted with a 680 g (24-oz) slice of a simulated bird. Figure 64 shows the TTUCS prior to and after impact. The entire LE protection system was torn off the blade. This appears as a white strip down the left edge on Figure 64. The airfoil was completely delaminated in addition to two cracks down in the dovetail.

S/N H/E 3 - Figure 65 shows the TTUCS of H/E 3 before impact. This blade sustained 100% delamination after being impacted with a 680 g (24-oz) slice of a 1134 g (40 oz) duck and could not be scanned.

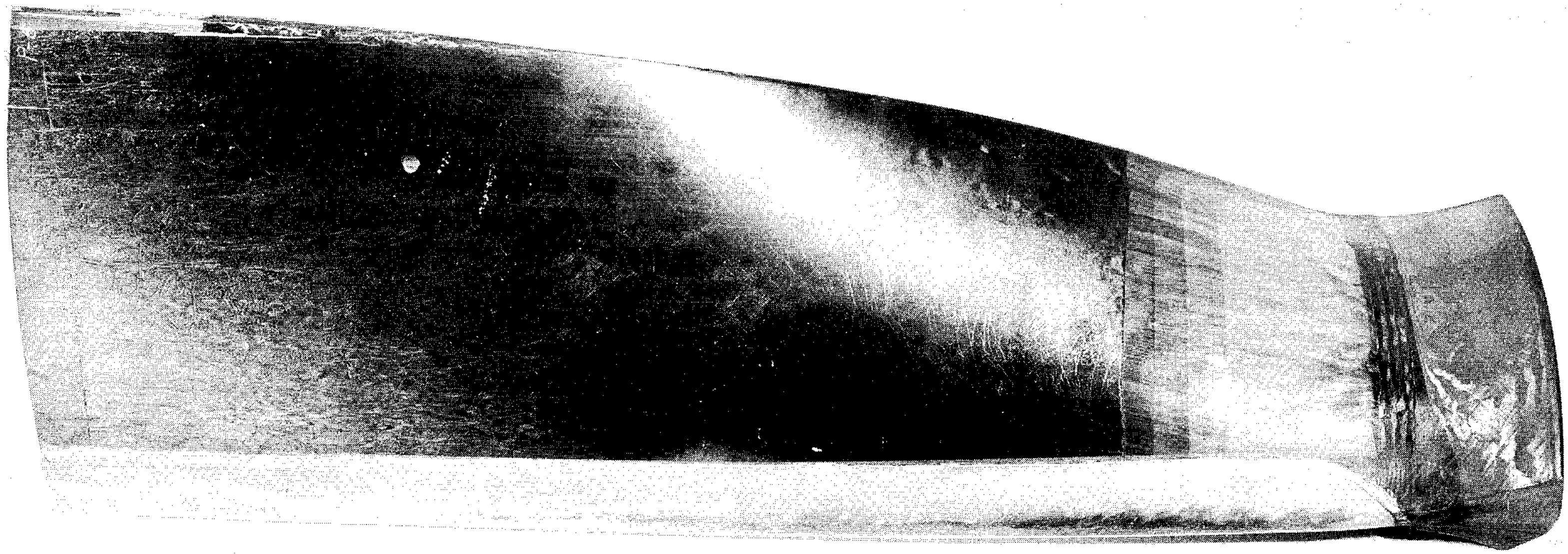
S/N H/E 4 - H/E 4 suffered local tip delamination, LE protection separation, and a single crack in the dovetail after impact with an 227 g *8-oz) slice of a simulated bird (Figure 66).

S/N H/E 5, H/E 6 - Both H/E 5 and H/E 6 sustained 100% delamination after impact with 765 g (27-oz) and 567 g (20-oz) slices of birds, respectively. H/E 5 broke off at the root, while H/E 6 remained in one piece. Figure 67 shows these blades prior to test.

Figure 54. Typical RTV Simulated Bird Before Test.

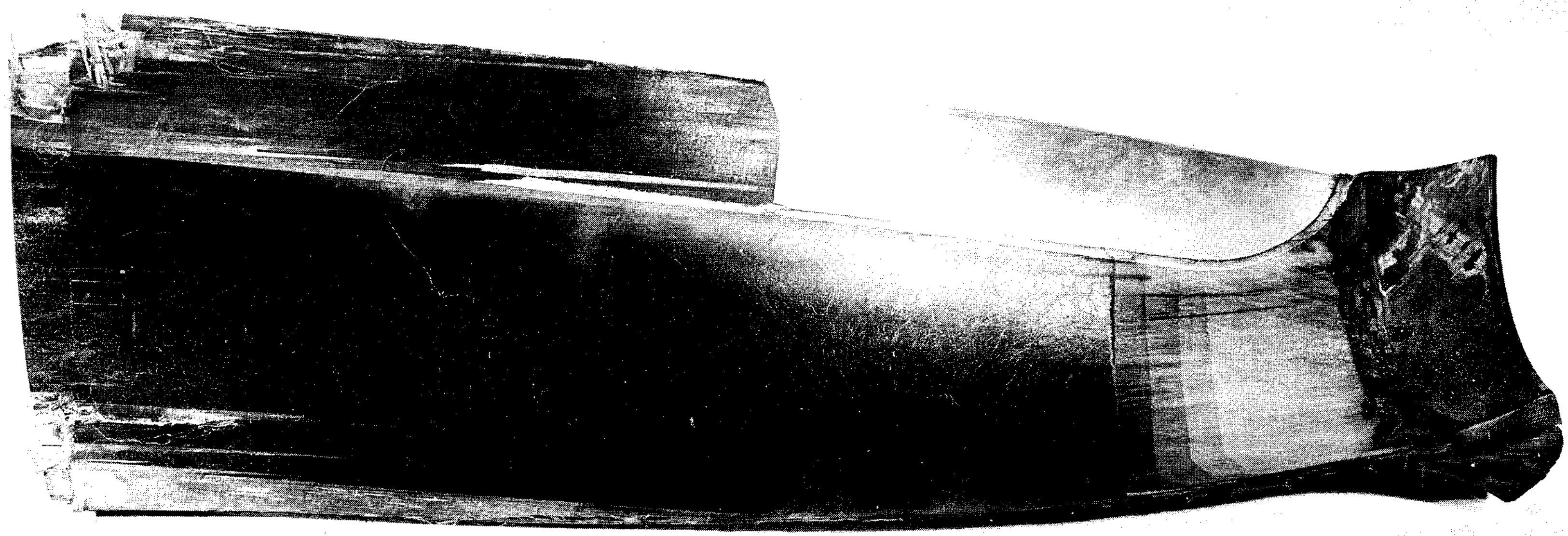
Figure 55. Wild Mallard Duck Used in Hybrid/Epoxy Blade Tests.

Figure 56. Mallard Duck Positioned for Impact in Whirligig Test Facility.



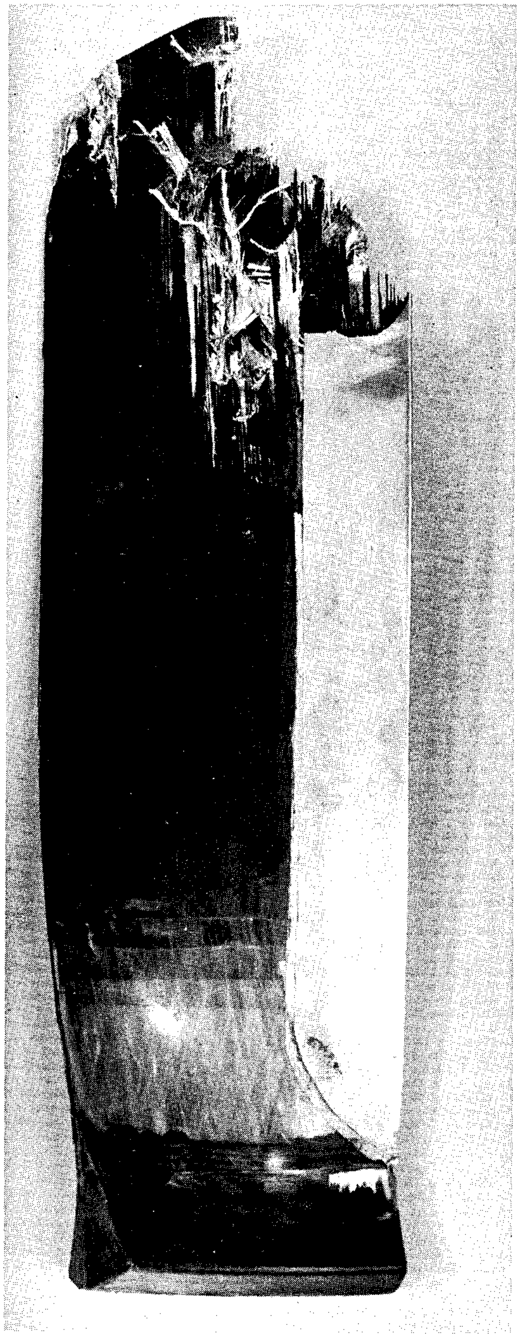
NASA-FOD Program
Blade S/N H/El
Design No. 2 Material/Lay-Up
RTV Simulated Bird
Bird Size: 794 g (28 oz)
Slice Size: 200 g (7 oz)
Blade Tip Speed: 244 m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 57. Blade S/N H/El After Impact.



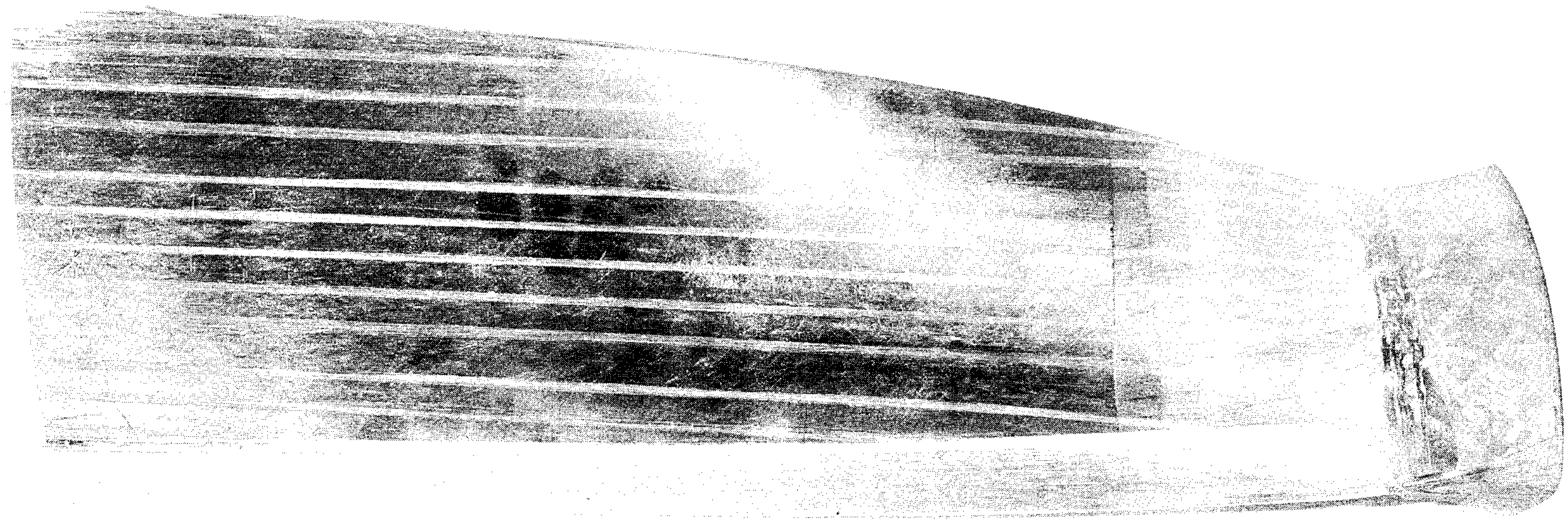
NASA-FOD Program
Blade S/N H/E2
Design No. 2 Material/Lay-Up
RTV Simulated Bird
Bird Size: 1360 g (48 oz)
Slice Size: 680 g (24 oz)
Blade Tip Speed: 244 m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 58. Blade S/N H/E2 After Impact.



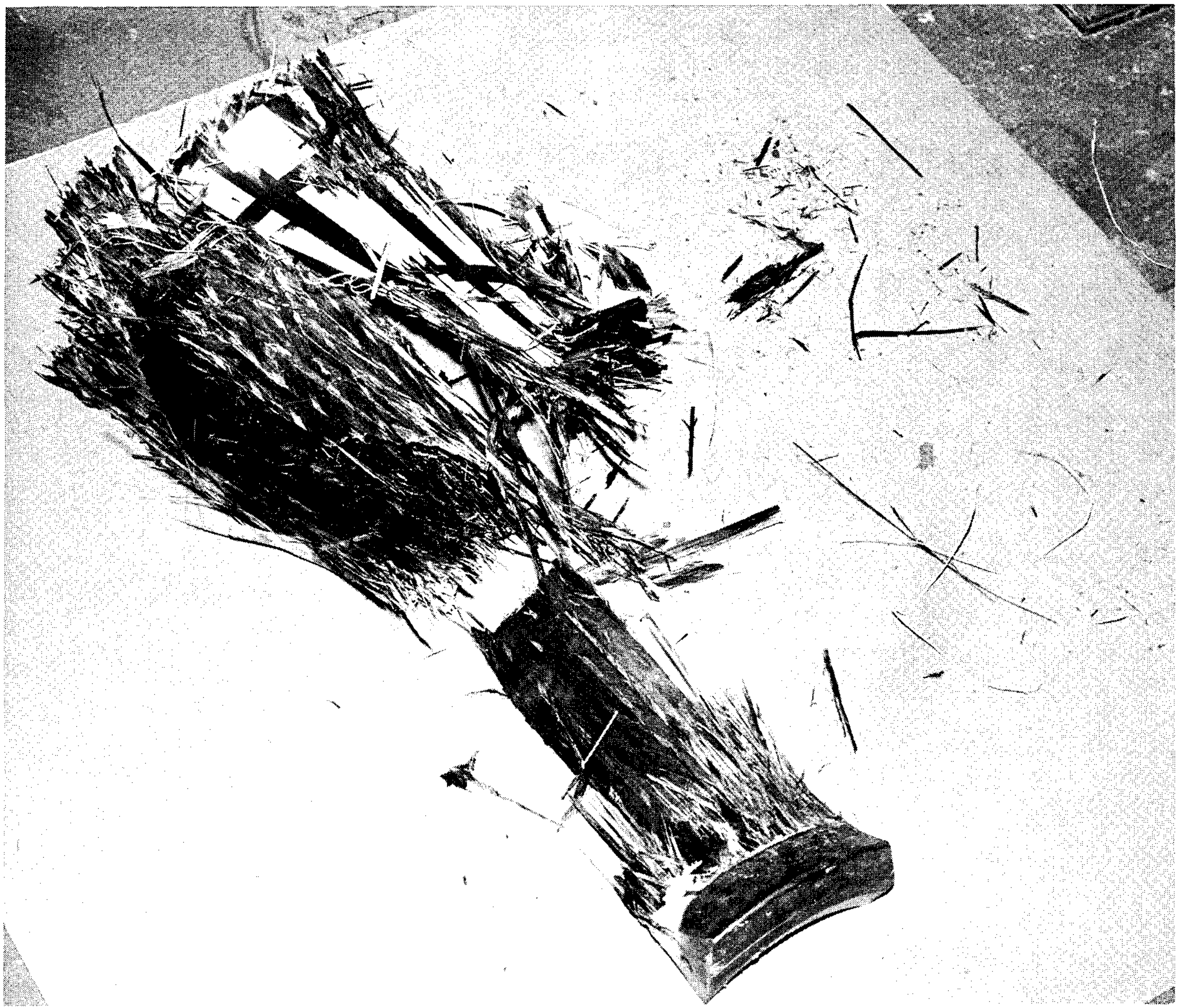
NASA-FOD Program
Blade S/N H/E3
Design No. 2 Material
Real Mallard Duck
Bird Size: 1134 g (40 oz)
Slice Size: 680 g (24 oz)
Blade Tip Speed: 244 m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 59. Blade S/N H/E3 After Impact.



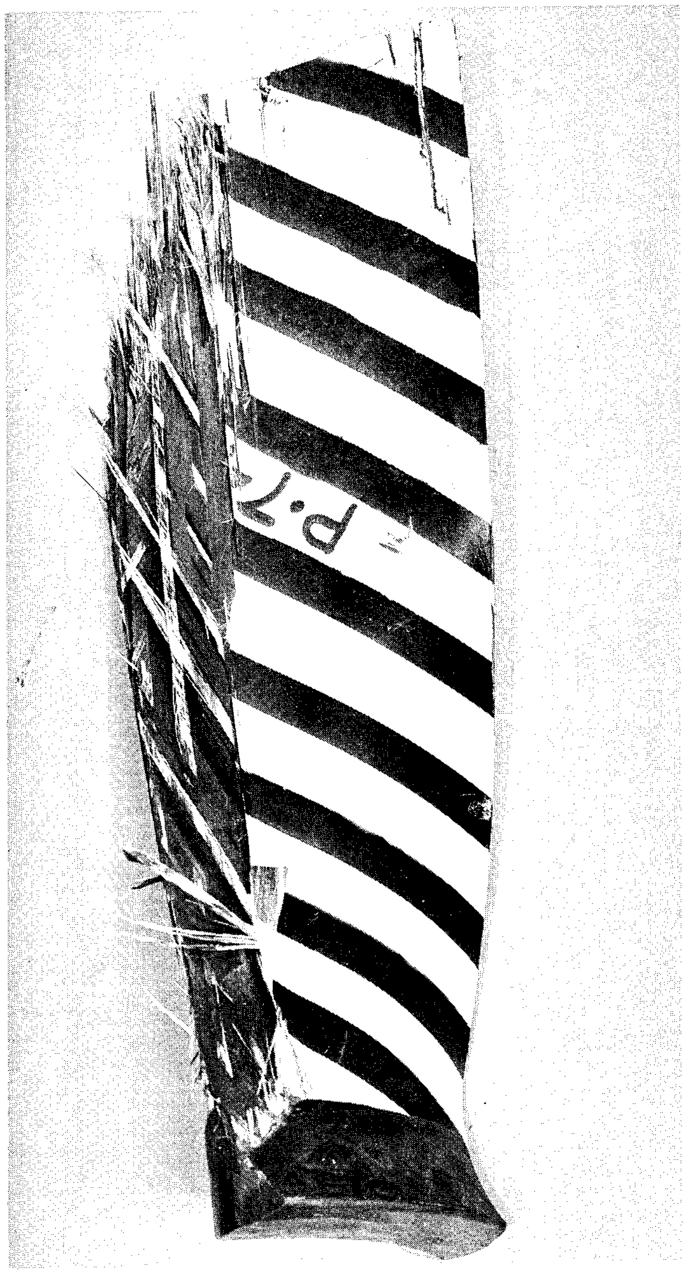
NASA-FOD Program
Blade S/N H/E4
Design No. 1 Material/Lay-Up
RTV Simulated Bird
Bird Size: 794 g (28 oz)
Slice Size: 227 g (8 oz)
Blade Tip Speed: 244 m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 60. Blade S/N H/E4 After Impact.



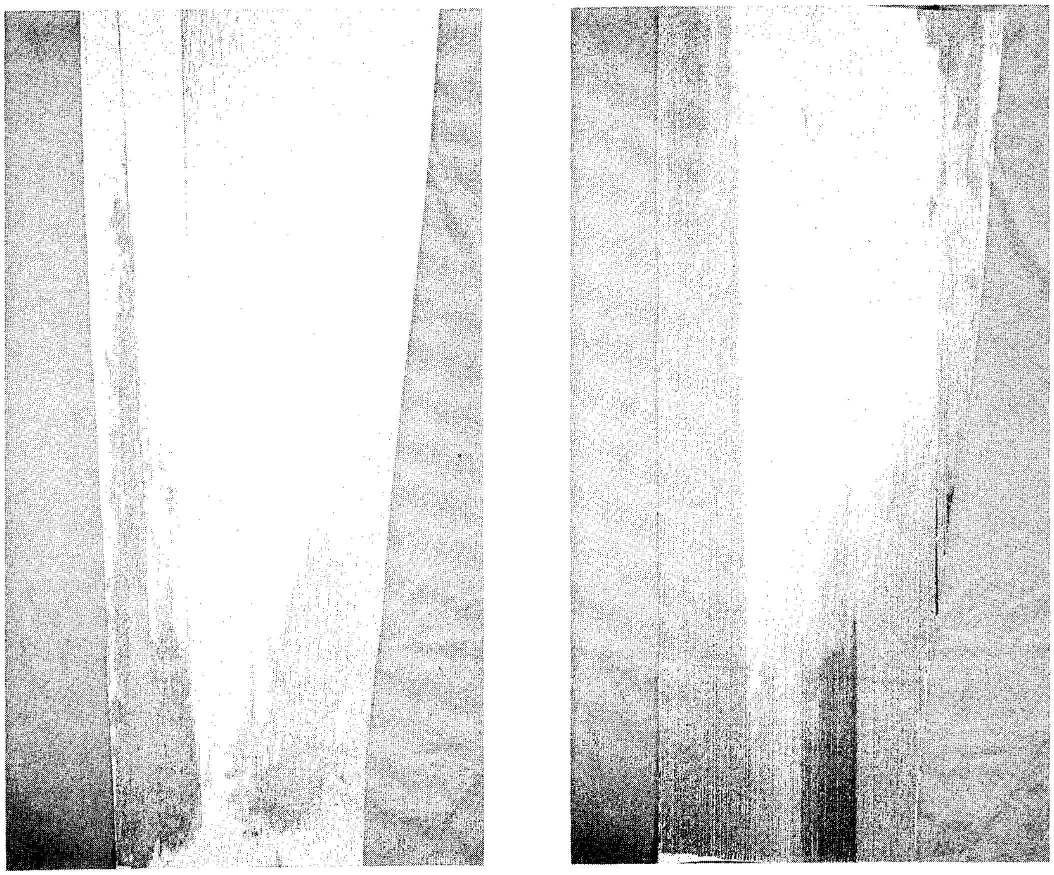
NASA-FOD Program
Blade S/N H/E5
Design No. 1 Material
RTV Simulated Bird
Bird Size: 1360 g (48 oz)
Slice Size: 765 g (27 oz)
Blade Tip Speed: 244 m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 61. Blade S/N H/E5 After Impact.



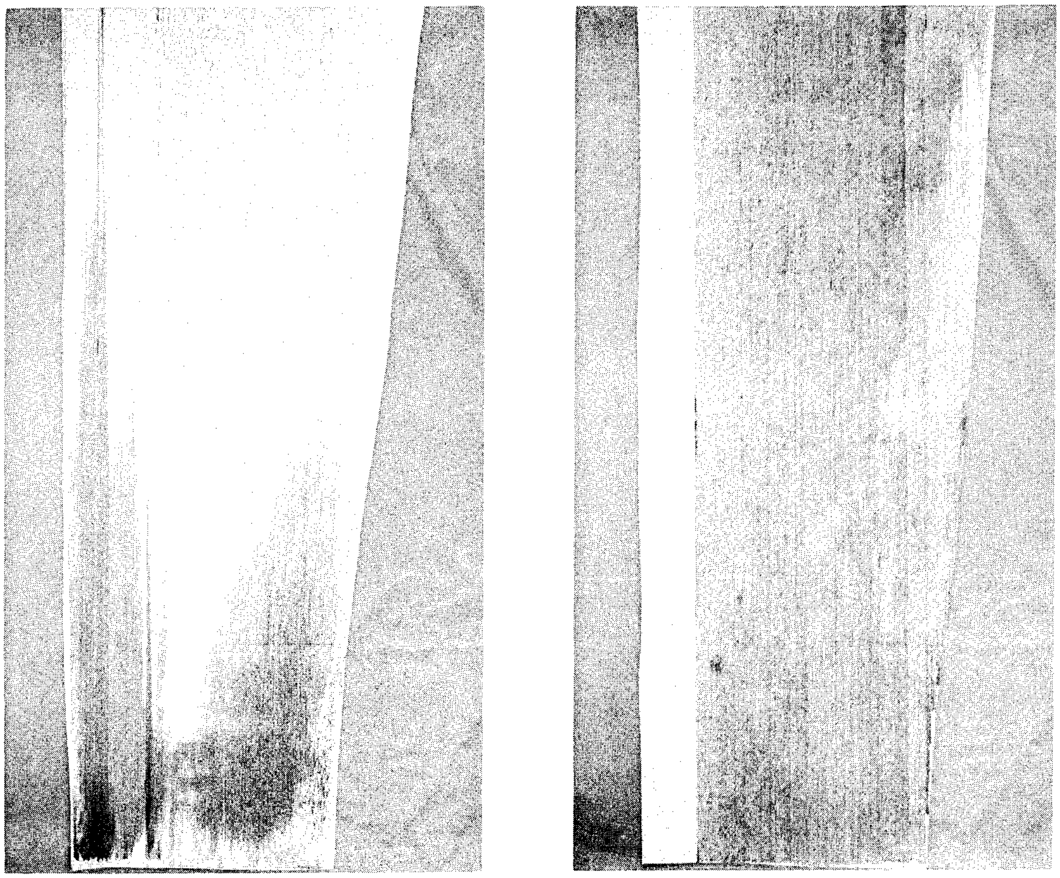
NASA-FOD Program
Blade S/N H/E6
Design No. 1 Material
Real Mallard Duck
Bird Size: 1134 g (40 oz)
Slice Size: 570 g (20 oz)
Blade Tip Speed: 244m/sec (800 ft/sec)
Incidence Angle: 0.384 Radians (22°)

Figure 62. Blade S/N H/E6 After Impact.



Before Impact After Impact

Figure 63. TTUCS of Hybrid/Epoxy Blade S/N H/El.



Before Impact   After Impact

Figure 64. TTUCS of Hybrid/Epoxy Blade S/N H/E2.

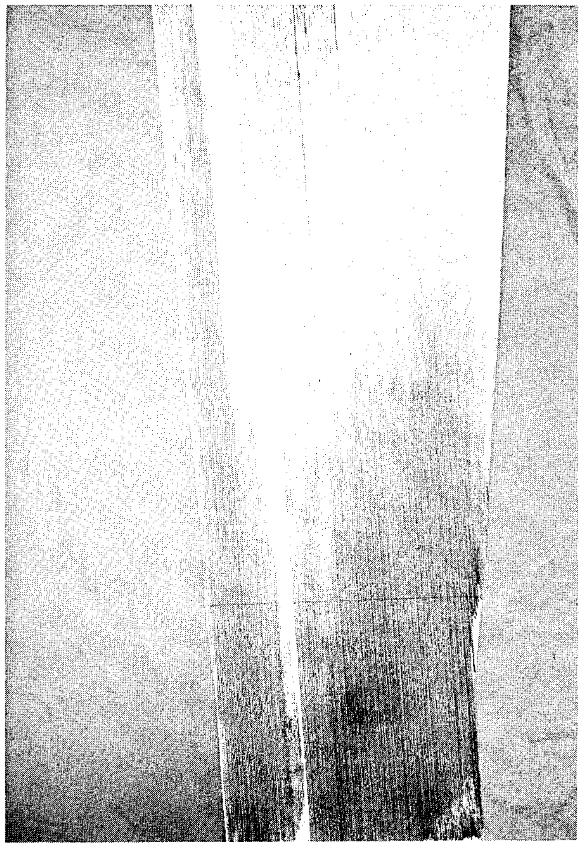
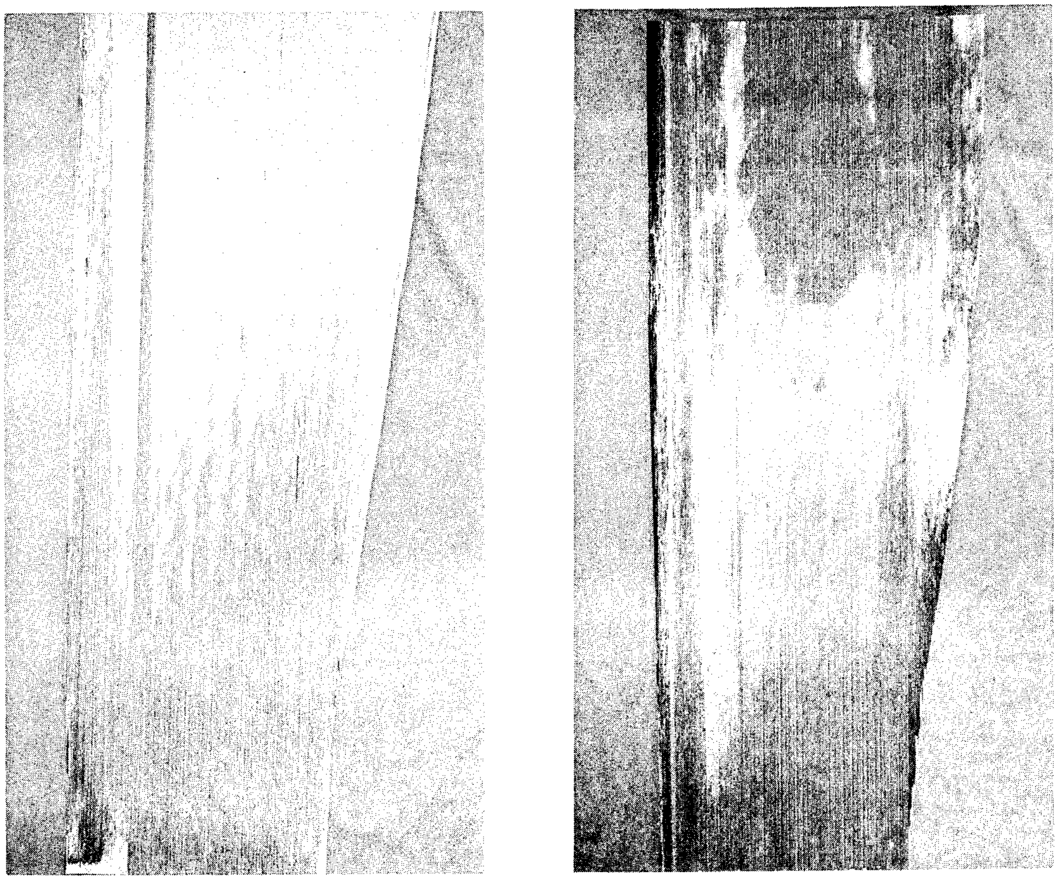
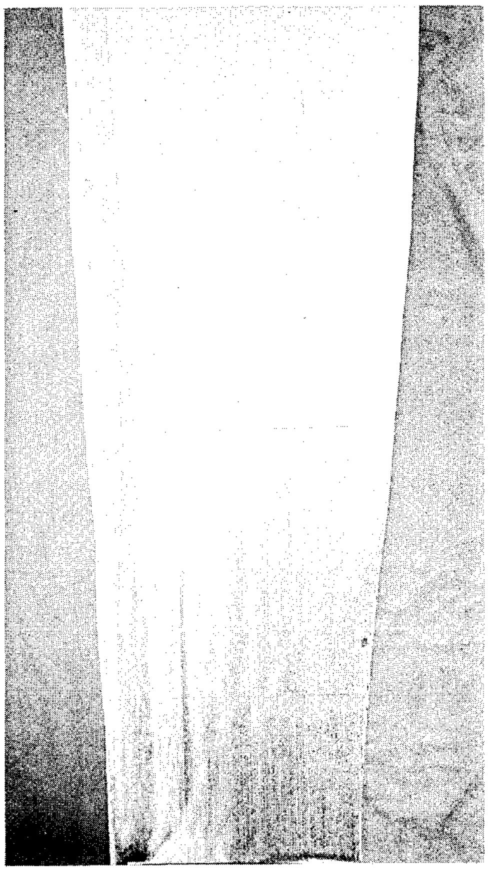


Figure 65. TTUCS of Hybrid/Epoxy Blade S/N H/E3, Before Test.

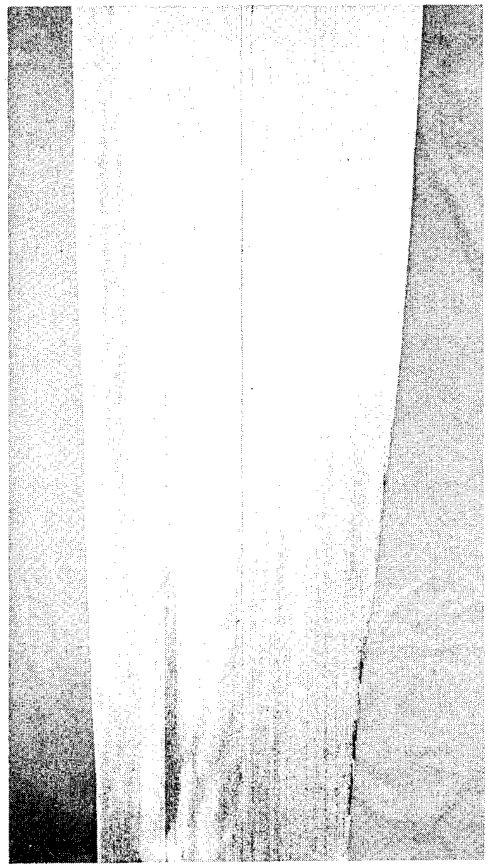


Before Impact   After Impact

Figure 66. TTUCS of Hybrid/Epoxy Blade S/N H/E4.



H/E5



H/E6

Figure 67. TTUCS of Hybrid/Epoxy Blade S/N H/E5 and H/E6, Before Test.

6.0 CONCLUSIONS

Based on the data generated by this program, the following conclusions can be made.

- The threshold level of bird slice which results in local damage for graphite/epoxy and boron/epoxy composite blades is between 142 g (5 oz) and 170 g (6 oz). This is based on results of iceball and 170 g (6 oz) bird tests.

- The threshold level of bird slice which results in bending failure of the blade, for both graphite/epoxy and boron/epoxy composite blades of the TF39 fixed root design is approximately 340 g (12 oz).

- The TF39 metallic titanium blade (unshrouded) suffered essentially no damage when impacted with a 227 g (8 oz) slice of a real pigeon. Damage has occurred for similar impacts of shrouded blades in service due to the inability of the blade to absorb the impact in bending strain energy.

- Based on the above observations, solid graphite/epoxy and boron/epoxy blades of the fixed root design cannot absorb large bird impacts without failure and, therefore, are unsuitable replacements for metallic blades.

- The leading edge protection employed during this program demonstrated sufficient capability to withstand iceball, rock, and small bird impacts without damage.

- Use of RTV birds provides a more controllable, repeatable material to simulate single blade bird impacts than do real birds.

- RTV Bird impact conditions are slightly more severe than those of real birds for the same bite size.

- Strain gage data obtained from whirligig impact tests appear to be consistent and realistic for bird impacts less than 277 g (8 oz). For large bird impacts, where strains become very high, current strain gages do not appear adequate.

- The mode of failure observed during inertial head testing is slightly different from whirligig results, with damage taking place in between the loading straps. The blade stiffness in the tip region is somewhat unnatural due to the strap attachment and reinforcement method used. It was concluded that this method of testing was not as representative as testing in the whiligig.

- Hybrid reinforced graphite/epoxy composite blades offer more than a two-to-one improvement in large bird impact capability [680 g (24 oz) slice compared to 312 g (11 oz) size].

- Hybrid blades developed during this program are capable of saving from 30 to 35% of the rotor weight including savings in disc weight.

- The best two hybrid blade designs selected from the panel test results were PR 288/80% AU/20% S-Glass (Design 1) and PR 288/AU with 8 plies PRD in tip/S-Glass in lower surface plies (Design 2).

- Both designs showed a significant improvement in bird impact capability over the solid G/E blade after whirligig testing; the Design 2 blade being somewhat more resistant to large bird impact.

- Whirligig impact tests of the Design 2 hybrid blade show no root failure after impacts of a 136 kg (3 lb) RTV bird, 6.8 kg (1.5 lb) slice, and 11.3 kg (2.5 lb) mallard duck, 6.8 kg (1.5 lb) slice.

- FOD panel test results indicate that static test conditions are much more severe than dynamic whirligig blade testing. This is due primarily to the higher shear loading induced in the shorter panels as compared to a full-sized blade and the fixity induced at the clamped end. Based on the results of this program, however, this method shows good correlations when comparing results on a relative damage basis.

- S-Glass plies were used successfully on the surface near the root of both hybrid blade designs rendering higher strain-to-failure characteristics of the blades during large bird impact.

- Transverse plies of Kevlar 49 material used in the tip region of the Design 2 hybrid blade showed an increased resistance to local damage in the tip of the blade.

- The process used in the manufacture of the hybrid blades produced good quality blades; however, more work is required to develop a more automated process for manufacturing low cost hybrid blades.

- Of the NDT methods used to evaluate the composite blades and panels, the TTUCS method appears best for evaluating blade impact damage.

- Die penetrant inspection proved to be useful in detecting cracks in the dovetail. It also can be used to detect areas of high porosity in the dovetail.

7.0 RECOMMENDATIONS

The following recommendations are made based on the results of this program.

- Simulated birds should be used for most single blade whirligig impact testing.
- Hybrid material characterization needs to be pursued to determine tensile, shear, and crushing strengths both from a static and fatigue standpoint, for those designs which provide the best bird impact capability.
- Single blade impact testing should be conducted in a whirligig arm rig to obtain the most meaningful test results.
- The hybrid blade designs tested in this program should be investigated in combination with other energy absorbing root designs.
- Due to the mode of failure being delamination in hybrid blades rather than transverse failure of the fibers, new tip designs should be developed to provide dynamic impact strength through the thickness of the airfoil.
- Full-scale engine testing should be conducted on hybrid blades.

APPENDIX

QUALITY CONTROL DATA

ON INCOMING MATERIALS

Q.C. DATA SUMMARY - BORON/5505 PREPREG

(SPECIFICATION MMS 545A)

Prepreg Lot No. 425 Date Received 9-07-72

Number of Pounds 41

Boron Batch No. ______ Resin Batch No. ______

A. Boron Data:

	Vendor	M&PTL	Spec.	Accept	Reject
Tensile Str.,KSI,Avg.		XXX	450 Min.	○	○
Tensile Mod., MSI,Avg.		XXX	55 Min.	○	○
Density,gms/cc,Avg.		XXX	2.57-2.63	○	○

B. Prepreg Data:

	Vendor	M&PTL	Spec.	Accept	Reject
Resin Content, % WT	32.3	32.2	30-34	⊗	○
Resin Flow, % WT	12.2	15.0	10-20	⊗	○
Volatiles, % WT	0.5	1.2	1.5 Max.	⊗	○
Tack	Pass	Pass	Shall Adhere	⊗	○
Gel Time @ 250F,Mins.	---	40'	20' Min.	⊗	○
Visual Discrepancies					

C. Laminate Data

	Vendor	Panel No. 425-1	Spec.	Accept	Reject
Roll No.'s		12			
Gel Time in Die,Mins.		40'			
Thickness, In.		0.079	0.080 + .003	⊗	○
Flex.Str. @ R.T.,KSI	274	256/249	225/200	⊗	○
@ 350F,KSI	214	227/225	185/160	⊗	○
Flex.Mod. @ R.T.,MSI	28.5	28.9/28.2	26.0/24.0	⊗	○
@ 350F,MSI	23.3	24.9/24.0	23.0/22.0	⊗	○
SBS Str. @ R.T.,KSI	15.2	13.9/13.4	13.0/11.0	⊗	○
@ 350F,KSI	6.3	6.3/6.0	5.0/4.0	⊗	○
Fiber Volume, %		54.0	Report	⊗	○
Resin Content, % WT		27.1	Report	⊗	○
Voids, %		2.9	Report	⊗	○
Density, gms/cc		1.94	Report	⊗	○

D. Material Disposition

Accept for All Usage XXXX. Accept for Limited Use ______.

Reject ______ and (a) Return to Vendor ______ or (b) Scrap ______.

Q.C. Eng. D. Beeler Date: 9-22-72

Q.C. DATA SUMMARY - BORON/5505 PREPREG

(SPECIFICATION MMS 545A)

Prepreg Lot No. 426   Date Received 9-07-72

Number of Pounds 7

Boron Batch No. ________   Resin Batch No. ________

	Vendor	M&PTL	Spec.	Accept	Reject
A. Boron Data:					
Tensile Str.,KSI,Avg.		XXX	450 Min.	O	O
Tensile Mod., MSI,Avg.		XXX	55 Min.	O	O
Density,gms/cc,Avg.		XXX	2.57-2.63	O	O
B. Prepreg Data:					
Resin Content, % WT	32.6	33.5	30-34	⊗	O
Resin Flow, % WT	11.3	15.0	10-20	⊗	O
Volatiles, % WT	0.7	1.1	1.5 Max.	⊗	O
Tack	Pass	Pass	Shall Adhere	⊗	O
Gel Time @ 250F,Mins.	---	20'	20' Min.	⊗	O
Visual Discrepancies					
C. Laminate Data — Panel No.		426-1			
Roll No.'s		1			
Gel Time in Die,Mins.		20'			
Thickness, In.		0.079	0.080 + .003	⊗	O
Flex.Str. @ R.T.,KSI	265	249/226	225/200	⊗	O
@ 350F,KSI	207	222/207	185/160	⊗	O
Flex.Mod. @ R.T.,MSI	30.5	28.1/25.3	26.0/24.0	⊗	O
@ 350F,MSI	23.8	25.7/23.1	23.0/22.0	⊗	O
SBS Str. @ R.T.,KSI	14.2	13.2/12.9	13.0/11.0	⊗	O
@ 350F,KSI	5.8	3.8/5.6	5.0/4.0	⊗	O
Fiber Volume, %	---	54.5	Report	⊗	O
Resin Content, % WT		26.7	Report	⊗	O
Voids, %		2.9	Report	⊗	O
Density, gms/cc		1.95	Report	⊗	O

D. Material Disposition

Accept for All Usage XXXX . Accept for Limited Use ________.

Reject ________ and (a) Return to Vendor ________ or (b) Scrap ________.

Q.C. Eng. D. Beeler   Date: 9/22/72

Q.C. DATA SUMMARY - BORON/5505 PREPREG

(SPECIFICATION MMS 545A)

Prepreg Lot No. 427 — Date Received 12-29-72

Number of Pounds 10.5

Boron Batch No. --- — Resin Batch No. ---

	Vendor	M&PTL	Spec.	Accept	Reject
A. Boron Data:					
Tensile Str., KSI, Avg.	XXX	XXX	450 Min.	O	O
Tensile Mod., MSI, Avg.	XXX	XXX	55 Min.	O	O
Density, gms/cc, Avg.	XXX	XXX	2.57-2.63	O	O
B. Prepreg Data:					
Resin Content, % WT	30.7		30-34	O	O
Resin Flow, % WT	9.9		10-20	O	O
Volatiles, % WT	0.9		1.5 Max.	O	O
Tack	Pass	Pass	Shall Adhere	O	O
Gel Time @ 250F, Mins.	XXX		20' Min.	O	O
Visual Discrepancies					
C. Laminate Data — Panel No.		427-1			
Roll No.'s		1, 2			
Gel Time in Die, Mins.					
Thickness, In.	XXX		0.080 $\pm$ .003	O	O
Flex. Str. @ R.T., KSI	271		225/200	O	O
@ 350F, KSI	218		185/160	O	O
Flex. Mod. @ R.T., MSI	29.8		26.0/24.0	O	O
@ 350F, MSI	25.4		23.0/22.0	O	O
SBS Str. @ R.T., KSI	15.1		13.0/11.0	O	O
@ 350F, KSI	5.9		5.0/4.0	O	O
Fiber Volume, %	XXX		60 $\pm$ 2	O	O
Resin Content, % WT	XXX		Report	O	O
Voids, %	XXX		2% Max.	O	O
Density, gms/cc	XXX		Report	O	O

D. Material Disposition

Accept for All Usage ______. Accept for Limited Use ______.

Reject ______ and (a) Return to Vendor ______ or (b) Scrap ______.

Q.C. Eng. ______ Date: ______

Q.C. DATA SUMMARY - TYPE A-U/PR288 PREPREG

(SPECIFICATION 4013155-156)

Prepreg Lot No. 458 Rolls #2-7 — Date Received 10-18-72

Number of Pounds 88.3

Graphite Batch No. 4-5 — Resin Batch No. 55TP

	Vendor	M&PTL	Spec.	Accept	Reject
A. Graphite Data:					
Tensile Str.,KSI,Avg.	439	XXX	400 Min.	⊗	O
Tensile Mod.,MSI,Avg.	32.2	XXX	30-34	⊗	O
Density,gms/cc,Avg.	1.799	1.795	1.80-1.85	⊗	O
B. Prepreg Data:					
Graphite,gms/ft^{2}*,Avg.	12.85	12.8	12.7 ± 0.3	⊗	O
Individual Specimens**	18/18	14/15	2/3	⊗	O
Resin,gms/ft^{2},Avg.	7.1	7.0	7.2 ± 0.3	⊗	O
Individual Specimens**	13/18	10/15	2/3	⊗	O
Vols., %Wt.,Avg.	0.1	0.1	2% Max.	⊗	O
Individual Specimens**	18/18	15/15	2/3	⊗	O
Gel Time,Mins.@ 265° F	25'45"	20'	21 Min.	⊗	O
Flow, % @ 265° F	15.4	--	3 - 7	O	O
Visual Discrepancies					
C. Laminate Data — Panel No.		458-2			
Sheet No.'s.		Rolls #2-7			
Gel Time in Die,Mins.		XXX			
Thickness, In.		.080	0.080 ± .003	⊗	O
Flex.Str. @ R.T.,KSI	291/288	314/296	235/215	⊗	O
Flex.Str. @ 250°F,KSI	226/214	221/189	160/145	⊗	O
Flex.Mod. @ R.T.,MSI	16.7/16.3	20.0/19.6	Report	⊗	O
Flex.Mod. @ 250°F,MSI	16.3/16.0	19.6/18.7	Report	⊗	O
SBS Str. @ R.T.,KSI	14.1/13.6	13.5/12.0	Report	⊗	O
SBS Str. @ 250°F,KSI	8.6/8.5	8.0/7.9	Report	⊗	O
Fiber Volume, %	---	***	60 ± 2	O	O
Resin Content, % Wt.	---				
Voids, %	0.04		2% Max.	⊗	O
Density, gms/cc	1.59				

D. **Material Disposition**

Accept for All Usage XXXXX. Accept for Limited Use ______.

Reject ______ and (a) Return to Vendor ______ or (b) Scrap ______.

Q.C. Eng. D. Beeler Date: 11/1/72

*Fiber Wt. = 7.08 x SP. GR. of fiber

**No. specimens in Spec./No. specimens tested

***Chemistry results in error

QC DATA SUMMARY - PR 288/AU PREPREG

(SPECIFICATION 4013155-087)

Prepreg Lot No. 467 Date Received 11-16-72

Number of Pounds 140 Resin Batch No. 60 TP

	Vendor	M&PTL	Spec.	Accept	Reject
A. Graphite Data:					
Batch No.	6-2	---			
Tensile Str.,ksi,Avg.	452	---	410 Min.	⊗	○
Tensile Mod.,msi, Avg.	31.8	---	29 - 34	⊗	○
Density,gms/cc,Avg.	1.82	---	1.785-1.827	⊗	○
B. Prepreg Data:					
Graphite, gms/ft^2,Avg.	12.8	12.9	12.9 ± 0.4*	⊗	○
Individ. Specimens***	24/30		2/3	○	○
S-Glass,gms/ft^2,Avg.	---		± 0.3**	○	○
Individ. Specimens***	---		2/3	○	○
Total fiber wt,gms/ft^2,Avg.	---		± 0.4	○	○
Individ. Specimens	---		2/3	○	○
Resin,gms/ft^2,Avg.	7.3	7.1	7.2 ± 0.3	⊗	○
Individ. Specimens***	29/30		2/3	○	○
Vols., % Wt.,Avg.	0.1	0.2	2% Max.	⊗	○
Individ. Specimens***	30/30		2/3	○	○
Gel Time,Mins.@ 230°F	---		25 Min.	○	○
Flow, % @ 230°F	---		3 - 7	○	○
Visual Discrepancies					

C. Laminate Data	Panel No.	---	Spec.	Accept	Reject
Roll No.'s		1-5			
Gel Time in Die, Mins.		60			
Thickness, In.	.080	.080	0.080 ± .002	⊗	○
Flex.Str. @ R.T.,ksi	235	288		⊗	○
@ 250°F,ksi	173	203		⊗	○
Flex.Mod. @ R.T.,msi	16.1	17.7		⊗	○
@ 250°F,msi	15.8	17.3		⊗	○
SBS Str. @ R.T.,ksi	13.8	12.0		⊗	○
@ 250°F,ksi	8.3	7.6		⊗	○
Fiber Volume, %	60.0	60.3	60 ± 2	⊗	○
Resin Content, % Wt.	---	32.0	Report		
Voids, %	0.0	0.0	2% Max.	⊗	○
Density, gms/cc	1.60	1.60	Report		

D. Material Disposition

Accept for All Usage ________. Reject ________ and (a) Return to Vendor ________ or (b) Available for Limited Use Only ________.

Q.C. Eng. DRB Date: 11-28-72

*Graphite Wt. = 5.66 x specific gravity of fiber

**S-Glass Wt. = 1.42 x specific gravity of fiber

***No. specimens in Spec./No. specimens tested

Q.C. DATA SUMMARY - TYPE A-U/PR288 PREPREG

(SPECIFICATION 4013155-156)

Prepreg Lot No. 483 Date Received 12/21 & 12/28

Number of Pounds 360

Graphite Batch No. 6-5 Resin Batch No. 80A

A. Graphite Data:

	Vendor	M&PTL	Spec.	Accept	Reject
Tensile Str., KSI, Avg.	431	XXX	400 Min.	⊗	O
Tensile Mod., MSI, Avg.	31.7	XXX	30-34	⊗	O
Density, gms/cc, Avg.	1.81	1.80	1.80-1.85	⊗	O

B. Prepreg Data:

	Vendor	M&PTL	Spec.	Accept	Reject
Graphite, gms/ft^2*, Avg.	12.9	12.8	12.8 $\pm$ 0.3	⊗	O
Individual Specimens**	69/72	28/30	2/3	⊗	O
Resin, gms/ft^2, Avg.	7.1	7.2	7.2 $\pm$ 0.3	⊗	O
Individual Specimens**	69/72	29/30	2/3	⊗	O
Vols., %Wt., Avg.	0.14	0.05	2% Max.	⊗	O
Individual Specimens**	72/72	30/30	2/3	⊗	O
Gel Time, Mins. @ 230°F	21 @ 265°F	50-60	21 Min.	⊗	O
Flow, % @ 230°F	15.1 @ 265°F	---	3 - 7	⊗	O

Visual Discrepancies: Spotted areas of dry fibers, wrinkled tows, and gaps

C. Laminate Data Panel No. 483

	Vendor	M&PTL	Spec.	Accept	Reject
Sheet No.'s.	(4 panels)	---			
Gel Time in Die, Mins.		60			
Thickness, In.	0.080	0.080	0.080 $\pm$ .003	⊗	O
Flex. Str. @ R.T., KSI	283/269	292/264	235/215	⊗	O
@ 250°F, KSI	205/198	202/174	160/145	⊗	O
Flex. Mod. @ R.T., MSI	16.3/15.9	17.2/16.5	Report	⊗	O
@ 250°F, MSI	16.1/15.5	16.6/16.1	Report	⊗	O
SBS Str. @ R.T., KSI	12.3/10.9	10.4/8.2	Report	⊗	O
@ 250°F, KSI	8.6/7.8	7.0/5.8	Report	⊗	O
Fiber Volume, %	57.8	59.8	60 $\pm$ 2	⊗	O
Resin Content, % Wt.	---	---			
Voids, %	0.04	0.0	2% Max.	⊗	O
Density, gms/cc	1.585	1.589			

D. Material Disposition

Accept for All Usage XXX. Accept for Limited Use ______.

Reject ______ and (a) Return to Vendor ______ or (b) Scrap ______.

Q.C. Eng. D. Beeler Date: 2/23/73

*Fiber Wt. = 7.08 x Specific Gravity of fiber

**No. specimens in Spec./No. specimens tested

Q.C. DATA SUMMARY - TYPE A-U/PR288 PREPREG

(SPECIFICATION 4013155-156)

Prepreg Lot No. 536   Date Received 6/73

Number of Pounds 10

Graphite Batch No. ---   Resin Batch No. ---

	Vendor	M&PTL	Spec.	Accept	Reject
A. Graphite Data:					
Tensile Str.,KSI,Avg.			400 Min.	O	O
Tensile Mod.,MSI,Avg.			30-34	O	O
Density,gms/cc,Avg.			1.80-1.85	O	O
B. Prepreg Data:					
Fiber, gms/ft^2*,Avg.	14.7	14.9	± 0.3	O	O
Individual Specimens**			2/3	O	O
Resin,gms/ft^2,Avg.	6.9	6.0	7.2 ± 0.3	O	O
Individual Specimens**	3/6	0/3	2/3	O	O
Vols., %Wt.,Avg.	0.3	---	2% Max.	O	O
Individual Specimens**	6/6	---	2/3	O	O
Gel Time,Mins.@ 230°F	---		21 Min.	O	O
Flow, % @ 230°F	---	---	3 - 7	O	O
Visual Discrepancies					
C. Laminate Data Panel No.					
Sheet No.'s.					
Gel Time in Die,Mins.					
Thickness, In.		0.080	0.080 ± .003	O	O
Flex.Str. @ R.T.,KSI		221/206	235/215	O	O
@ 250°F,KSI		179/161	160/145	O	O
Flex.Mod. @ R.T.,MSI		16.2/15.9	Report	O	O
@ 250°F,MSI		15.7/15.6	Report	O	O
SBS Str. @ R.T.,KSI		8.270	Report	O	O
@ 250°F,KSI		6.150	Report	O	O
Fiber Volume, %		50/12.2	60 ± 2	O	O
Resin Content, % Wt.		27.0			
Voids, %		2.6	2% Max.	O	O
Density, gms/cc		1.65			

D. Material Disposition

Accept for All Usage ________. Accept for Limited Use Evaluation.

Reject ________ and (a) Return to Vendor ________ or (b) Scrap ________.

Q.C. Eng. D. Beeler   Date: 7/73

*Fiber Wt. = 7.08 x specific gravity of fiber

**No. specimens in Spec./No. specimens tested

Q.C. DATA SUMMARY - PR288/AU/S-glass PREPREG

(SPECIFICATION 4013155-087)

Prepreg Lot No. 561 — Date Received 3-15-74

Number of Pounds 110 — Resin Batch No. L 222TP[1]

	Vendor	M&PTL	Spec.	Accept	Reject
A. Graphite Data:					
Batch No.	28-3	---			
Tensile Str.,ksi,Avg.	410	---	410 Min.	ⓧ	O
Tensile Mod.,msi, Avg.	33.1	---	29 - 34	ⓧ	O
Density,gms/cc,Avg.	1.78	1.79	1.785-1.827	ⓧ	O
B. Prepreg Data:					
Graphite, gms/ft^2,Avg.	---	10.6	10.1 ± 0.4*	O	ⓧ
Individ. Specimens***	---	13/24	2/3	O	ⓧ
S-Glass,gms/ft^2,Avg.	---	4.1	3.5 ± 0.3**	O	ⓧ
Individ. Specimens***	---	1/24	2/3	O	ⓧ
Total fiber wt,gms/ft^2,Avg.	14.6	14.6	13.6 ± 0.4	O	ⓧ
Individ. Specimens	0/24	0/24	2/3	O	ⓧ
Resin,gms/ft^2,Avg.	7.8	7.8	7.2 ± 0.3	O	ⓧ
Individ. Specimens***	5/24	5/24	2/3	O	ⓧ
Vols., % Wt.,Avg.	0.2	0.0	2% Max.	ⓧ	O
Individ. Specimens***	8/8	24/24	2/3	ⓧ	O
Gel Time,Mins.@ 230°F	---	60	25 Min.	ⓧ	O
Flow, % @ 230°F	---	---	3 - 7	O	O
Visual Discrepancies					

C. Laminate Data Panel No. 561-1, -2, -3

	Vendor	M&PTL	Spec.	Accept	Reject
Roll No.'s		---			
Gel Time in Die, Mins.		~60			
Thickness, In.		.080	0.080 ± .002	ⓧ	O
Flex.Str. @ R.T.,ksi	241	255		ⓧ	O
@ 250°F,ksi	161	201		ⓧ	O
Flex.Mod. @ R.T.,msi	14.3	15.9		ⓧ	O
@ 250°F,msi	13.1	15.3		ⓧ	O
SBS Str. @ R.T.,ksi	9.0	10.8		ⓧ	O
@ 250°F,ksi	5.7	7.1		ⓧ	O
Fiber Volume, %	59.6	47.6/13.1	60 ± 2	ⓧ	O
Resin Content, % Wt	---	29.4	Report		
Voids, %	---	0.7	2% Max.	ⓧ	O
Density, gms/cc	---	1.67	Report		

D. Material Disposition

Accept for All Usage ________. Reject XXX and (a) Return to Vendor XXX or (b) Available for Limited Use Only ________.

Q.C. Eng. DRB Date: 4/1/74

*Graphite Wt. = 5.66 x SP. GR. of fiber
**S-Glass Wt. = 1.42 x SP. GR. of fiber
***No. specimens in Spec./No. specimens tested

1. A second resin film was used which was 39 weeks old. Was not made to GE spec. - high RC.

QC DATA SUMMARY - Kevlar 49/PR 288 PREPREG

(SPECIFICATION 4013155-156)

Prepreg Lot No. 532

Date Received 6/14/73

Number of Pounds 30

Graphite Batch No. ______

Resin Batch No. ______

	Vendor	M&PTL	Spec.	Accept	Reject
A. Graphite Data:					
Tensile Str.,KSI,Avg.	---	---	400 Min.	O	O
Tensile Mod.,MSI,Avg.	---	---	30-34	O	O
Density,gms/cc,Avg.	---	---	1.80-1.85	O	O
B. Prepreg Data:					
Graphite,gms/ft^{2}*,Avg.	10.3	10.3	10.1 ± 0.3	O	O
Individual Specimens**			2/3	O	O
Resin,gms/ft^{2},Avg.	7.1	7.0	7.2 ± 0.3	O	O
Individual Specimens**			2/3	O	O
Vols., %Wt.,Avg.	1.8	0.5	2% Max.	O	O
Individual Specimens**			2/3	O	O
Gel Time,Mins.@ 230°F		68'	21 Min.	O	O
Flow, % @ 230°F			3 - 7	O	O
Visual Discrepancies					
C. Laminate Data Panel No.		532-1			
Sheet No.'s.		---			
Gel Time in Die,Mins.		68'			
Thickness, In.	.080	.080	0.080 ± .003	⊗	O
Flex.Str. @ R.T.,KSI	97.7	94/92	Report	⊗	O
@ 250°F,KSI	61.9	61/61	Report	⊗	O
Flex.Mod. @ R.T.,MSI	9.9	9.4/9.2	Report	⊗	O
@ 250°F,MSI	7.7	8.1/8.0	Report	⊗	O
SBS Str. @ R.T.,KSI	10,200	7.8/7.4	Report	⊗	O
@ 250°F,KSI	7,300	5.9/5.7	Report	⊗	O
Fiber Volume, %	60.0	63.6	60 ± 2	⊗	O
Resin Content, % Wt.	36.9	30.6			
Voids, %	---	4.4	2% Max.	O	O
Density, gms/cc	---	1.33			

D. Material Disposition

Accept for All Usage ______. Accept for Limited Use Evaluation.

Reject ______ and (a) Return to Vendor ______ or (b) Scrap ______.

Q.C. Eng. D. Beeler Date: 7/73

*Fiber Wt. = 7.08 x specific gravity of fiber

**No. specimens in Spec./No. specimens tested

QC DATA SUMMARY - PR 288/S-GLASS PREPREG

(SPECIFICATION 4013155-087)

Prepreg Lot No. 46 — Date Received 6/25/73

Number of Pounds 10 — Resin Batch No. ---

	Vendor	M&PTL	Spec.	Accept	Reject
A. Graphite Data:					
Batch No.	N/A				
Tensile Str.,ksi,Avg.			410 Min.	O	O
Tensile Mod.,msi, Avg.			29 - 34	O	O
Density,gms/cc,Avg.			1.785-1.827	O	O
B. Prepreg Data:					
Graphite, gms/ft^2,Avg.			± 0.4*	O	O
Individ. Specimens***			2/3	O	O
S-Glass,gms/ft^2,Avg.	17.5	17.4	17.6 ± 0.3**	O	O
Individ. Specimens***			2/3	O	O
Total fiber wt,gms/ft^2,Avg.			± 0.4	O	O
Individ. Specimens			2/3	O	O
Resin,gms/ft^2,Avg.	8.1	8.1	7.2 ± 0.3	O	O
Individ. Specimens***			2/3	O	O
Vols., % Wt.,Avg.	0.1	0.3	2% Max.	O	O
Individ. Specimens***			2/3	O	O
Gel Time,Mins.@ 230°F			25 Min.	O	O
Flow, % @ 230°F			3 - 7	O	O
Visual Discrepancies					
C. Laminate Data Panel No.					
Roll No.'s		1-1			
Gel Time in Die, Mins.		57			
Thickness, In.		.080	0.080 ± .002	O	O
Flex.Str. @ R.T.,ksi	243	245		O	O
@ 250°F,ksi	191	215		O	O
Flex.Mod. @ R.T.,msi	7.5	7.6		O	O
@ 250°F,msi	7.1	7.5		O	O
SBS Str. @ R.T.,ksi	16.9	14.0		O	O
@ 250°F,ksi	8.9	9.3		O	O
Fiber Volume, %	---	58.3	60 ± 2	O	O
Resin Content, % Wt.	25.0	25.9	Report		
Voids, %	---	1.7	2% Max.	O	O
Density, gms/cc	---	1.96	Report		

D. Material Disposition

Accept for All Usage ________. Reject ________ and (a) Return to Vendor ________ or (b) Available for Limited Use Only ________.

Q.C. Eng. ________ Date: ________

*Graphite Wt. = 5.66 x specific gravity of fiber
**S-Glass Wt. = 1.42 x specific gravity of fiber
***No. specimens in Spec./No. specimens tested

QC DATA SUMMARY - PR 288/AU/KEVLAR 49 PREPREG

(SPECIFICATION 4013155-087)

Prepreg Lot No. 535 Date Received 6/25/73

Number of Pounds 15 Resin Batch No. ---

A. Graphite Data:	Vendor	M&PTL	Spec.	Accept	Reject
Batch No.					
Tensile Str.,ksi,Avg.			410 Min.	O	O
Tensile Mod.,msi, Avg.			29 - 34	O	O
Density,gms/cc,Avg.			1.785-1.827	O	O

B. Prepreg Data:	Vendor	M&PTL	Spec.	Accept	Reject
Graphite, gms/ft^2,Avg.	---	10.9	10.1 ± 0.4*	O	O
Individ. Specimens***			2/3	O	O
S-Glass,gms/ft^2,Avg.	---	1.9	2.1 ± 0.3**	O	O
Individ. Specimens***			2/3	O	O
Total fiber wt,gms/ft^2,Avg.	12.6	12.8	12.2 ± 0.4	O	O
Individ. Specimens			2/3	O	O
Resin,gms/ft^2,Avg.	6.8	6.8	7.2 ± 0.3	O	O
Individ. Specimens***			2/3	O	O
Vols., % Wt.,Avg.	0.4	---	2% Max.	O	O
Individ. Specimens***			2/3	O	O
Gel Time,Mins.@ 230°F			25 Min.	O	O
Flow, % @ 230°F			3 - 7	O	O
Visual Discrepancies					

C. Laminate Data	Panel No.	535-1	Spec.	Accept	Reject
Roll No.'s		1			
Gel Time in Die, Mins.					
Thickness, In.		.080	0.080 ± .002	O	O
Flex.Str. @ R.T.,ksi		250		O	O
@ 250°F,ksi		156		O	O
Flex.Mod. @ R.T.,msi		16.0		O	O
@ 250°F,msi		15.3		O	O
SBS Str. @ R.T.,ksi		8.0		O	O
@ 250°F,ksi		6.6		O	O
Fiber Volume, %		62.3	60 ± 2	O	O
Resin Content, % Wt.		29.0	Report		
Voids, %		0.0	2% Max.	O	O
Density, gms/cc		1.53	Report		

D. Material Disposition

Accept for All Usage __________. Reject __________ and (a) Return to Vendor __________ or (b) Available for Limited Use Only __________.

Q.C. Eng. DRB Date: 5/15/74

*Graphite Wt. = 5.66 x specific gravity of fiber

**S-Glass Wt. = 1.42 x specific gravity of fiber

***No. specimens in Spec./No. specimens tested