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STRUCTURAL ELEMENT TESTING AND REAL BLADE IMPACT TESTING

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FOR THE COMMANDER

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Three types of blade materials, geometries, and sizes were investigated using ice and substitute bird material as the impactors. The fan blades investigated were the J79 using 403 stainless steel material, the F101 blade using 8A1-1Mo-1V (8-1-1) titanium, and the APSI metal matrix blade material of boron/aluminum.

The simple elements, such as beams and plates, were impact tested with progressive introduction of airfoil geometric parameters to validate experimentally the analytical predictions of Tasks V and VIII of the overall program. General Electric Company was to conduct the Tasks V and VIII phases of the program. Impact tests were also conducted on actual fan blades to permit deriving a correlation between the structural element specimens and the full-scale blades.

The data collected from the impact tests included accurate impact conditions, dynamic displacement of the specimens at discreet points, strain/time histories local to the impact site and at critical blade stress regions identified from the structural response models, pre-test and post-test material properties, and damage assessment.

Because of the enormous amount of data (especially strain and strain rate plots versus time), the Task VI work is described in two reports (Volumes I and II). The Volume I report described in detail selected impacts where the strain data was expanded for the first several milliseconds. Volume I also gave the deflection data and photographs showing the damage specimens and actual blades. This report (Volume II) gives all of the unexpanded strain and strain rate data.

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## SECTION 1 INTRODUCTION

Turbine blade damage resulting from the ingestion of foreign objects is a real threat to aircraft operation and an obstacle to the development of more efficient engines. Foreign objects range from large birds and ice to small hard particles such as sand. Impacts will almost always cause at least localized minor damage that may be corrected by maintenance procedures. Impact damage to blades may also be severe enough to cause catastrophic failure of an engine, resulting in immediate power loss, and jeopardizing the entire aircraft.

The threat is inevitably associated by the environment in which the engine is constrained to operate. Engine speed, blade material, blade geometry, point of impact, and type and size of the impactor all play important roles in determining the nature and severity of damage which might occur. The blade designer's task is to either design a blade which has a specified level of resistance to foreign object damage (FOD) or to evaluate a given blade and predict the extent of damage to be expected from a particular threat.

The FOD response of fan blades can be divided into two separate problem areas. One concerns the local blade damage and the second deals with the structural damage. Local damage occurs during the impact event and is confined to within several projectile diameters of the center of the impact site. Structural damage occurs at later times and at points which are, in general, well away from the impact site.

The overall design problem has two aspects. The first aspect is a ballistic impact problem. In this instance, a method must be developed to relate the mode and extent of damage to the threat and target parameters. The second aspect of the design problem is to relate the ballistic impact induced damage to the residual properties of the blade. It is the degradation of the mechanical properties of the blade that is the most serious consequence of an FOD event.

This report contains all of the unexpanded strain and strain rate results of an experimental program concerned with perfroming nonrotating bench impact tests on test specimens ranging from simple contilevered beams and plates to real This study was carried out under Task VI "Structural blades. Element Tests" which is part of the overall program "Foreign Object Impact Damage Criteria". The simple elements, such as beams and plates, were to be tested with progressive introduction of airfoil geometric parameters to validate experimentally the analytical predictions of Tasks V and VIII of the overall program. The purpose of Task V is to derive parametric relationships describing the changes in dynamic structural response of impacted simple elements such as plates and beams with the progressive introduction of blade airfoil geometric features. The purpose of Task VIII is to derive criteria for predicting foreign object impact damage tolerance.

Because of the enormous amount of data (especially strain and strain rate plots versus time), the Task VI work is described in two reports (Volumes I and II). Volume I described in detail selected impacts where the strain data is expanded for the first several milliseconds. Volume I also gives the deflection data and photographs showing the damaged specimens and actual blades. Appendix B of this report contains all of the unexpanded strain and strain rate time histories. The strain and strain rate data in the form of plots versus time in Appendix B are originals which are attachments to the Volume II Report. The reason this approach was taken was because of the massive amount of data. It would be unreasonable to consider reproducing all of the data contained in Appendix B. A single copy of the original plots was delivered to A. F. Storace, MS H36, General Electric Company, Aircraft Engine Group, Evendale Plant, Evendale, Ohio 45215.

## SECTION 2 EXPERIMENTAL PROGRAM

The experimental program involved conducting nonrotating bench impact tests on test specimens ranging from simple cantilevered beams and plates to real blades. The response of the test specimens to impacts of substitute birds or ice was determined in the testing. The simple elements, such as beams or plates, were tested with progressive introduction of airfoil geometric parameters to validate experimentally the analytical predictions of Tasks V and VIII and to derive a correlation between structural element specimens and full-scale blades. This report contains all of the unexpanded strain and strain rate results of the impact tests in Appendix B.

Three types of blade materials, geometries, and sizes were investigated using ice and substitute bird materials as the impactors. The impactors were gun launched to impact the leading edge of the test specimens in the majority of the testing.

### 2.1 STUDY OBJECTIVES AND APPROACH

The overall objective of this study was to experimentally determine the response (both local and structural) of the various blade materials investigated. The data collected from the impact tests included accurate impact conditions, dynamic displacement of the specimens at discreet points, strain/time histories local to the impact site and at critical blade stress regions identified from the structural repsonse models, pre-test and post-test material properties, and damage assessment. The simple elements were tested with progressive introduction of airfoil geometric parameters to validate experimentally the analytical predictions of Tasks V and VIII. Impact tests were also conducted on real blades to derive a correlation between structural element specimens and full-scale blades.

The three blade types investigated in the study were the J79 blade using 403 stainless steel; the F101 blade using 8A1-1M0-IV (8-1-1) titanium; and the APSI metal matrix boron/ aluminum blade. The geometries of the test specimens were similar to the geometries at the 50 percent span location of the three blade types investigated. For example, the material, leading edge thickness, trailing edge thickness, taper angle, specimen thickness, width, and span length of the test specimens were identical to that of the actual blades at the 50 percent span location.

A baseline series of tests was conducted on the titanium material, a supplementary series was conducted on the stainless steel material, and a more complete series was conducted on the advanced composite material. Titanium was chosen as the baseline material as it is the most common current blade material. Stainless steel, being a metal, was anticipated to behave basically similar to titanium and would not require such a complete investigation. The composite material was expected to behave significantly different from the metals and a more thorough investigation would be required.

As indicated earlier, the titanium material was used as the baseline material. The test conditions of the impact tests conducted on the titanium material are summarized in Table 1. This baseline series of impact tests considered all impact conditions and blade geometrical effects were introduced progressively (not independently) except camber and twist. It was established early in the study that camber and twist would be very expensive to incorporate on titanium; therefore, camber and twist would be investigated utilizing stainless steel and the composite specimens. The impact tests for all the materials were conducted at ambient temperature conditions.

The supplementary series of impact tests on 403 stainless steel specimens is summarized in Table 2. The basic behavior of stainless steel was assumed to be similar to that of the titanium

TABLE 1. BASELINE TEST CONDITIONS FOR TITANIUM SPECIMENS

Impact	Mass (85 g and 680 g birds, 50.8 mm ice balls)	(3)
	Impact Velocity (no damage, threshold damage, severe damage)	(3)
Parameters	Location/Angle (70% span/ Center-normal; Edge-oblique) (30% span/Center-normal;	(2)
	Edge-oblique)	(2)
	(Aspect Ratio (1/2 blade-like, blade-like)	(2)
Blade Geometry Parameters	Thickness/Chord Ratio (1/2 blade-like, blade-like)	(2)
	Shape (constant thickness, airfoil, blade-like)	(3)
	Shrouds (none, blade-like)	(2)

# TABLE 2. IMPACT TESTS FOR STAINLESS STEEL SPECIMENS

	(Mass (680 g birds)	(1)
Impact Parameters	Impact velocity (no damage, threshold damage, severe damage)	(3)
	Location Angle (70% span/ edge-oblique)	(1)
Blade	Aspect Ratio (blade-like) Shape (constant thickness)	(1)
Geometry Parameters	Camber	(1)
	Twist	(1)

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material. Ice impactors were also considered not to be an important threat on the stainless steel specimens, therefore ice impacts were not considered. As indicated earlier, the camber and twist blade parameters were investigated using the stainless steel specimens. The camber and twist blade parameters were introduced progressively (not independently). In addition, flat specimens with a blade-like aspect ratio were also investigated in regards to their response to oblique bird impacts. Only 680 g (1.5 pound) substitute bird impacts were considered in the impact testing of the stainless steel specimens. All the impacts were conducted at the 70 percent span location with the impacts being oblique leading edge impacts.

The boron/aluminum composite material specimen series of impact tests is outlined in Table 3. The composite material was considered to behave quite differently from the metals; therefore, all the impact conditions were given consideration. The only projectile considered was the 85 g (3 ounce) substitute bird. All of the impacts were leading edge oblique impacts at the 70 percent span location on the specimens. The blade parameters investigated included the aspect ratio, thickness to chord ratio, shape, camber, and twist. Again, as for the titanium material, the blade geometrical effects were introduced progressively (not independently).

The testing is organized into groups. The test matrix for the impacts on the various material specimen groups is described in Table 4. The table describes the structural elements, element fixity and material, the loading and impactor, and the impact location and angle. Details of the shape, size and configuration of the structural elements are provided in Table 5. The structural elements are discussed in greater detail in the Volume I report describing the results of the testing.

In addition to impact testing of beam and plate-like test specimens, a number of impact tests were also conducted on full

TABLE 3. TEST CONDITIONS FOR BORON/ALUMINUM COMPOSITE SPECIMENS

Impact Parameters	Mass (85 g bird) Impact Velocity (no damage, thresh- old damage, severe damage) Location Angle (70% span/edge- oblique)
Blade Geometry Parameters	Aspect Ratio (1/2 blade-like, blade-like) Thickness/Chord Ratio (1/2 blade- like, blade-like) Shape (constant thickness, blade-like Camber Twist

scale component blades. This impact testing of the actual blades was coordinated with the full scale blade testing of Task IVA where the impact tests were conducted to establish the strain rate limits for the material property tests of Task IVA. The results of this testing was described in the Volume I report. The test matrix for the Task IVA and Task VI work is outlined in Table 6. The Task IVA blade testing was to establish the strain rate limits of the blades; therefore, the impact velocities to be used in these impact tests corresponded to those which would be typical of an impact at 70 percent span and 30 percent span levels at full power settings of the engine during takeoff for each of the blade types. Impacts at the 70 percent span level are representative of the highest velocity impacts experienced by a blade. Impacts at the 30 percent percent span level are typical of those in the highest stress regions of the blade where it is most vulnerable to the effects of impact degradation. In the case for the Task VI blade

# TABLE 4. PARAMETRIC MATRIX DEFINING STRUCTURAL ELEMENTS AND IMPACTS CONDITIONS

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Geolop Nurvee	Structural Element	Impactor	Impact Location	Impact Incidence	Shroud Restraint	Specimen Material
ı	flat Plate with Blade- Type Aspect Ratio	15 g (] ounce) Bird	Center Impact § 70% Span	Normal	.90	T1 8-1-1
2	Same as Group 1	50.8 mm (2 inch) Ice 8a11	Edge Impact } 10% Span	Oblique	No	Ti 9-1-1
3	Same as Group 1	35 g (3 ounce) Bard	Edge Impact § 70% Span	Splique	No	T1 3-1-1
١	Flat Plate with One- Half Blade-Type Aspect Ratio	85 g (3 ounce) Bird	Center Impact § 70% Span	Normai	No	T1 8-1-1
5	Same as Group 4	680 g (1.5 1b) Bird	Edge Impact ] JON Span	Oblique	No	T1 8-1-1
6	Flat Plate with Slade- Type Aspect Ratio and One-Half Slade-Type Thickness/Chord Ratio	85 g (] ounce) Bird	Center Impact 3 70% Span	Normal	NO	Ti 8-1-1
7	Plate with Blade-Type Aspect Ratio and Airfoil (Tapered Cross Section)	85 g (3 ounce) Bird	Edge Impact 3 70% Span	Oblique	No	T1 9-1-1
ı	Same as Group '	580 g (1.5 lb) Bird	Edge Impact § 70% Span	Oblique	NO	Ti 8-1-1
9	Plate with Blade-Type Aspect Satio and Bladelike Cross Section	690 g (1.5 lb) Bird	Edge Impact 3 70% Span	Oblique	NO	Ti 8-1-1
10	Same as Group 9	85 g (3 ounce) Bird	Center Impact 3 70% Span	Normal	Yes	Ti 8-1-1
11	Flat Plate with Blade- Type Aspect Ratio	680 g (1.5 lb) Bird	Edge Impact ? 70% Span	Oblique	:40	403 Stainless S <b>teel</b>
12	Cambered Flat Plate with Slade-Type Aspect Plate	680g (1.5 lb) Bird	Edge Impact ? 70% Span	Oblique	No	403 Stainiess Steel
13	Cambered Twisted Flat Plate with Blade-Type Aspect Ratio	680 g (1.5 lb) Bird	Edge Impact 3 70% Span	Oblique	No	403 Stainless Steel
14	Cross Ply Flat Panel with Blade-Type Aspect Ratio	85 g (l ounce) âird	Edge Impact 3 70% Span	Oblique	No	Boron/ Aluminum
15	Cross Ply Flat Panel With One-Half Slade- Type Aspect Satio	25 g (3 ounce) Bird	Edge, Impact 3 70% Span	Opitdme	No	80ron/ Aluminum
16	Cross Ply flat Panel with Blade-Type Aspect Ratio and One-Half Blade-Type Thickness to Chord Ratio	35 g (3 ounce) Bird	Edge Impact 9 70% Span	Oblique	No	Boron/ Aluminum
17	Cross Ply Panel with Slade-Type Aspect Ratio and Sladelike Cross Section	85 g (3 ounce) Bird	Edge Impact 9 70% Span	Oblique	No	Boron/ Alumiaum
18	Cross Ply Flat Panel with Blade-Type Aspect Ratio and Camber	85 g (3 ounce) Bird	Edge Impact ] 70% Span	opfidne	Xe	Boron/ Aluminum
19	Cross Ply flat Panel with Blade-Type Aspect Patio With Camber and Turner	85 g () ounce) Bird	Edge Impact 4 70% Span	Oblique	No	90ron∕ Soron∕

Groups	Specimen Span Length (mm)	Specimen Cross Section	Specimen Material
1-3	311.150	Specimen Cross Section #1	Ti 8-1-1
4-5	155.575	4.2672 mm ¥	
		← 88.519 mm →	
6	311.150	Specimen Cross Section #2	Ti 8-1-1
		mm ↑ ↓ ← 88.519mm →	
7-8	311.150	Specimen Cross Section #3	Ti 8-1-1
		0.8128mm 4.2672	5
9–10	311.150	Specimen Cross Section #4	Ti 8-1-1
		0. <u>8128</u> mm 4.2672 mm 1.016mm	
		L.E. 88.519 mm T.E.	

# TABLE <sup>5</sup>. SHAPE, SIZE, AND CONFIGURATION DETAILS OF STRUCTURAL ELEMENTS

# TABLE 5. SHAPE, SIZE, AND CONFIGURATION DETAILS OF STRUCTURAL ELEMENTS (Continued)

Groups	Specimen Span Length (mm)	Specimen Cross Section	Specimen Material
11	245.872	Specimen Cross Section #5 4.5974 mm 	403 Stainless Steel
12	245.872	Specimen Cross Section #6 Same as specimen Cross Section #5, but with Camber with Radius of Curvature of 27.7 cm.	403 Stainless Steel
13	245.872	Specimen Cross Section #7 Same as specimen Cross Section #6, but with twist of 49° through free span	403 Stainless Steel
14 15	154.940 77.470	Specimen Cross Section #8 Cross Ply Layup (0°/22°/0°/-22°)	B/Al
16	154.940	Specimen Cross Section #9 Cross Ply Layup (0°/22°/0°/-22°)	B/Al

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# TABLE 5. SHAPE, SIZE, AND CONFIGURATION DETAILS OF STRUCTURAL ELEMENTS (Continued)

Groups	Specimen Span Length (mm)	Specimen Cross Section	Specimen Material
17	101.600	Specimen Cross Section #10 Cross Ply Layup (0°/22°/0°/-22°) with blade-like cross section	B/Al
		- 38.1 mm - 0.91 mm 0.91 mm 3.81 mm L.E. 76.2 mm T.E.	
18	154.940	Specimen Cross Section #11 Constant Chord Airfoil Shape Cross Ply Layup (0°/22°/0°/-22°) with Camber of Radius of Curvature of 101.6 mm (4.0 inches).	B/Al
19	154.940	<b>O.94 mm</b> Specimen Cross Section #12 Same as Specimen Cross Section #11, but with twist of approximately 3.0°.	B/Al

TABLE 6. MATRIX AND TEST CONDITIONS FOR ACTUAL BLADE IMPACTS

Group	Blade Tvpe	Purpose of		Impact	Imuact	Shroud	Spectmen
Number	and Comments	Test	Impactor	Location	Incidence	Kestraint	Material
18	F101	Determine Strain Rates	85g (3 ounce) Bird	Edge Impact ê 30% Span	Oblique	Yes	T1 8-1-1
2B	F101	Determine Strain Rates	85g (3 ounce) Bird	Edge Impact ê 70% Span	Oblique	Yes	Ti 8-1-1
æ	F101	Determine Strain Rates	680g (1.5 lb.) Bird	Edge Impact ê 30% Span	Oblique	Yes	Ti 8-1-1
4B	F101	Determine Strain Rates	680g (1.5 lb.) Bird	Edge Impact ê 70% Span	Obligue	Yes	Ti 8-1-1
5B	F101	Analysis	Slab Ice	Edge Impact Ø 70% Span	Oblique	Yes	Ti 8-1-1
68	97 <b>9</b>	Determine Strain Rates	85g (3 ounce) Bird	Edge Impact @ 30% Span	Obligue	0 N	403 Stainless Steel
7B	6LC	Determine Strain Rates	85g (3 ounce) Bird	Edge Impact ê 70% Span	Obligue	0 M	403 Stainless Steel
8B	J79	Deternine Strain Rates	680g (1.5 lb.) Bird	Edge Impact @ 30% Span	Oblique	N	403 Stainless Steel
9B	97 <b>9</b>	Determine Strain Rates and Analysis	680G (1.5 lb.) Bird	Edge Impact ê 70% Span	Obligue	N N	403 Stainless Steel
108	97 <b>9</b>	Analysis	50.8 mm (2 inch) Ice Ball	Edge Impact ê 30% Span	Obligue	NO	403 Stainless Steel
116	979	Analysis	Slab Ice	Edge Impact ê 30% Span	Obligue	<del>Q</del>	403 Stainless Steel
12B	ISAA	Determine Strain Rates	85g (3 ounce) Bird	Edge Impact ê 30% Span	Oblique	NO	Boron/ Aluminum
138	APSI	Determine Strain Rates and Analysis	85 g (3 ounce) Bird	Edge Impact ê 70% Span	Oblique	N	Boron/ Aluminum
148	ISAR	Analysis	50.8 mm (2 inch) Ice Ball	Edge Impact ê 30% Span	0b1 i que	NO	Boron/ Aluminum
15B	APSI	Analysis	Slab Ice	Edye Impact 0 30% Span	obligue	NC	Boron∕ Aluminum

impacts, the impact velocity was varied to obtain no damage, threshold damage, and severe damage of the blade. The impact angles on the various test specimen and actual blade impacts were to correspond to the impact angles that would occur on the actual blades for a given span location. These impact angles, impact velocities, and bird mass values were determined from the blade geometry, the blade velocity for a given span location, and the aircraft speed.

## 2.1.1 Specimen Materials and Geometries

As indicated earlier, the three blade types to be investigated were the FlO1 blade using 8-1-1 titanium, the J79 blade using 403 stainless steel, and the APSI blade using boron/ aluminum material. These choices correspond to those which would be investigated, analytically and experimentally in other tasks of the overall program. The geometries of the test specimens used in the study were similar to the geometries of the actual blades at the 50 percent span location. The material, leading edge and trailing edge thickness, overall thickness, taper angle, chord width, and span length values of the test specimens were identical to that of the various blade types.

2.1.1.1 F101 Test Specimens

The test specimens simulating the F101 blade were fabricated from 8-1-1 titanium material. The leading edge thickness for the plate specimens with a blade-type aspect ratio and an airfoil (tapered cross section) shape was 0.813 mm (0.032 inches). The trailing edge thickness was 1.016 mm (0.040 inches) and the maximum thickness was 4.267 mm (0.168 inches). The chord width was 88.519 mm (3.485 inches) and the span length was 311.150 mm (12.250 inches). All of the titanium specimens were in the shot peened condition to an intensity of 0.005 - 0.008 N using glass beads 0.58 - 0.84 mm (0.023 - 0.033 inch) diameter.

#### 2.1.1.2 J79 Test Specimens

The test specimens simulating the J79 blade were fabricated of 403 stainless steel material. The maximum thickness of the blade-type aspect ratio specimens were 4.5974 mm (0.181 inches) and the chord width was 56.617 mm (2.229 inches). The span length for the specimens was 245.872 mm (9.680 inches). The camber for the J79 specimens had a radius of curvature of 276.900 mm (10.9 inches). The twist angle for the J79 specimens was 49 degrees from the root to the leading edge tip of the specimens.

#### 2.1.1.3 APSI Test Specimens

Test specimens of boron/aluminum material simulating the APSI blade were fabricated by the General Electric Company. The leading edge thickness for the airfoil cross section specimens was 0.559 mm (0.022 inches) and the maximum thickness was 3.937 mm (0.155 inches). The specimens were symmetrical in shape. The chord width was 76.2 mm (3.0 inches) and the span length was 154.940 mm (6.1 inches). The cambered panels were fabricated using a J79 specimen die. The radius of curvature for the cambered specimens was about 101.6 mm (4.0 inches). The test angle for the twisted panels was approximately 3.0 degrees from the root to the leading edge tip of the specimens. The specimens had a stainless steel wire mesh outer The symmetrical layup used in the specimens was 0°/22°/0°/ ply. -22° with the number of plies being sufficient to obtain the desired thickness. Measurements of the twist of the boron/ aluminum specimens with camber and twist (Group 19 specimens of Tables 4 and 5) were determined before the impact for each specimen. Figure 1 shows how these twist measurements were conducted while Table 7 gives the measurements for each specimen.

## 2.1.2 Impactors

The substitute birds used instead of real birds were 85 g (3-ounce) and 680 g (1.5-pound) sizes. The



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Method Used to Determine Twist for Each Group 19 Boron/Aluminum Specimen. Figure l.

Specimen No.	Root (mm)	#1 (mm)	#2 (mm)	#3 (mm)	Tip (mm)
VI AF-13	2.311	4.496	6.731	8.839	10.795
VI AF-14	2.261	4.064	6.147	8.052	9.728
VI AF-15	2.286	4.318	5.994	7.696	9.271
VI AF-16	2.413	4.242	6.248	8.230	9.906
VI AF-17	2.235	4.445	6.477	8.382	10.058
VI AF-18	2.413	4.318	6.147	7.747	9.348
VI AF-19	2.489	4.166	5.766	7.239	8.560
VI AF-20	2.311	3.962	5.207	6.858	8.484
VI AF-21	2.261	4.343	6.426	8.331	10.160
VI AF-22	2.388	4.369	6.223	7.798	9.423
VI AF-24	2.362	5.080	7.696	10.211	12.548
VI AF-25	2.438	4.826	7.137	9.474	11.430

# TABLE7.PREIMPACT TWIST MEASUREMENTS FOR GROUP 19 BORON/<br/>ALUMINUM STRUCTURAL ELEMENT SPECIMENS

85 g (3-ounce) bird was used to simulate a starling size bird while the 680 g (1.5-pound) bird was used to simulate a seagull sized bird. The artificial birds were cylindrical in shape with a length to diameter ratio of two. The artificial bird material was a mixture of microballoons and gelatin to obtain a porosity of 10 to 15 percent. The small bird had a diameter of 38.1 mm (1.5 inches) while the larger bird had a diameter of 76.2 mm (3.0 inches).

The mass of the 50.8 mm (2 inch) ice balls was approximately 65 g. These ice balls were molded using demineralized water. The slab ice was molded to a shape of a cylinder having a diameter of 73.0 mm (2.875 inches) and a length of 203.2 mm (8.0 inches). The mass of the slab ice in the impacts varied from 687 to 867 g dependeing on the final diameter and length values.

#### 2.2 EXPERIMENTAL SETUP AND PROCEDURES

The impact tests were conducted on the large compressed gas gun range. The range configuration is capable of launching 25.4 to 76.2 mm (1.0 to 3.0 inch) diameter spheres or cylinders up to velocities of 350 m/s (1150 ft/s) using air as the gas medium. Higher velocities can be obtained using helium as the gas medium in the gun. A brief description of the range setup is given below.

#### 2.2.1 Large Bore Compressed Gas Gun Range

Early in the study, the range setup for the artificial bird impacts were conducted on an 89 mm (3.5 inch) diameter smooth-bore gas gun having a launch length of 6.1 m (20.0 ft) and a sabot stopper section having a length of 2.9 m (9.5 ft). The projectile was launched in a standard one-piece balsa wood sabot with a cylindrical pocket. The size of the pocket in the sabot depended on the bird size to be fired. After launch, the gas pressure was released through slots in the sabot stopper tube and the sabot was stopped in the stopper section. The projectile would free-flight to the target over a distance of about 1.8 m (6.0 ft). A preslicer was used in conjunction with the launch system to slice a portion of the bird or ice projectile prior to impact such that only the center portion of the impactor diameter would actually load the target specimen since the majority of the impacts were leading edge hits. The preslicer shown in Figure 2 was not used for the normal chord center impacts on the flat plate or beam impacts. In the leading edge impacts, the specimens were positioned such that slicing would occur; thus, only the center portion of the projectile would load the target specimen.

The normal center impacts on the cantilevered flat plates were conducted using a 51 mm (2.0 inch) diameter smooth bore gun having a length of 7.9 m (26.0 ft). This particular gun setup was utilized without a sabot stopper section or a preslicer. In this case, the impactors were again launched



in a standard one-piece balsa wood sabot having a cylindrical pocket. No attempt was made to stop balsa wood sabots for this setup configuration; therefore, the balsa wood was permitted to impact the target specimens along with the desired impactor. The mass of the balsa wood sabot was added to the impactor mass to give the total impact mass for these impacts.

The final setup configuration used in the study was a setup using an 89 mm (3.5 inch) diameter smooth-bore launch tube having a length of 6.1 m (20.0 ft). A stopper section together with a vent section having a length of 1.83 m (6.0 ft) was used with the launch system. Molded urethane plastic sabots were utilized with the launch system to launch the impactor. Figure 3 shows the setup of the launch system. A metal target box was utilized to confine the target specimens as shown in Figure 3.

### 2.2.2 Blade and Specimen Mounting Procedure

All of the testing were conducted using the cantilivered method of mounting. The specimens were cantilever mounted in a vise-like fixture which conformed to the base cross-sectional geometry of the specimens. Each blade type used a special fixture to cantilever the blades. All of the fixtures were either directly or indirectly attached to the range "H" beam to provide a rigid and sturdy mounting system. The use of these mounting fixtures also permitted proper alignment and orientation of the targets with respect to the projectile trajectory.

In the case of the F101 blades, the tips were also restrained to simulate the tip shrouds in the actual engine. Figure 4 shows the system utilized to restrain the tip of the F101 blades.

## 2.2.3 <u>Slice Size Determination</u>

The mass of the projectile which actually impacts the target was of great importance in the leading edge impacts. The most satisfactory technique for determining the impact



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Figure 3. Photographs of Range Set-Up.



Figure 4. Photograph of Technique Utilized to Restrain F101 Blade Tips.

mass involved recovering the presliced portion and the nondeflected portion (slice across leading edge of the target) of the impactor and accurately weighing them. The mass recovered was then subtracted from the initial mass of the impactor to provide a reliable and accurate value for the impact slice mass.

### 2.2.4 Impact Velocity Measurements

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The projectile velocity for the large bore compressed gas gun was measured by utilizing a pair of HeNe laser/ photomultiplier stations spaced a known distance apart. Each laser projects a beam that intersects the projectile trajectory normal to trajectory and illuminates one of the photomultiplier stations. When the projectile interrupts the first beam, the first photomultiplier station generates a voltage pulse to start a counter-timer and trigger a light source for a still The counter-timer is stopped and the other light camera. source is triggered when the projectile interrupts the second laser beam. The projectile impact velocity was then calculated from the recorded measured time and the distance traveled. This technique provided accurate velocity measurements and also information on the integrity of the impactor just prior to impact.

#### 2.3 DATA COLLECTION

The data collected and reported in detail in the Volume I report from the impact tests included accurate impact conditions, dynamic displacements of the specimens at discreet locations, strain/time histories local to the impact site and at critical blade stress regions identified from the structural response models, and damage assessment of the impacted targets. Each test was documented to record test conditions, test results, and damage results to permit an accurate interpretation of the results. These results could then be compared with the predictions from the analyses of Tasks V and VIII of the overall program.

### 2.3.1 Strain Measurements

The strain was detected utilizing high frequency strain gages mounted at critical locations on the target specimens and actual blades. Strain versus time and strain rate versus time curves were used to evaluate the results of the impacts. Gages were located at the root of the target specimens and blades in addition to several gages being positioned on the side of the targets opposite the impact site.

Digital data acquisition equipment was employed to record the data. The digital system has a "quick-look" capability which is very helpful in evaluating data early after the impact. The system has a 200 KHz bandwidth and a storage capability of 2048 data points. The data was recorded on cassette tapes to provide a permanent record of the strain data.

The significant local impact frequencies were estimated to extend to 20 KHz; therefore, low pass filters were used with the system to attenuate frequencies above 20 KHz. The sampling rate for the actual blade shot was 100 kHz while the sampling rate for the majority of the specimen impacts was 20 KHz.

The far field structural response was estimated to extend to about 4 KHz. Prior to impact testing on selected shots of the actual blades, frequency checks were made to establish the natural frequencies of the blades. In this case, the sampling rate used was 20 KHz with 4 KHz low-pass filters to attenuate frequencies above 4 KHz. After the impact was conducted the blades were again frequency checked to establish the natural frequencies. Any difference between the pre-test and post-test frequency checks would be attributed to blade damage due to the impact.

#### 2.4 DAMAGE ASSESSMENT

The damage assessment portion of the data collected in the study was given particular consideration. The mode of

damage was determined and the extent of damage measured. It was anticipated that tests would be conducted on the impact damaged specimens and blades to determine the residual tensile strength and residual fatigue strength properties; however, the majority of the damage received was plastic deflections at the root area or actual breaking off at the root section for the blades and test specimens. This type of damage would not affect the residual tensile strength or fatigue strength to any extent.

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### 2.4.1 Mode and Extent of Damage Measurements

The foreign object damage (FOD) problem can be divided into two separate areas, both of which are associated with a damage threshold. One deals with local blade or specimen damage; the other is associated with large scale structural damage. It was the purpose of this study to investigate and evaluate the damage for both the local and structural damage areas.

Since the impactors in the study were either artificial birds or ice, the damage mode for the metal materials usually was in the form of plastic deformation at the root area without cracking or curlback or a large amount of local bending at the impact site. In several cases, the specimens broke off at the root area. The local damage was characterized by measuring the maximum plastic deformation of the target leading edge (L.E.) and trailing edge (T.E.) whenever possible. Twist damage was also measured where specimens encountered twist damage. Plastic deformation at the root area was characterized by measuring the maximum deformation for the whole span length.

The damage for the APSI blade and test specimens was similar to that for the metal materials except that in several instances, material would be broken out at the impact site. This mass loss damage was characterized by making length and width measurements of the affected area. If plastic deformation was experienced, the damage was characterized by measuring the

the maximum deformation identical to the technique used for the metal materials.

In all cases, photographs of the damaged blades and test specimens were taken to document the damage. These photographs showing the impact damage were presented in the Volume I report describing in detail selected impacts for each group of structural specimens and actual blades.

# SECTION 3 EXPERIMENTAL RESULTS

The experimental strain and strain rate results of the impact tests to investigate the response of test specimens ranging from simple cantilevered beams and plates to real blades from either artificial (substitute) birds or ice impacts are given in this report. A total of about 200 shots were fired to obtain 133 good impact data shots in the study. The majority of testing (92 shots) was conducted on simple element test specimens and 41 data shots were conducted on full scale blades.

#### 3.1 SIMPLE ELEMENT TEST SPECIMENS

As indicated earlier, the three blade types investigated in the study included the FlO1 blade using 8-1-1 titanium, the J79 blade using 403 stainless steel, and the APSI blade using boron/aluminum material. These choices correspond to those which would be investigated analytically and experimentally in other tasks of the overall program. The geometries of the structural element test specimens were similar to the geometries of the actual blades at the 50 percent span location. The material, leading edge and trailing edge thickness, overall thickness, taper angle, chord width, and span length values of the test specimens were identical to that of the various blade types. These simple elements were tested with progressive introduction of airfoil geometric parameters to validate experimentally the analytical predictions of other tasks in the program and to derive a correlation between the structural element specimens and full scale blades.

Results of the static impact test on the structural element specimens are given in Table 8. The table gives the test conditions, specimen geometry and material type for each impact, the proper figure of Appendix A which describes the
TABLE 8. RESULTS OF STATIC IMPACT TESTING

efor <b>ma</b> tion Plot	ž	£	Yes	Yes	£	Y es
Camera Franting D Rate (frames/sec)	;	:	20,800	20, 752	1	Timing carks 1000/sec
Migh-Speed Camera Type	No film	No film	Dynafax	Dynafax	No film	Hy can
Damage Description and Comments	Plastic deformation of specimen at root: 1.35 cm deflection on left side and 1.51 cm deflection on right side measured at tip.	Plastic deformation of specimen at root: 7.62 cm deflection for both speci- men sides measured at tip.	Plastic deformation of specimen at root; 1.98 cm deflection measured at tip.	Plastic deformation of specimen at root: 0.71 cm deflection measured at tip.	Plastic deformation of specimen at root: 0.15 cm deflection measured at tip.	Plastic deformation of specimen through free span: 0.38 cm deflec- tion measured at tip.
Impact velocity (m/s)	125.0	201.0	122.6	85.7	43.9	59.1
Shroud testraint	2	£	Ŷ	£	£	Ŷ
Impact Angle 1 (*)	0.06	90.0	<del>ه</del> . ه	0.06	0.06	0.06
Strain Gauge Locations	to çauges	No çauges	See Figure 7A	See Figure 7A	See Figure 7A	See Figure 7A
Impact Distance from Root (cm)	22.5	22.2	21.8	21.8	21.8	21.8
Span Location for ()	Center Lupact 2 70% sµan	Center Arpact 2 70% Span	Center ispact a 70% span	Center impact ê 70% span	Center İmpact Ş 70% span	Center İmpact Ø 70% span
Target Material and Description	8-1-1 Ti flat plate with blade- type aspect ratio of FlO1 blade)	8-1-1 Ti flat plate with blade- type aspect ratio of flo1 blade)	8-1-1 Ti Elat plate with blade- t:pe aspect ratio of Flol blade	8-1-1 Ti flat plate with blade- type aspect ratio of FlO1 blade	8-1-1 Ti flat plate with blade- type aspect ratio of FlOl blade	8-1-1 Ti flat plate with blade- type aspect ratio of Flol blade
Nass Impacting (g)	82.0	82.6	101.2	107.4	98 . 6	5.99
Haes Co	62.0	82.6	101.2	107.4	98.6 9	99.2
Projecti Type	licro-balloon gelatin Lird (cylinder) (3.81 cr dia. k 7.62 cm long)	licro-balloon gelatin bird (cylinder) (3.51 cm dia. k 7.62 cm long)	licro-balloon celatin bird (cylinder) (3.Cl cm dia. x 7.62 cm	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon Gelatin bird (cylinder) (3.51 cm dia. x 7.62 cm long)	ilicro-ballon çelatin bird (çylinder) (3.81 cm dia. x 7.62 cm long)
Shot No.	4-9052	4-0056	2-0090	1500-2	2-0092	2-0093
Group Ro.	-	-	~	-	-	-

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Project Type	11e Mass (g)	Maas Impacting Target (g)	Target Matarial and Description	Span Location for impact (s)	Impact Distance Root (CM)	Strain Gauge Locations	Impact Angle (*)	Shroud Restraint	impact Valocity (m/a)	Damage Description and Comments	High-Speed Camera Type	Camera Frantng Rate (frames/sec)	<b>Deformation</b> Plot
 Micro-balloon gelatin bird (cylinder) (3.01 cm dia. x 7.62 cm iong)	100.5	100.5	8-1-1 Ti flat plate with blade- type aspect ratio of riol blade	Center Lagact e 704 span	21.8	see Figure 7A	0.0 <b>6</b>	£	177.4	Plastic deformation of speciaen at root: 6.50 cm deflection measured at tip.	Hycaa	Timing marks 1,000/sec	ļ
Micro-balloon gelatin bird cylinder) (3.81 cm dia. x 7.62 cm long)	85.9	85.9	8-1-1 Ti flat plate with blade- type aspect ratio of FlOI blade	Center Lapact e 709 upen	21.0	see Pigure 7A	0.06	£	189.6	Plastic deformation of speciaen at root and impact site, 5.69 cm deflection measured at tip.	Hycan	Timing marks 1,000/sec	Yes
5.08 cm dia. ice ball	64.7	64.7	8-1-1 T1 flat plate with blade- type ampect ratio of FlOI blade	Center Lepact 9 305 span	9.3	rigure 7A	0.06	<u>S</u>	161.7	Plastic deformation of specimen at impact site, 0.32 cm bow measured at impact site. No strain gauge data.	No film		£
 5.06 cm dia. ice ball	63.5	63.5	8-1-1 Ti flat plate with blade- type ampect ratio of r101 blade	Center Lepect 9 305	6.9	rigure 7A	0.06	£	103.0	Plastic deformation of specimen at impact site, 0.32 cm bow measured at impact site.	Dynafax	20,544	£
 5.06 cm die. ice ball	62.4	62.4	6-1-1 Ti flat plate with blade- type aspect ratio of rlol blade	Center Lepect 9 309 spen	6.9	see Flgure 7A	0.06	£	130.02	No strain gauge data or film. Velocity esti- mated. No visible demage on specimen.	No film	ł	£

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Deformation Plot	£	£	£	£	£ .	£
Camera Franding Nata (frames/sec)	20, 464	20, 736	20,576	20, 720	20,832	20,864
Kigh-Speed Camera Type	Dynafax	Dynafax	Dynafax	Dynafax	Dynafax	Dynafax
Demoge Description and Communits	No visible damage: projectile broke up upon launch.	No visibile damage on speciaen.	Specimen bowed 1.14 cm on right side and 1.40 cm on left side at impact site. Specimen twisted 0.46 cm. Impact hit off center to left side.	Specimen bowed 1.66 cm on right side and 1.60 cm on left side at impact site. Specimen twisted 0.16 cm.	Mo visible <b>dama</b> ge on specimen.	No visible damege on specimen.
Impact Velocity (m/s)	116.5	125.3	259.1	262.2	96.6	110.1
Shroud Restraint	£	£	£	£	<u>2</u>	£
Amgle ( )	0.06	0.06	<b>90</b> .0	0.06	36.4	36.4
strain Gauge Locations	see Figure 7A	see rigure 7A	rigure 7A	see Figure 7 A	see Figure 8A	see Figure 8A
listance from Moot a (CB)	6.9	6.9	6.9	6.9	21.8	21.8
Boar ton for ton ()	Center Lapact 8 309 span	Center Japact 9 30% span	Center Lapact 9 305 span	Center Lapect 9 30s apen	Center Lapact e 70% span	Center Lapact 0 70% spen
Target Intarial and Description	8-1-1 Ti flat plate with blade- type aspect ratio of r101 blade	8-1-1 Ti flat plate with blade- type aspect ratio of Fl01 blade	8-1-1 Ti flat plate vith blade- type aspect ratio of riol blade	8-1-1 Ti flat plate vith blade- type aspect ratio of riol blade	8-1-1 Ti flat plate with blade- type aspect ratio of FlO1 blade	8-1-1 fi flat plate with blade- type aspect ratio of rioi blade
Maa Targat (g)	62.5	64.0	61.7	65.9	18.1	23.3
	62.5	64.0	61.7	65.9	9.19	0.08
Project Type	5.08 cm dia. ice ball	5.06 cm dia. Ice ball	5.08 cm dia. ice ball	5.06 cm dia. ice ball	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.62 cm long)	Micro-balloon gelatin bird (sylinder) (3.01 cm dia. x 7.62 cm long)
	2-0171	2-0172	2-0173	2-0174	2-0111	2-0112
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Deformation Plot	£	£	4 <b>6</b> 8	£	¥	Ŷ
Camera Franting Nate (frames/sec)	20, 816		Timing marks 1,000/sec	{	Timing marks 1,000/sec	Timing marks 1,090/sec
High-Speed Camera Type	Dynafax	No film	Rycan	No film	Rycau	Hyce
Damage Description and Comments	No visible damage on speci- men. Specimen moved in mount due to impact.	No visible damage on specimen.	Plattic deformation at root and impact site. Landing edge deflection at tip-1.53 cs. Trailing edge deflection at tip-1.59 cm. Speciment twist through epan-0.24 cm.	No visibie damage on speciaen.	No visible damage on speciaen.	Mo visible damage specimen.
Impact Velocity (m/s)	188.4	191.2	302.1	445.7	441.2	E.964
shroud Restraint	2 2	£	Ŷ	ê	£	£
Impact Angle (*)	36.4	36.4	36.4	36.4	24.4	24.4
Strein Gauge Locations	see Figure 8A	see Figure 8A	see Figure 8A	see Figure 8A	see Figure 8A	Figure 8A 8A
Impact Distance from Noot (cm)	21.8	21.8	21.8	21.8	31.8	21.8
Bpan Location for (1)	Center Lagact 8 70% span	Center Japact 8 70% Span	Center Japact 9 709 span	Center Ampact 9 70% upan	Center Lapact e 704 span	Center Lapact 9 704 Span
Target Material . and Description	8-1-1 Ti flat plate with blade- type aspect ratio of FlOI blade	8-1-1 fi flat plate with blade- type aspect ratio of rill blade	8-1-1 T1 flat plate with blade- type aspect ratio of r101 blade	<b>B-1-1 Fi</b> flat plats with blads- type aspect ratio of ratio of	<b>B-1-1 Ti</b> flat plate with blade- type aspect ratio of rill blade	8-1-1 fi flat plate with blade- type amped ratio of floi blade
Mass Impacting Target (g)	54.9	45.9	53.1	66.2	20.1	22.8
(g)	84.6	84.6	82.6	95.2	81.4	83.0
Projecti Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.01 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.62 cm iong)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm lone)
Shot No.	2-0113	2-0114	2-0115	2-0121	3-0136	2-0127
Roup BO	m	m	m	-	-	~
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beformation Plot	£	P,	2	Yes	£
Camera Camera Franking Rata Rata (frame/sec)	Timing marks 1,000/sec	Tiaing marka 1,000/sec	Tiaing marks 1,000/sec	Timing marks 1,000/sec	1
Righ-Speed Camara Type	Rycen	Hycam	Aycan	Hycan	No filla
bumage bescription and comments	Plantic deformation of specimen at root, 0.71 cm deflection measured at tip. Specimen mount moved due to impact.	Plastic deformation of specimen at root 1.11 cm deflection measured at tip.	Plastic deformation of speciaen at root: 0.71 cm deflection measured at tip.	Plastic deformation of specimen at root, 6.12 cm deflection measured at tip.	No visible damage on specimen. No struin gauge data or film.
Impact Velocity (m/s)	32.7	4.66	90.2	150.6	190.9
Shroud Restraint	£	2	2	2	2
Impact Angle (*)	90.06	90.0	90.0	0.06	41.0
Strain Gauge Locations	rigure Pigure 9A	<b>Pigure</b> 9 9A	see Pigure a 9A	see rigure 9A	see Figure d 10A
Impact Distance from Moot (cm)	10.9	10.9	10.9	10.9	10.9
Bpan Location for Impact (s)	Center Ampact 9 700 span	Center Lapact 9 705 span	Center Japact 9 709 span	Center Lapact 9 705 span	Center Inpact 9 304 spen
Target Material and Description	0-1-1 fl Elat piate with one- half blade- type ampect ratio of rill blade	<pre>0-1-1 T1 flat plate with on0- half blade- type aspect ratio of Flo1 blade</pre>	8-1-1 Fi flat plate with one- half blade- type aspect ratio of Flol blade	8-1-1 Ti flat plate with one- half blade- type aspect ratio of Floi blade	8-1-1 T1 flat plate with one- half blade- type appect ratio of riol blade
Maa Impacting Target (g)	101.1	9.96	6.29	¥.	£.01
(3) (9)	101.1	9. <del>0</del> 6	95.9	96.4	678.3
Project Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.62 cm long)	Micro-balloon geletin bird (cylinder) (3.81 cm dia. z 7.62 cm long)	Micro-belloon geletin bird (cylinder) (3.81 cm die. x 7.62 cm long)	Micro-belloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)
	2-0095	3-0096	2-0097	3-0098	2-0193
group	•	<ul> <li></li> </ul>	•	•	۳

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Deformation Plot	£	£	£	ŝ
Camera Praning Nate (frames/sec)	20,320	20,480		1
Nigh-Speed Camera Type	Dynefax	Dynafax	₽ <b>1</b> 73 94	<b>1</b> 11 2
Damage Description and Comments	Mo visible damage on specimen.	No visible damage on specimen.	Plastic deformation of specimen at root; 3.02 cm deflection on left side and 3.18 cm deflection on right side measured at tip.	speciaen broke off at root.
Impact velocity (m/m)	8.161	C.262	6. 4	126.1
Shroud Restraint	£	£	£	£
Lepact Angle (*)	41.0	41.0	0.06	0.06
Strain Gauge Locations	see Figure 10A	rigure 10A	No gauges	eenae on
limpict From Moot (cm)	10.9	10.9	23.6	1.62
Bpan Location for Impact (s)	Center Lapact 9 309 spen	Center Lapact 9 304 Span	Center Lapact 704 apan	Center Anpact 9 704 9pen -
Target Material and Description	8-1-1 Ti flat plate with one- half blade type aspect ratio of Flo1 blade	8-1-1 Ti flat plate with one- half blade type aspect ratio of riol blade	B-1-1 Ti flat plate with blade- with blade- cone-haif blade-type thickness/ t	8-1-1 Ti flat plate type ampede- type and retio and blade-type thicknesype thicknesype thicknesype thicknesype thicknesype thicknesype thicknesype thicknesype
Mass Impacting Target (g)	154.5	<b>19.9</b>	1.18	63.5
• <b>1</b> • •	668.1	681.6	1.68	8. 5
Project Type	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird cylinder) (7.62 cm dia. z 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. 1.82 cm iong)	Micro-balloon gelatin bird (3.11.ad dia. 1.81.ad dia. x 7.62 ad long)
Shot Ro.	2-0194	2-0195	6600	¥:00-+
Group No.	Ś	<b>n</b>	<b>1</b>	<b>1</b> 9

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era ulng Deformation te plot s/sec)	₽	2	£
gh-Speed Fran Camera Fa Type (france	1		afax 20, 68
Damage Description Hi. and Comments	Plastic deformation of M specimen at root; 10.95 cm deflection for both sides measured at tip.	Flastic deformation of Dy Presiment to tot and im- pact site. Impact site deflection-0.81 cm. Tip deflection-15.24 cm on lift side and 14.73 cm on right side. Specimen impacted 0.64 cm to left of centar.	Plastic deformation of Dyn specimen at root. Tip deflection is 7.87 cm for both sides of specimen.
Impact Velocity (m/s)	6. 60 1	134.1k Valocity Estimated	0.
Shroud Restraint	£	£	2
Impact Angle (*)	0.06	0.06	0.0
Strain Gauge Locations	No gauges	see Figure ' 7A	see Figure 7A
Impact from Moot (cm)	22.5	21.8	21.6
Span for for threat ()	Center Lapact 9 709 apan	Center Arpect 9 704 span	Center Japact 8 70% span
Target Material and Description	8-1-1 Ti flat plate vith blade- type ampect type and one-half bi.de-type chord ratio of Fl01 blade	8-1-1 Fi flat plate with blade- vitye ampect ratio and one-haif blade-type thickness/ chickness/ chickness/ chickness/ chickness/ blade	8-1-1 %1 flat plate with blade- type aspect type aspect type and one-haif blade-type thickness/ chickness/ of %101
Rese Target (g)	82.6	85.2	85.3
-1 -1 -1 -1 -1 	82.6	85.2	85.3
Project Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. 3.62 cm dia. 10ng)	Mcro-balloon gelatin bird (vjinder) (3.81 cm dia. 3.62 cm iong)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. (7.62 cm long)
	4-0055	2-0175	2-0176
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Deformation Plot	Ŷ	Ŷ	1 e e
Camera Framing Rate (frames/sec)	Timing marks 1,000/sec	Timing marks 1,000/eec	Tiaing marks 1,000/sec
High-Speed Camera Type	Hyces	Hycaa	Hycean
Demage Description and Comments	Plastic deformation of specimen at leading edge at impact site. Impact site leading edge deflec- tion-1.65 cm. Tip de- flection is 1.14 cm for leading edge and 0.89 cm for trailing edge.	ito visible damage on speciamen.	Plautic deformation on specimen leading edge at impact site with 0.16 cm bow.
Impact Velocity (m/s)	323.2	135.4	211.0
Shroud Restraint	£	£	£
Impact Angle (•)	24.4	24.4	24.4
Strain Gauge Locations	see Figure 8A	500 Figure - 8A	see Pigure 8A
Impact Distance from Noot (cm)	21.8	8.12 1	21.0
Span Location for Impact (s)	Rdge Lingact 8 70% span	Edge Lapact 9 700 epan	Rdge 1mpact epen
Target Material and Description	8-1-1 Tf place with blade-type aspect ratio and airfoll tapered cross sec- tion of riol blade	8-1-1 Ti plate with blade-type appect ratio and airfoll (tapered cross sec- tion) of 7101 blade	8-1-1 Ti plate with plate with aspect ratio and arroil the (tapered riot) of riot blade
Mass Impacting Target (g)	35.1	13.7	1.31
- <b>1</b> 0	82.6	8.2	1.28
Project Type	Mícro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. 1.62 cm long)	Micro-balloon gelatin bird (cyilmder) 3.81 cm dia. x 7.62 cm long)
shot stot	2-0128	2-0129	2-0130
	1	1	1

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beformation Plot	£	£	£
Camera Franting Rate (frames/sec)	Tiaing marks 1,000/sec	Tialing sarks 1,000/sec	Tiaing marks 1,000/sec
High-Speed Camera Type	Hycana	Hycan	Hy can
Damage Description and Comments	Plantic deformation on epecimen leading edge at impect site with 0.16 cm bow.	Mo visible damage on specimen.	Plastic deformation of specimen at root. Deflec- tion of tip for leading edge is 15.72 cm and 14.45 cm for trailing edge. Specimen twist measured 1.27 cm.
Impact Velocity (m/e)	1.62		0.981
Shroud Restraint	<u>e</u>	£	ŝ
Impact Angle (°)		36.4	34.4
Strain Gauge Locations	see Figure - BA	see Figure ≠ 8A	see Figure 8A
Impact Distance from Noot (cm)	57 · •	21.8	21.6
Ipan Location Lapact ()	Bidge Lagract 9 706 epun	adare Lagard	Máge Langact e 708 er
farget Matarial and Description	8-1-1 Ti plate with blade-type appet ratio and airfoil airfoil tapered tross sec- tios of r10 blade	8-1-1 fi plate with blade-type appect airfoll airfoll (tapered cross sec- tion of ylol blade	B-1-1 Ti plate with plate with ampet ratio and atrioi trois (tapered tion of Tiol blade
Mass Impacting Target (g)	109.5	24.1	130.1
•	2.683	679.4	699.2
Project Type	Mcro-balloon galatia bird (cylimder) (.5.2 cm dia. 1.62 cm dia. ioeg)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. r 15.24 cm loog)	Micro-balloon gelatia bird (7.51inder) (7.62 an dia. k 15.24 cm long)
Shot No.	2-0164	3-0165 	
<u>B</u> i	•	•	•

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8. RESULTS OF STATIC IMPACT TESTING (CONTINUED) TABLE

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Deformation Plot	Ę	£	£	£
Camera Framing Rate (frames/sec)	1,000/sec	20,704	1	
Nigh-Speed Canera Type	Hycen	Dynafax	No fila	92 11
<b>Damage Des</b> cription and Comments	Plastic deformation of specimen at root. De- flection at tip for ledding edge is 20.96 cm and 20.32 for tralling edd 20.32 for tralling edd 0.64 cm.	specimen broke off at root.	to visible damage on speciaen.	No strain gauge data or film. Impact velocity estimated and impact mass not determined.
Impact Velocity (m/s)	130.5	n .	6.	100.02
Shroud Restraint	£	£	£	£
Impact Angle (')	24.4	24.4	24.4	<b>X</b> .
Strain Gauge Locations	see Figure 8A	see Figure 8A	see Figure 8A	see Figure 8A
lietance from Noot (CB)	21.8	21.6	21.6	21.8
Bpan Location for ()	Edge Legact 9 706 spen	Råge 9 70% spen	Båge Lapact 9 70% spen	Edge Japact e 709 span
Target Matarial and Description	8-1-1 Ti plate with blade-type aspect ratio and airfoil dirfoil (tapered cross sec- tion) of YlOl blade	6-1-1 Ti plate with blade-type aspect aspect and-13ke cross-esi- tion of riol blade	e-1-1 Ti plate with blade-type ampect angle-like cross-and tion of riol blade	B-1-1 T1 plate with blade-type aspect ratio and ratio and rous-sec- tion of riol blade
Impecting Target (g)	119.5	329.2	1.8.1	1
11- (9)	618.6	0.163	649.2	681.0
Project Type	Micro-balloon gelatin bird (cyiinder) (7.62 cm dia. 1.5.24 cm long)	Micro-balloon gelatin bird (cyllinder) (.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (7.52 cm dia. 13.24 cm Long)	Micro-balloon gelatia bird (cylinder) (7.62 cm dia. 15.24 cm 10ng)
Shot No.	2-0167	2-0180	1910-2	2-0162
group Bo.	•	•	•	•

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Deformation Plot	£	2	£	2
Camera Frantng Rate (frames/sec)	20, 592	20, 544	20, 688	
High-Speed Camera Type	Dyna fax	byna fax	byna fax	8 11
bamage bescription and comments	Bird hit target tank upon entry. No visible damage on speciaen. Impect mess unable to be determined.	No visible damage on speciaen. Bird valocity to load speciaen after being presided too low bo target speciaen.	No visible damage on speciaen. Bitd hit target tank upon entry. Impact assa umble to be detarrained.	No visible damage on epecimen. No file. Unable to determine impact mass.
Impact Valocity (a/s)	9 6 9	100.3	114.0	120.1
ghroud Restraint	£	£	£	£
Impact Angle (*)	4. 2	24.4	24.4	24.4
Strain Gauge Locations	rigure - BA	rigure Pigure 8A	Figure 8A	see Figure 8A
firmer from from from	17.0	21.8	21.8	21.8
Span Bran for Impact (s)	Edge Lagect Prov span	Labort Labort 1704	Edge Larpact 9 70% apen	itdge Lapact e 704 epen
Target Material and Description	8-1-1 Ti plate with blade-type aspect ratio and blade-like cross-sec- tion of flon of	8-1-1 Fi plate with blade-type suppect ratio and blade-like cross-sec- tion of flot blade	8-1-1 Fi plate with blade-type ampect ratio and blade-like cross-sec- tion of rlol blade	8-1-1 ri plate with blade-type aspect ratio and blade-like cross-sec- tion of rion of
hnee Impecting Target (g)	ł	1	1	1
tile Mas (g)	<b>6</b> .163	670.0	680.0	0.065
Projec Type	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cyiinder) (7.62 cm dia. x 15.24 cm iong)
	2-0183	2-0184	2-0185	2-0186
	Ø	•	•	•

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Deformation Plot	0 æ	£	£	7.e
Camera Framing Rate (frames/sec)	1	20,816	20, 704	20, 224
High-Speed Camera Type	NO FILM	byna fa x	Dynafax	Cyaffe.
Demage Description and Comments	No visible damage on specimen. No film. Unble to determine impact mass.	No visible damage on specimen. No film and velocity was estimated. Umable to determine import mass.	No visible damage on specimen.	No visible damage on epecimen.
Impact Velocity (m/s)	1512	183.05	8.	105.4
Shroud Restraint	£	£	£	£
lepact Angle (*)	24.4	24.4	21.4	37.4
Strain Gauge Locations	see Figure 8A	see Figure 8A	see Flgure 8A	rigure BA
Impact Distance from Noot (cm)	21.8	21.8	21.6	21.8
Span Location for Impact ()	Båge 1 mpact 9 70a span	Edge Lagact 9 70% apen	Råge Læpact 9 70% 9 pun	Båge Lapact 0 70 spån
Target Matarial and Description	8-1-1 Ti plate with blade-type supect ratio and blade-like cross-sec- tion of rlol blade	8-1-1 Ti plate with blade-type supect supect blade-like cross-sec- tion of riol blade	<pre>8-1-1 fi plate with blade-type aspect aspect blade-like cross-sec- tion of riol blade</pre>	B-1-1 fi plate with blade-type ampect ratio and blade-like cross-sec- tion of riol blade
Mass Target (g)	1	1	s. 04	1.101
11. (9)	675.0	675.2	5.9.5	681.6
Projeci Type	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Hicro-balloon latin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. k 15.24 cm long)	Hicro-balloon gelatin bird (cylinder) (7.62 cm dia. r 15.24 cm iong)
		2-0188	2-0169	5-0190
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Deformation Plot	£	£	£	£
Camera Franting Rate (frames/sec)	:	20, 352	21,024	20,736
High-Speed Camera Type	Rila M	bynafax	Dynaf ex	Dynaf ax
Damage Description and Comments	No visible damage on speciaen. Bird hit tar- get tank upon entry. No film.	Severe damage. Specimen bent and broke at root area.	Plastic deformation of specimen at impact site. Bow of 0.95 cm on left side of specimen and 0.95 cm on right side.	No visible damage on speciaen. Velocity estimated.
lepect Velocity (m/e)	239.9	7.602	136.5	29.3
Shroud Restraint	£	2	5	ş.
Impact Angle (°)	24.4	24.4	0.06	0.06
Strain Gauge Locations	see Figure BA	see Figure 8A	see Figure 11A	see Figure 11A
Impact Distance Noot (cm)	21.8	21.8	21.8	21.8
Bpan location for lapact ()	Kdge Lepact span	Rdge Lapact 9 704 apan.	Center Lapact 0 70% spun	Center Jagact e 706 span
Target Material and Description	8-1-1 71 plate with blade-type aspect ratio and blade-like cross-sec- tion of riol blade	8-1-1 Ti plate with blade-type appect ratio and blade-like cross-soc- tion of floi blade	8-1-1 Ti plate with blade-type appect ratio and blade-like cross-soc- tion of riol blade	B-1-1 Ti plate with blade-type aspect ratio and blade-like trons-sec- tion of Tiol blade
Maa Impecting Target (g)	1	6.,11	C. 28	<b>.</b>
	679.9	686.2	85.J	C.199
Project Type	Hicro-balloon gelatin bird (ryihuder) (1.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (1.62 cm dia. z 15.24 cm long)	Micro-balloon gelatin bird (cylloder) (1.81 cm dia. x 7.62 cm long) long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. 7.62 cm long)
	2-0191	2-0192	2-0177	2-0178
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<b>Deformation</b> Plot	£	£	£	£
Comera Praming Rate (frames/sec)	20,689	Tiaing sarks 1,000/sec	fining marks 1,000/sec	tialing marks 1,000/sec
High-Speed Casera Type	Dynafax	Hyce	Hyce	Hycen
bamage Description and Comments	Shroud restraint tore loose from mount. Tip deflection of 17.59 cm on left side of specimen and 17.72 cm on right side.	Specimen rocked back in mount. Plastic deforma- tion of specimen at root by bending. The deflec- tion of 17.24 cm of leading edge and 16.26 cm of trailing edge.	No local damage, however, specimen bent at root. Tip deflection of 7.14 cm.	No visible damage to spectame. Velocity low enough each that bird was not cut all the wey through by spectame. Impect mass estimated.
Impect Velocity (m/m)	203.4	101.8	<b>5</b> .	47.9
Shroud Restraint	Tea	£	ŝ	£
Impact Angle (*)	0.08	36.4	36.4	36.4
Strain Gauge Locations	see Figure 11A	see Figure 12A	see rigure 12A	see Figure 12A
Impact Distance from Noot (cm)	21.8	17.2	17.2	17.2
Span Location for Impact ()	Center Lingact 8 70% apan	Rdge Lugart 8 709 span	Rdge Lapact 9 70% apan	Edge Lapact 70% span
Target Material and Description	8-1-1 Ti plate with blade-type ampect ratio and blade-like cross-sec- tion of riol blade	403 Stain- less steel fiat plate with blade- type aspect ratio of J79 blade	403 Stain- less steel flat plate with blade- type ampect ratio of J79 blade	403 Stain- less steel cambered flat plate with blade- type aspect ratio of J79 blade
Mass Impacting Target (g)	85.3	265.7	253.8	~ 300.0
•11 •11 •1	85.3	682.3	652.8	666.7
Projeci Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm iong)	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm iong)
	2-0179	2-0157	3-0158	2-0159
61 00 10 00 10 00	10	1	1	13

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Deformation Flot	ŗ	Į	£	£
Camera Franting Bate (frames/sec)	Timing marks 1,000/sec	Tiaing marks 1,000/sec	fielng marks	Timing marks 1,000/sec
High-Speed Camera Type	Hycaan	Hycen	Rycan.	Hycan
Damage Description and Comments	Plastic deformation of specimen by bending at root. Tip deflection of 9.84 cm.	Plastic deformation of specimen by banding at root. Tip deflection of 2.54 cm.	Plastic deformation of specimen by bending at root. Tip deflection of 17.78 cm.	No visible damage to spectaen.
Impact Velocity (m/s)	92.4	63.7	s. 85	<b>65.1</b>
Shroud Restraint	£	£	£	2
Lapact Angle (*)	<b>J6.4</b>	₹.9E	36. 4	18.9
Btrain Gauge Locations	see Figure 12A	see rigure 12A	see rigure 12A	see Pigure 13A
Impact Platance from Noot (cm)	17.2	2.11	17.2	10.8
Bpan Location Lapact ()	Ridge Lapact 9 706 span	itdge Lagact 70a span	Rdge 1 TON 1 TON	Ndge Lapact 9 704 spen
Target Material and Description	403 Stain- less stael cambered flat plate vith blade- type aspect ratio of J 79 blade	403 Stain- leas fteel tuisted tuisted blade-type aspect ratio of J79 blade	403 Stain- less steel twisted thisted blade-type amped tratio of J79 blade	Boron/Al crose ply flat pamel vith biade type ampect type ampect tratio of APSI blade
Impacting Throat (9)	172.3	148.6	192.3	<b>T</b> .
-11 (6)	712.7	605.4	692.0	0.59
Project Type	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm iong)	Mcro-balloon gelatin bird (cylinder) (72 cm dia. 15.24 cm iong)	Micro-balloon gelatin bird (cylimdar) (7.5 cm dia. x 15.24 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. (3.81 cm dia. iong)
	2-0163	2-0161	2-0162	2-0132 epeci- vi 38
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Deformation Plot	С. М	₽ ₽	i ee	£
Casters Framing Nate (frames/sec)	Timing warks 1,000/sec	Timing warks 1,000/sec	Timing marks 1,000/sec	Tialing marks 1,000/sec
High-Speed Camera Type	Hycan	Hycan	Hycam	Ry can
Damage ' scription and 'ssta	No visible damage to specimen.	Plastic deformation of specimen by bending at root. Tip deflection of 0.13 cm.	No visible damage on epeciann.	Plastic deformation of specimen by bending at root. Tip deflaction of 0.23 cm. Specimen also spilled and broke opposite impact site on leading edge over an area of 5.64 x 1.65 cm velocity estimated.
Impact Velocity (m/s)	105.8	161.9	164.0	243.98
Shroud Restraint	£	£	£	8
Impact Angle (*)	18.9	10.9	18.9	18.9
strain Gauge Locations	see Figure 13A	see Figure 13A	rigure 13A	see Figure 13A
Impact Distance Noot (CB)	10.8	10.8	10.8	10.8
Span Location for [1]	Bdge Lagact 9 70% span	Rdge impact span	Båge ingact 9 704 spån	Bólge Lagact 8 pan
Target Naterial and Description	Boron/Al cross ply flat panel with blade- type aspect ratio of APSI blade	Boron/Al crose ply flat panel with blade- type aspect ratio of APSI blade	Boron/Al cross ply flat pamel with blade- type aspect ratio of APSI blade	Boron/Al cross ply flat panel with blade- type aspect ratio of APSI blade
Maas Impecting Target (g)	12.9	10.7	16.5	E.11
11e 169	85.6	87.5	84.5	6. 6.
Project Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. 3.762 cm long)
Shot No.	2-0133 speci- men f VI lB	2-0134 speci- wen 9 vi 1A	2-0135 spect- men 8 vi 18	2-0136 mpeci- vr ls
Group Bo	2	7	3	3

8. RESULTS OF STATIC IMPACT TESTING (CONTINUED) TABLE

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Plot	Ŷ	£	£	ŝ
Camera Franing D Rate (frames/sec)	Tining marks 1,000/sec	Timing marka 1,000/sec	Timing marks 1,000/sec	Timing marks 1,000/sec
Hígh-Speed Camera Type	Hycaa	Rycan	Hycaan	Rycean
Damage Description and Comments	No visible damage on specimen.	Specimen broke at root. Tip deflection of 8.26 cm.	No visible damage on specimen. Impuct mass was estimated because bird hit "C" clamp in back of specimen.	Speciaen broke off at root.
Impact Velocity (m/s)	256.1	312.8	185.4	306.4
Shroud Restraint	£	۶	£	£
Impact Angle (*)	18.9	10.9	18.9	15.9
strain Gauge Locations	see Figure 13A	see Figure 13A	see Figure ' I 4A	see Figure 14A
Impact Distance Noot Com	10.8	10.8	<b>₹</b> .	<b>9</b> - 9
Span Location for tapact (s)	Edge Lapact e 70% span	Edge Lapact @ 70s epan	Edge Sapact 9 709 span	Bidge Lagact 9 70% span
Target Material and Description	Boron/Al cross ply flat banel with blade- type aspect ratio of APST blade	Boron/Al cross ply flat panel with blade- type aspect ratio of AFEI blade	Boron/Al cross ply flat panel with one- huit blade- type aspect ratio of AFI blade	Boron/Al cross ply flat panel with one- half blade- type ampect ratio of AFI blade
Mass Lapacting Target (g)	15.9	20.8	0.064	23.8
11 10 10 10 10	83.0	8.48	65.3	83.6
Project. Type	Micro-balloon gelatin bird (sylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.01 cm dia. x 7.62 cm long)	Hicro-balloon gelatin bird (cylinder) (381 cm dia. 1 7.62 cm long)	Nicro-balloon gelatin bird (cyilmder) (3-81 cm dia. 7.62 cm long)
Shot Stot	2-0137 spect- men 6 VI 38	2-0139 speci- wen #	2-0149 speci- vi 5A	2-0150 spect- men 0 VI 58
Group Bo	2	7	<b>x</b>	<b>n</b>
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<b>Deformation</b> Plot	Ŷ	£	۶.
Camera Camera Franing Rate (frames/sec)	Tining marke 1.000/sec	1,000/sec 1,000/sec	11-11-11-11-1-1-1-1-1-1-1-1-1-1-1-1-1-
Righ-Speed Camera Type	Hycan	Hyon	Rycea
besage bescription and comments	Specimen broke off at root.	Specimen broke off at 70% span location at impuct site.	Specimen broke off at root. Also broke off at 70% span location at impact site approximately 12.7 cm long along leading edge and 5.72 cm long along trail- ing edge from tip.
Impact Valocity (m/s)	229.9	241.8	119.5
Bhroud Restraint	Ŷ	£	£
Lepact Angle (*)	18.9	16.9	18.9
Strain Gauge Locations	see Figure 14A	see Figure I 3A	see Figure 13A
Impact Distance from Noot (cm)	5.4	10.8	10.8
Span Location for Impect (N)	Edge impact 8 70% span	Bdge İmpact 9 704 span	Båge Ångact 8 706 Span
Target Material and Description	Boron/Al cross ply flat panel with one- with blade- type aspect ratio of APSI blade	Boron/Al cross ply with blade- type aspect tatio and cons-haif blade-type to chord tatio of APSI blade	Boron/Al cross ply with blade- type aspect- type aspect- type and cretio and blade-type thickness to chord ratio of NST blade
Mase Impecting Target (g)	46.1	0.01	5°.1
:11e Mase (g)	83.6	84.2	<b>•</b>
Project Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. 1.62 cm long)	Micro-balloon gelatin bird (cyiluder) (3.Bl cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)
Shot No.	2-0151 speci- men # VI 5A	2-0138 speci- men E VI 7A	2-0140 speci- men 9 VI 75
Ro.	<b>n</b>	2	16

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<b>beformation</b> Plot	C <b>X</b>	¥	¥	Ŷ	Yes
Camera Franting Bate (frames/sec)	20, 384	20, 240	1	20, 368	20, 448
Nigh-Speed Camera Type	Dyna fax	Dynafax	No film	Dynefex	Dyna fax
<b>Demage Description</b> and Comments	No visible damage. Bird tumbling during fiight.	No visible damage. Bird tumbling during flight.	No visible damage. Bird alsed speciaen.	No visible damage on specimen.	Mo visible damage on speciaen.
Tepact Velocity (m/e)	8.761	122.9	121.0	133.8	194.2
Shroud Restraint	£	£	2	£	£
Impact Angle (*)	16.9	18.9	18.9	18.9	18.9
Strain Gauge Locations	see Figure 15A	see Figure 15A	rigure 15A	see Figure 15A	see Figure 15A
Impact Distance from Noot (cm)	7.1	1.1	1.1	7.1	1.1
Span for for (N)	Edge Japact 9 706 span	Edge Lapact 9 70% span	Råge Lapect 8 709 spen	Edge Lapect 9 705 spen	Kdge İmpact 9 709 epan
Target Material and Description	Boron/Al cross ply pamel with blade-like cross- section	Boron/Al cross ply panel with blade-like cross- section	Boron/Al cross ply panel with blade-like cross- section	Boron/Al cross ply pamel with blade-like cross- section	Boron/Al cross ply panel with blade-like cross- section
Mass Impacting Target (g)	2.8	4.5	0.0	5.3	0.8
•11 • • • • • • • • • • • • • • • • • •	P.E8	82.2	0.08	82.0	81.7
Project Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.52 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.8° cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.62 cm iong)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm iong)
	2-0208	2-0209	2-0210	2-0211	2-0212
Group HD.	11	<b>n</b> .	s	11	11

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Deformation Plot	Ŷ	£	5	£
Camera Framing Rate (frames/sec)	20,224	Timing marks 1,000/sec	Timing warks 1,000/sec	Tiaing marks 1,000/sec
High-Speed Camera Type	Dynafax	Hycaa	Hycaa	Hy caun
Demage Description and Comments	Speciaen broke into many smaller type pieces at impact site area.	No visibile damage on specimen.	Mo visibie damage on speciaen.	Specimen broke off at root and also just below 70% span location.
Impact Velocity (m/s)	247.3	138.7	202.7	8.91E
Shroud Restraint	£	£	£	£
Impact Angle (*)	18.9	18.9	18.9	18.9
Strain Gauge Locations	see rigure 15A	see Figure 16A	see Figure 16A	see Figure 16A
Impact Distance from Root (CB)	1.7	10.8	10.3	10.6
Span Location for (s)	Edge Lapact 0 70% span	Edge Lapact e 70% e:san	Rdge Lapact e 70a span	Rdge Lagact e 70% span
Target Material and Description	Boron/Al cross ply panel vith blade-like cross- section	Boron/Al cross ply constant chord air- foil panel with blanel type aspect ratio and camber	Boron/Al cross ply constant chord air- foll panel vith blade- type aspect ratio and camber	Boron/Al cross ply constant chord air- foil panel type aspect type aspect cambo
Mass Impecting Target (g)	1.1E	1. E	6.1	35.6 1
11e Hase (g)	81.5	85.9	82.8	87.3
Project Type	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. z 7.62 cm long)	Micro-bal.c.n gelatin bird (cylinder) (3.01 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cyilnder) (13.91 cm dia. (13.91 cm dia. long)	Micro-balloon gelatin bird (cylinder) (3.01 cm dia. x 7.62 cm iong)
shot Wo.	2-0213	2-0143 spect- wen 8 vI AP2	2-0144 apect- man 9 VI AF1	2-0145 spect- men 8 vi Ar3
Group	11	<b>9</b>	8	=

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beformation Plot	£	3	£
Connera Franing Rate (frames/sec)	Timing marks 1,000/sec	Timing marks 1,000/sec	Tialny marks 1,000/sec
High-Speed Canera Type	Hycean	Hycem	Hycean
bamage Description and Comments	Specimen broke off at root.	No visible damage on specimen.	Specimen broke off at root.
Impact Velocity (m/m)	208.8	1.921	185.7
Shroud Restraint	¥	2	£
tmpact Angle (*)	18.9	18.9	18.9
Strain Gauge Locations	see Figure 16A	see Figure 16A	see Figure 16A
Impact Distance from Noot (cm)	10. 9.	10.	10. 8.
Span Span Location for Impact (s)	Bidge Angesch span	Kdge Lagart 9 704 span	Båge Lapact 9 700 spån
Target Material and Description	Boron/Al cross ply cross tart chord air- foil panel vith blade- type aspect trio, and tvist	beron/Al cross ply crossint constant constant constant constant four and vith blade- type appect ratio, ratio, ratio	Beronval cross ply constant constant constant constant constant constant constant vith blada- type aspect type aspect type the constant type aspect
Mass Impacting Target (g)	47.0	2.11	1.66
•1 (5)	85.6	85.7	6. 5
Projecti Type	Hicro-balloon gelatin bird (cyilmder) (3.81 cm die. x 7.62 cm long)	Hicro-balloon gelatin bird (cylindar) (381 cm dia. 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.61 cm dia. 3.7.62 cm long)
Shot No.	2-0146 speci- men 0 VI AF 25	2-0147 spect- win # 24 24	2-0148 speci- men 8 VI AF 22
Group Ho	51	61	a

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strain gage locations, the impact mass loading the specimens, the span location and type of impact, and a description of the damage generated on each specimen. Appendix A presents Figures 1A through 16A which are sketches showing the strain gage locations for both specimen and real blade impacts.

As indicated earlier, 93 impacts were conducted on structural element test specimens. Five of the specimens in this testing were tested without strain gages to measure out-of-plane displacements of a specimen surface using the Moiré fringe apparatus. The remaining impact tests were conducted using specimens instrumented with six strain gages. High speed photography was also used in every test where strain gages were installed on the specimens.

The strain was detected using high frequency strain gages mounted at critical locations of the test specimens and actual blades. Strain versus time and strain rate versus time plots were used to evaluate the results of the impacts. Gages were located at the root of the cantilevered test specimens and blades in addition to several gages being positioned directly opposite the impact site. The majority of the specimen tests were conducted using a sampling rate of 20 KHz on the strain data acquisition equipment with 4 KHz low-pass filters.

## 3.1.1 Impact Results of Structural Element Tests

The testing involved conducting either center or leading-edge impacts on 19 different groups of structural element specimens. As indicated earlier, the impactors were either artificial birds or ice projectiles which were fired on the cantilevered specimens. In several cases, the specimen tip was also restrained to simulate a tip shroud. The strain and strain rate data resulting from the impact are presented in Appendix B in the form of plots of strain and strain rate versus time. Tension is characterized as a positive strain value while compression is a negative strain for all cases unless noted. The impact velocity was varied in the testing from a low velocity range to generate elastic deformation response (no visible damage), to a medium range to generate plastic deformation (threshold damage), and finally a high velocity range where plastic/tear deformations were produced (severe damage).

## 3.2 IMPACT RESULTS ON ACTUAL BLADES

The testing involved conducting leading edge impacts on the three blade types investigated in the program. Various test conditions were used to determine the impact response of the blades. Tests were performed on 15 groups of blades as presented in Table 6 given earlier in this report. The impactors were either artificial birds or ice projectiles (both slab ice and spheres) in the study on the actual blades. The F101 blade using 8-1-1 titanium has a tip shroud which was restrained. The tip shroud was permitted to move in the spanwise direction during the impact event as shown in Figure 4. The strain and strain rate data resulting from the impacts are presented in Appendix B in the form of strain and strain rate versus time plots. Two sizes of birds were utilized in the testing (85 g and 680 g). The 85 g (3 ounce) bird was used to simulate a starling sized bird and the 680 g (1.5 pound) bird would be a seagull sized bird. The ice impactors used in the study were either a cylinder 7.62 cm (3.0 inches) diameter with a length of 17.78 cm (7.0 inches) or a 5.08 cm (2.0 inch) ice sphere. The ice cylinder (mass of 850 g) was used to simulate an ice slab while the ice sphere (mass of 65 g) simulated hail size ice balls. The impact site was either at the 30 percent or 70 percent span locations.

Table 9 gives the results of the impact tests for the actual blades. The table gives the test conditions, the blade and material type, the proper figure of Appendix A which

## RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONCLUDED) σ TABLE

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beformation Flot	3	ž	<u>3</u>
Camera Framiny Rate (frames/sec)		20 27	+n: ' · 7
High-Speed Camera Type	10 EI m	U';nafax	Uynafax
Damage Description and Comments	No visible damage on blade, frojectile broke up upon launcu. No strain gauge data. Imyact mass estimated to be half of initial ice ball mass.	severe damage by breaking out 5.08-1.27 cm (length width) section of leadiny edge a impact site. Impact mass estimated to be half of initial ice ball mass.	Severe damage by breaking off at platform close to root area and breaking out 9.65.1.52 cm (length width) section of leading edge at
Impact Velocity (m/s)	0.67	42.7	2. 95.
Shroud Restraint	Ŷ	2	£
Impact Angle (*)	30.8	38.8	36.8
Strain Gauge Locations	ste F19. 5A	see Fig. 5A	see F19. 5A
Impact Distance from Platforn (cm)	7 7	4 4	4 4
Span Location for Impact (A)	Edge ìmpact ð 30% span	Edge 1 mpact 8 Jos span	Edge impact ê 30% span
Target Material and Description	Boron/ aluminum APSI blade	Boron/ alumanuma APSI blade	Boron/ aluminum APSI blade
Mass Impacting Target (g)	۲. <b>34</b> .9	2.467	135.7
ctile Mass (9)	6y.8	68.3	716.1
Proje( Type	Icc ball (5.08 cm dia. s <sub>i</sub> dere)	Ice ball (5.08 cm dia. sphere)	Ice cylinder (7.62 cm dia. x 17.78 cm iony)
Shut No.	2-0217 Blade #040	2-0218 Blad⊨ Fi)40	2-0233 Blade BUGB
Group No.	77	146	ect.

RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONTINUED) • TABLE

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Deformation Plot	Yes	Yes	<b>₽</b>	Ŷ	2
Camera Framıny Rate (frames/sec)	20,912	20,764	! :	20,224	:
lligh-Speed Camera Type	Dynafax	Dynafax	No film	Dynafax	No film
Damage Description and Connents	Blade cracked along plat- form across chord 5.08 cm starting at leading edge side. Sabot also impacted blade. Unable to deter- mine impact mass	Blade broke off along platforn close to root area. Also broke out material at tip 10.16 cm down along leading edge and 2.29 cm width. Unable to determine impact mass.	No visible damage on blade. Projectile broke up upon launch. Impact mass etimated to be half of initial ice ball mass.	Blade bowed 0.25 cm on leading edge at impact site. Projectile broke up upon launch. Impact mass estimated to be half of initial ice ball mass.	Severe damage by break- ing out 6.60'1.27 cm (length'width) section of leading edge at impact site. Impact mass esti- mated to be half of initial ice ball mass.
Impact Velocity (m/s)	418.9	406.1	133.8	198.8	132.3
Shroud Restraint	02 Z	Ŷ	£	£	2
Impact Angle (*)	38.8	18. '	98.8 9.	38.8	38.8
Strain Gauge Locations	see Fig. 3A	see Fig. 3A	see Fig. 5A	see Fig. 5A	see rig. 5A
Impact Distance from 2latforr (cm)	4.4	10.8	4.4	4	4 4
Span Location for Impact ()	Edge impact 8 30% 5pan	Edge à mpact span	Edge impact 3 30% span	Edge impact § 304 span	Edge impact 8 Jun span
Target Material and Description	Boron/ alumunum APSI blade	Borcon/ alumtinuma APSI blade	Borcon/ alumainum APSI blade	Boron/ aluminum APSI blade	Boron/ aluminum APSI blade
Mass Impacting Target (g)			0. IEr	r.26v	1.262
tile Mass (g)	65 °.	<b>65.</b>	<b>62</b> .0	65.3	65.4
Project Type	Micro-balloon yelatın bird (cylinder) (3.61 cm dia. x 7.62 cm long)	Hicro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	ice ball 5.u8 cm dia. sphere)	Ice ball (5.08 cm dia. sphere)	Ice ball (5.08 cm dìa. sphere)
Shot No.	2-0023 Blade #073	2-0/22 Blade #059	2-0214 Blade #076	2-0215 Blade FU76	2-u216 B1ade 1046
dno Q	178	86 T	877	4 4 8	89

9. RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONTINUED) TABLE

befor <b>ma</b> t Ion Flot	ž	2	¥ Kes	2	Ŋ
Camera Framiny Rate (frames/sec)	20, 568	:	20, 288	20, 240	1
High-Speed Camera Type	Dynefax	No film	Dynafax	Dynafax	No film
Damage Description and Comments	Plastic deformation of bowing at impact site. Bow of 1.58 cm along leading edge. Tip deflec- tion of 5.13 cm at leading edge and 8.49 cm at trail- ing edge Jmpact mass estimated to be half of ice sphere.	No visible damage on specimen.	No visible damage on specimen.	Plattic deflection of bowing at impact site. Tip deflection of 14.70 cm along leading edge and 15.49 cm along trailing edge.	Local damage at impact site by breaking off material along leading edge. Affected area vas 7.13 cm long and 1.80 cm maximum width.
Impact Velocity (m/s)	324.7	<b>P</b> . 66	97.6	9.661	259.1E
Shroud Restraint	£	Ň	£	ž	£
Impact Angle (°)	1.1ĉ	51.1	51.1	1.12	38.8
Strain Gauge Locations	6A 6A	see Fig. 6A	see Fig. 6A	see Fig. 6A	see Fig. 3A
Impact Distance from Platform (cm)	2.1	7.2	1.2	7.2	4.4
Span Location for [mpact ()	Edge à 30% span	Edge impact & 30% span	Edge Impact ê 301 span	Edge impact 8 30% span	Edge impact 9 30% span
Target Material and Description	4u3 Stain- less steel J79 blade	403 Stain- less stéel J79 blade	403 Stain- less steel J79 blade	403 Stain- less steel J79 blade	Boron/ aluminum APS1 blade
Mass Impacting Target (g)	E . 2E.	147.8	207.4	158.4	16.0
tile Mass (q)	ç <b>1</b> .6	686.5	758.5	689 .6	<b>65</b> .0
Projec Type	lce uall (5.08 cm daa. spinere)	lce cylinder (7.62 cm dia. x 17.78 cm long)	Ice cylinder (7.62 cm dia. x 17.78 cm lony)	Ice cylinder (7.62 cm dia. x 17.78 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)
Shot No.	2-020 81ade 81-2	2-u232 Blade #1-3	2-U234 B1 ade #1-4	2-U235 Blade 81-4	2-0016 B1ade \$082
Group No.	Lou B	116	116	911	128

RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONTINUED) **б** TABLE

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Deformation Plot	£	χ. χ.	de X	¥	Ŷ	Ŷ
Camera Framing Rate (frames/sec)	:	20,800	20, 384	20, 384	20, 288	20, 136
High-Speed Camera Type	No film	Dynafax	Dynafax	Dynafax	Dynafax	Dynafax
Damage Description and Comments	Blade severely damaged by being knocked from fixture. Ceneral bowing through free span with tip deflection of 0.15 cm.	Blade severely damaged by being knocked from fixture. Specimen hit target tank. Large amount of bow damage of 9.8 om at impact site.	No visible damage on speciaen. Impuct mas estimate to be half of ice sphere.	No visible damage on specimen. Impact pass estimated to be half of ice sphere.	No visible damage on specimen. Ice ball broke up upon launch. Impact mess estimated to be haif of ice sphere.	Ceneral bending from root to tip through free span. Tip deflec- tion of 2.24 cm. Impact asse estimated to be haif of ice sphere.
Impact Velocity (m/m)	170.7	254.0	88.7	1.91	182.3	247.9
Shroud Restraint	¥	£	¥	£	2	£
Impact Angle (°)	51.1	<b>9</b> . •	1.12	51.1	1.12	1.12
gtrain Gauge Locations	<b>eee Fig.</b> 2A	eee Fig. 2A	ee rig. 6A	<b>6</b> . 6A	<b>6</b> A 6A	<b>6</b> A 6A
Impact Distance from Platforn (cm)	7.2	16.9	7.2	7.2	7.2	2.7
Bpan Location for Impact ()	Edge Lapact 9 301 apan	Rdge Lapact 9 70% span	Edge Lapact apen apen	Råge 1 mpact 1 pact	Kdge Lapact span	Rdge Lepect apen
Target Matarial and Description	403 Stain- less steel J79 blade	403 Stain- less stael J79 blade	403 Stain- les stael J79 blade	403 Stain- less steel J79 blads	403 Stain- less steel J79 blade	403 Stain- less stael J79 blade
Impecting Target (g)	0.116	161.0	~32.8	~32.S	8. IEV	~32.6
	680.0	680.0	65.6	65.0	63.5	65.2
Projec Type	Wicro-balloon gelatin bird (cylinder) (7.62 cm dia. z 15.24 cm long)	Micro-balloon gelatia bird (cylindar) <sup>-</sup> (7.62 cm dia. x 15.24 cm long)	ice ball (5.08 cm dia. sphare)	Ice ball (5.08 cm dia. sphare)	Ice ball (5.08 cm dia. sphare)	Ice ball (5.08 cm die. sphere)
	2-0015 R1ada 82	2-0024 B1ade 93	2-0219 Blade 1-1	2-0220 Blade \$1-1	2-021 81ada 81-2	2-0222 Blade 81-1
	8	8	10	108	108	101
			53			

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# RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONTINUED) TABLE 9.

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Target         Target           Description         Impacting         Materia           Description         190         190         Description           Materia         Target         100         Description           Materia         180         28.0         403         Stain	Projectile Impacting Materia Type Mass Target and (9) (9) Descripti Micro-balloon 85.0 28.0 403 Stain-	tile Imacting Miteria Ness Target and (9) (9) Descripti 85.0 28.0 403 Stain	Target Target Target Materia Target and (9) Descripti 28.0 403 Stain-	Target Materia and Descripti 403 Stain-	T U	Span Location for Impact ()	Impact Distance from Platforn (cm)	Strain Gauge Locations see Fig.	Impact Angle (*) 36.4	Shroud Restraint No	Impact Velocity (m/s) 300.0	Damage Description and Comments	High-Speed Camera Type	(amera Franing Rate (frames/sec	. – i
gelatin bird less steel (cylinder) (1.81 cm dia. x 7.62 cm long)	pelatin bird less steel (cylinder) J79 blade 1.81.cm dia. r 7.62 cm iong)	less steel J79 blade	less steel J79 blade	less steel J79 blade		i mpact 8 70% span		2A				Sabot impacted blade. Blade damaged by bowing at impact site. Bow of 5.38 cm at leading edge; 4.08 cm at trailing edge.	Dynafax	20,896	
l Micro-balloon 679.0 94.9 403 Stain- gelatin bird 679.0 94.9 403 Stain- (cylinder) J79 blade (7.62 cm dia. x 15.24 cm long)	wicro-balloon 679.0 94.9 403 Stain- pelatin bird [eylinder] 179 blade [cylinder] 176 Stain. 17.62 cm dia. t 15.24 cm	679.0 94.9 403 Stain- less steel J79 blade	94.9 403 Stain- less steel J79 blade	403 Stain- less steel J79 blade		Edge impact ê 30% span	7.2	see Fig. 2A	1.12	£	160.7	Blade damaged slightly by bowing at impact site of 0.25 cm.	Dynafax	20,786	
2 Mucro-balloon 668.0 403 Stain- gelatin bird less steel (vplinder) J79 blade (1.62 cm dia. x 15.24 cm long)	dcro-balloon 668.0 403 Stain- pelatin bird less steel cylinder) J79 blade 17.62 cm dia. i 15.24 cm	668.0 403 Stain- less steel J79 blade	403 Stain- less steel J79 blade	403 Stain- less stuel J79 blade		Edge 1 mpact 3 30% span	7.2	see Fig. 2A	1.12	£	161.6	No visible damage on specimen. No strain gauge data. Unable to determine impact mass.	No film	;	
3 Mtcro-balloon 678.5 403 Stain- gelatin bird (cylinder) J79 blade (7.52 cm dia. x 15.24 cm long)	Mccro-balloon 678.5 403 Stain- pelatin bird less steel (cylinder) J79 blade (15.24 cm (15.24 cm	678.5 403 Stain- less steel J79 blade	403 Stain- less steel J79 blade	403 Stain- less steel J79 blade		Edge impact ê 30% span	7.2	see Fig. 2A	1.12	£	167.4	No visible damage on specimen. Unable to determine impact mass.	No film	:	
4 Micro-balloon 660.0 37.0 403 Stain- gelatin bird (cylinder) 17.8 steel (cylinder) 173 blade (7.62 cm dia. 173 blade 17.62 cm dia. 15.24 cm hont 1.000 blade 10.000  blade 10.000  blade 10.000 blade 10.0000 blade 10.000 blade	ttcro-balloon 660.0 37.0 403 Stain- gelatin bird less steel [cylinder] J73 blade [7.62 cm dia.	660.0 37.0 403 Stain- less steel J73 blade	<b>37.0 403 Stain-</b> <b>less steel</b> J79 blade	403 Stain- less steel 179 blade		Edge impact 3 30% span	7.2	see Fig. 2A	51.1	£	170.4	No visible damage on specimen.	Dynafax	20, 720	

9. RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONTINUED) TABLE

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Deformation Plot	2	3	9 :-	2	2	Z
Canera Framing Rate (frames/sec)	2.7, 368	20,560	tot. 0.			20,396
High-Speed Camera Type	U;nafax	Dynafax	Dynafax	SE III ON	ND ELLEN	Dynafax
Damage Description and Comments	i∿ Visible damage on s.⇒cimen. Ice cylinder broke up uµon launch.	tiv visible damaqe on slecimen. Ice cylinder broke up upon launch.	Llade bowed at Impact Llade bowed at Impact Leading edge and 6.50 cm on trailing edge.	No visible damage on Specimen.	Mo visible damege on specimen.	No visible damäye on specimen.
Impect Velocity (m/s)	۲.٤۲	92.7	185.1	164.3	161.3	200.3
Shroud Restraint	ช 22 X-	Yes	se Xe	£	oz ·	Ŷ
Impact Angle (*)	t. +2	24.4	24.4	51.1	1.12	1.12
Strain Gauge Locations	see Fig. 4A	see Fig. 4A	see F1g. 4A	see Fig. 2A	see Fig. 2A	see Fig. 2A
Impact Distance from Platiorm (cm)	18.6	18.6	18.6	7.2	7.2	7.2
Span Span Location for (N)	Edge i npact ê 70% sµan	Edge Lapact 8 70% span	Edge impact 8 704 span	Edge 1 mpact 8 304 span	Edge Lapact Bpan	Edge impact 9 309 span
Target Material and Description	8-1-1 T1 F101 blade	8-1-1 Ti F101 blade	d-1-1 Ti FlO1 blade	403 Stain- less steel J79 blade	401 Stain- less steel J79 blade	403 Stain- less steel J79 blade
Mass Impacting Target (g)		:	75.8	15.1	48.1	48.1
ile Mass (g)	835.8	841.4	ġ67.1	. :09 2. :0	6.19	<b>8</b> 8.0
Project. Type	Ice cylinder (7.62 cm dia. x 17.78 cm long)	Ice cylinder (7.62 cm dia. × 17.78 cm long)	lce cylinder (7.62 cm dia. x 17.78 cm long)	Micro-balloon gelatin bird (cylinder) (3.81 cm dia. x 7.62 cm long)	Hicro-balloon gelatin bird (cylinder) (1.81 cm dia. x 7.62 cm long)	Micro-balloon gelatin bird (cylinder) (3.01 cm dia. x 7.62 cm long)
Shot No.	2-∪229 Blade∓ KGÃU1582	2-0230 Blade# KGA01582	2-3231	2-0068 Blade el	2-000 B1 ade #1	2-0010 Blade #1
Group No.	<b>a</b>	89. C	<b>a</b>	89 9	6 <b>8</b>	68

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RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES (CONTINUED) ъ. TABLE

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No.	p Shot No.	Projeci Type	tile Mass (g)	Mass Impacting Target (g)	Target Material and Description	Span Location for Impact	Impact Distance from Platform (cm)	strain Gauge Locations	I∎pact Angle (°)	Shroud Restraint	Impact velocity (m/s)	Damage Description and Comments	II Lyh-Speed Camera Type	Camera Framiny Rate (frames/sec)	læformation Flot
Ŧ	2-4197 B1ade# KGA01476	MLCTO-balloon gelatin bird 5 (cylinder) (7.62 cm dia. x 15.24 cm long)	681.4	64.3	8-1-1 Ti F101 blade	Edge impact Jos span	18.6	see Fig. 4A	24.4	Yes	117.7	No visible damage on specimen.	Dynafax	20,160	2
4	2- JL98 Bladet KGA01476	Micro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	681.4	40.7	8-1-1 Ti F101 blade	Edge implact 2/701 span	18.6	see Fig. 4A	24.4	X es	121.3	No visible damaye on speciaen.	Dynafax	20, 288	S Z
	2-0199 Blader KGA01476	Micro-balloon Gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	683.0	124.3	8-1-1 Ti F101 blade	Edge impact à 70% span	18.6 1	see Fig. 4A	24.4	Yes	187.2	No visible damage on specimen.	Dynafax	20,192	ç
a a	2-0200 Bladet KGA01476	Micro-balloon Gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	675.2		8-1-1 Ti FIOL blade	Edge impact 8 701 span	18.6	see Fig. 4A	24.4	Yes	230.5	No visible damage on speciaen. Unable to determine impact mass.	Dynafax	20,240	£
3	2-11401 B1ade# KGA01476	Mtcro-balloon gelatin bird (cylinder) (7.62 cm dia. x 15.24 cm long)	683.6	105.6	8-1-1 Ti F101 blade	Edge 1 mpact 8 701 span	18.6	see Fig. 4A	24.4	Yes	183.2	Blade knocked out of bottom fixture. Blade bowed at impact site 1.78 cm.	Dynafax	20, 336	2
<b>a</b>	2-0228 Bladefi KGA01582	Ice Cylinder (7.62 cm dia. x 17.78 cm long)	786.8		8-1-1 Ti FlOi blade	Edge impact 2 701 span	18.6	see Fig. 4A	24.4	Yes	95.4	No visible damage on specimen. Ice cylin- der broke up upon launch.	Dynafax	20,416	2 2

launch.

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RESULTS OF STATIC IMPACT TESTING ON ACTUAL BLADES **.** TABLE

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		1				
į	Deformation Plot	2	£	£	£	£
	Camera Framing Rate (frames/sec)	20,832	20, 752	20, 784	20,800	20,096
	H1gh-Speed Camera Type	Dynafax	Dynafax	Dy na fax	Dynafax	Dynafax
	Damage Description and Comments	No visible damage specimen.	Mo visible damage Mo risectaen. Unable to determine impact Mass.	Sabot impected blade. Blade damaged slightly by lading edge bow of 0.13 cm. Velocity esti- meted immet mass.	Blade damaged due to sabot impacting specimen. Veloc- ity estimated. Blade damaged by bowing at impact site. 3.00 cm bow on lead- ing edge and 3.81 cm bow on trailing edge.	Mo visible damage on specimen. Velocity estimated.
	Impact Velocity (m/m)	2. 692	353.4	259.1E	259.1E	106.7E
	Shroud Restraint	Xes	fes	2	<b>8</b> X	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
	Impact Angle	41.0	24.4	41.0	24.4	7.K
	Strain Gauge Locations	see F1g. LA	see Fig. 1A	IA Fig.	aae 71g. 1A	see Fig. 4A
	Distance from Platform	0.00	18.6	0.6	18.6	18.6
	for for for for	Edge Limpact Ban span	Kdge Lapact 9 704 spen	Rdge Lingeact e 304 spen	Kdge Lapact 9 704 span	Edge impact e 70% spen
	Material and Description	8-1-1 Ti Floi blade	8-1-1 Ti Flol blade	Floi blade	P-1-1 Ti Fiol blade	8-1-1 Ti Fiol blade
and a	Impacting Target (g)	25.0			214.0	27.4
	tile Maar (g)	85.0	85.0	672.0	678.0	679.7
	Projec Type	Micro-balloon gelatin bird (cylindar) (3.81 cm dia. x 7.62 cm	Micro-balloon Matin bird (cylinder) (3.81 cm dia. r 7.62 cm (ong)	thero-balloon palatin bird [cylindar] [7.62 cm dia. 13.24 cm ong)	Herr-balloon miatin bird cylindar) 7.62 cm dia. 15.24 cm ong)	ácro-balloon elatin bird cylinder) 7.62 cm dia. 15.24 cm
		2-0017 01ade 9 200017	-0018 11446 #	-0019	0020 00110 00112 00112 00112	01416 101476 101476 101476 101476
	ang i		л — 2 Л	м в <u>9</u> Я	4 E E	4 # <u>3</u> \$

describes the strain gage locations, the impact velocity and mass, the span location and type of impact, and a description of the damage generated on each blade.

As indicated earlier, 41 impacts were conducted on actual blades. All of the blades were instrumented with six strain gages. The sampling rate for the actual blade shots was 100 KHz and 20 KHz low-pass filters were used for this sampling rate. Frequency checks were also made on selected blades before and after each test. Any difference between the pretest and posttest frequency checks may be attributed to damage on the blade. These frequency checks were conducted at a sampling rate of 20 KHz with 4 KHz low-pass filters to attentuate frequencies above 4 KHz.

The impact velocity was also varied for the blade tests from a low velocity range to generate elastic deformation response (no visible damage), to a medium range to generate plastic deformation (threshold damage), and finally a high velocity range, where plastic/tear deformations were produced (severe damage). Tension is characterized as a positive strain value while compression is a negative strain for all cases except for Shots 2-0008 through 2-0024. In these cases, a negative strain denotes tension and a positive strain denotes compression.

## SECTION 4 SUMMARY AND CONCLUSIONS

The experimental program (Task VI) involved conducting nonrotating bench impact tests on test specimens ranging from simple cantilevered beams and plates to real blades. The response of the test specimens to impacts of substitute birds or ice was determined in the testing. The data collected included accurate impact conditions, dynamic displacement of the specimens at discreet points, strain/time histories local to the impact site and at critical blade stress regions identified from the structure response models, and damage assessment. The simple elements, such as beams or plates, were tested with progressive introduction of airfoil geometric parameters to validate experimentally the analytical predictions of Tasks V and VIII of the overall program and to derive a correlation between structural elemented specimens and full-scale blades.

Three types of blade materials, geometries, and sizes were investigated using ice and substitute birds as the impactors. The three blade types investigated in the study were the Fl01 blade using 8A1-1MO-IV (8-1-1) titanium, the J79 blade using 403 stainless steel, and the APSI metal matrix boron/aluminum blade. The geometries of the test specimens were similar to the geometries at the 50 percent span location of the three blade types investigated.

A baseline series of tests was conducted on the titanium material, a supplementary series was conducted on the stainless steel material, and a more complete series was conducted on the advanced composite material. The geometry effects which were believed to effect impact response were independently introduced in the testing and analysis. These effects included the aspect ratio, thickness to chord ratio, shape, shrouds, camber, and twist. Four impactors were used in the testing which included 85 g (3 ounce) and 680 g (1.5 pound) artificial birds, a 50.8 mm (2 ounce) ice ball, and 750 g (1.65 pound) ice cylinders to simulate slab ice. The impactors were gun launched to impact the leading edge of the test specimens in the majority of the testing.

A total of 92 impacts were conducted on the simple element test specimens. All of the specimens were strain gaged (except for the Moiré fringe shots) to obtain strain/time histories of the specimens local to the impact site and at critical blade stress regions for an impact. The impact velocity for the impacts was varied to obtain no damage, threshold damage, and severe damage on the specimens. The damage assessment of the data collected in the study included determining the mode of damage and measuring the extent of damage.

In addition to impact testing of simple element specimens, a number of impact tests (41 shots) were also conducted on full scale component blades. This impact testing of the actual blades was coordinated with the full scale blade testing of Task IVA where the impact tests were conducted to establish the strain rate limits for the material property tests of Task The impact velocities used in the Task IVA tests corre-IVA. sponded to those which would be typical of an impact at 70 percent span and 30 percent span locations at full power settings of the engine during takeoff for each of the blade types. Impacts at the 70 percent span level are representative of the highest velocity impacts experienced by a blade. Impacts at the 30 percent span level are typical of those in the highest stress regions of the blade where it is most vulnerable to the effects of impact degradation. The impact tests of Task IVA indicated that the highest strain rates developed were less than 400 in/in/sec in any of the types of blades tested (J79, F101, and APSI).

All of the strain and strain rate plots versus time are given in Appendix B for all impacts.

Appendix B is contained in two separate volumes of 11 x 13 sheets of graph paper. One of the volumes contains the data for shots 2-0008 through 2-0024 inclusive, shots 2-0090 through 2-0098 inclusive, shots 2-0111 through 2-0115 inclusive, shots 2-0115, 2-0121, and 2-0126 through 2-0150 inclusive, shots 2-0157 and 2-0158. The second volume of Appendix B contains the data for shots 2-0159 through 2-0167 inclusive, shot 2-0169, shots 2-0171 through 2-0181 inclusive, shots 2-0183 and 2-0184, shots 2-0186 through 2-0190, shot 2-0192, shots 2-0194 through 2-0201, shots 2-0206 through 2-0209 inclusive, shots 2-0211 through 2-0216 inclusive, shots 2-0218 through 2-0222, shot 2-0226, and shots 2-0228 through 2-0234 inclusive. Each volume contains approximately 800 pages of graphs. The University does not plan to retain copies of these graphs and has delivered the originals to the General Electric Company.

## APPENDIX A

## STRAIN GAGE LOCATIONS





Figure 1A. Strain Gage Locations for Group 1B, 2B, 3B, and 4B Blades.
GAUGE LOCATIONS MEASUREMENTS TO CENTER OF GAGE GRID



Figure 2A. Strain Gage Locations for Group 6B, 7B, 8B, and 9B Blades.



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GAUGE LOCATIONS MEASUREMENTS TO CENTER OF GAGE GRID







Strain Gage Locations for Group 1, 2, and 6 Struc-Figure 7A. trual Element Test Specimens.







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Figure 9A. Strain Gage Locations for Group 4 Structural Element Test Specimens.



Figure 10A. Strain Gage Locations for Group 5 Structural Ele-ment Test Specimens.







Figure 12A. Strain Gage Locations for Group 11, 12, and 13 Structural Element Test Specimens.





7.75 cm. ABOVE MOUNT













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