

NASA TECHNICAL MEMORANDUM

NASA TM X-71544

NASA TM X-71544

(NASA-TM-X-71544) FOD IMPACT TESTING OF
COMPOSITE FAN BLADES (NASA) 24 p HC
\$4.25

CSCL 21E

N74-23341

G3/28

Unclass
38114



FOD IMPACT TESTING OF COMPOSITE FAN BLADES

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TECHNICAL PAPER proposed for presentation at the
19th National SAMPE Symposium and Exhibition
sponsored by the Society for the Advancement of Material and
Processing Engineering
Buena Park, California, April 23-25, 1974

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ABSTRACT

The results of impact tests on large, fiber composite fan blades for aircraft turbofan engine applications are discussed. Solid composite blades of two different sizes and designs were tested. Both graphite/epoxy and boron/epoxy were evaluated. In addition, a spar-shell blade design was tested that had a boron/epoxy shell bonded to a titanium spar. All blades were tested one at a time in a rotating arm rig to simulate engine operating conditions. Impacting media included small gravel, two inch diameter ice balls, gelatin and RTV foam-simulated birds, as well as starlings and pigeons. The results showed little difference in performance between the graphite and boron/epoxy blades. The results also indicate that composite blades may be able to tolerate ice ball and small bird impacts but need improvement to tolerate birds in the small duck and larger category.

1. INTRODUCTION

A major goal in the development of the total transportation system of our nation is a successful and economical short-haul aircraft for operation between airfields having short runways such as might be feasible near major city centers. Such aircraft would, of necessity, have steep ascent and descent rates to minimize noise problems over adjacent populated areas. The field length required for such vehicles might be on the order of one-fourth that required for conventional aircraft (CTOL). However, the thrust-to-weight ratio required for the short take off and landing (STOL) aircraft (fig. 1) is about twice that required for today's airplanes having a similar payload and range. Because of the large power requirement, the weight and size of the engines become much more important than for conventional aircraft.

Figure 2 shows one example of an aircraft for STOL-type short-haul operation. This type of powered lift airplane is able to operate from relatively short runways by taking advantage of the additional lift obtained by externally blowing the engine exhaust gases along the lower surface of a properly configured airfoil and flap arrangement. For maximum overall efficiency, the engine for this externally blown-flap (EBF) airplane would be a high bypass ratio turbofan. This means that the large majority of the air passing through the fan of the engine would bypass the core of the engine before impinging on the underside of the wing. Such high bypass ratio engines have large diameter fans which might be prohibitively heavy if conventional metallic materials such as titanium are used for the blades.

The use of fiber composite materials in STOL aircraft engines may be mandatory to make such aircraft feasible. Because these materials have high strength and stiffness while at the same time have low density, their use can result in lightweight and efficient engines. Reduced engine weights can also result in further weight reductions throughout the aircraft. However, the greatest obstacle to utilizing composites for fan blade applications has been their relatively low resistance to impact damage from foreign objects ingested by the engine such as ice, birds, gravel, tire tread, and small nuts, bolts, and rivets. Composites are also very susceptible to erosion by rain and dust and thus need a protective coating to minimize such damage. To determine whether current design fiber composite fan blades are sufficiently resistant to foreign object damage (FOD) to permit their adaptation to advanced STOL fan engines, controlled tests were run under contract to quantitatively evaluate existing blade designs under STOL operating conditions. Some of the results of these tests will be presented in this paper.

2. COMPOSITE FAN CHARACTERISTICS

Figure 3 shows a cross-section of one concept of what a future short-haul engine might look like. The NASA-Lewis Research Center recently awarded a contract to design and build two different quiet, clean, short-haul experimental engines (QCSEE) for testing purposes. Their final designs will probably be somewhat different from that shown in the figure.

The engine shown in the figure does not have the usual thrust reverser at the aft end. Instead, the fan stage is designed to have variable pitch blades, such as used on conventional propellers, and thus permit obtaining reverse thrust by simply reversing the pitch of the blades.

Some of the advantages of using composite fan blades in turbofan engines are given in figure 4. First and foremost is the usual payoff associated with most applications of advanced composite materials, namely, reduced weight. This is the primary reason for utilizing composites in fan blades. An important secondary advantage associated both with reduced weight and the nature of composites is that the containment of failed fan blades is easier and at lower cost in terms of both dollars and weight. An important FAA requirement is that any fan blades lost from FOD or for other reasons must be contained within the engine nacelle so that neither nearby engines nor the cabin are penetrated by debris. Consequently, current titanium fan engines have large steel rings around the fan stage which weigh as much as three or four hundred pounds. The reduced weight of composite fan blades would permit reduced weight fan containment rings. In addition the frangible characteristics of advanced fiber composites being evaluated for fan blades should minimize the containment problem even more.

An important design consideration permitted by utilizing composites in the fan blades is that it makes the previously mentioned variable pitch fan stage practical. Variable pitch fans allow elimination of conventional thrust reversers and their associated high weight, initial cost, and main-

tenance costs. An important side benefit of variable pitch fans is some increased safety for landing and go-around capability. This is possible because the reduced thrust required for a steep landing approach can be obtained at full engine rpm by simply reducing the pitch of the fan blades. If the pilot must stop his descent and abort the landing for an emergency condition such as an obstacle on the runway, he can regain full thrust almost instantaneously by simply increasing the pitch of the fan blades.

A typical example of the weight reduction possible by using composites in the fan blades of a STOL engine is given in figure 5. In this particular case, an engine with a variable pitch composite fan stage would weigh about 270 pounds less than one with a conventional fixed-pitch titanium fan and a thrust reverser. If it were necessary to have a variable pitch fan, but composites were not used, the option would probably be hollow titanium fan blades weighing about 530 pounds more per stage than the corresponding composite fan stage. Since the effect of reducing the weight of the engine produces an attendant reduction in airframe weight and fuel requirements, it can be seen that composites are extremely attractive for fan blade applications. If one considers that the weights just discussed are for one engine, and that the airplane considered in figure 5 has four engines, the significance of composites for fan blades for turbofan engines becomes very obvious.

3. BLADE DESIGNS TESTED

To obtain an indication of the ability of composite fan blades to survive FOD under STOL operating conditions, it was decided to test large composite fan blades under STOL takeoff conditions. At the time the decision was made to make such tests, three large composite fan blade designs were available (fig. 6). Because it was imperative that the results be obtained as expeditiously as possible to permit their use in engine design studies and decisions, it was decided to test only currently available blades. Two of the three available designs were for engines designed for conventional takeoff and landing airplanes. The third was for a variable pitch fan being tested for STOL engine applications. Because the three blade designs available were all very different from each other, it was decided to test all three to obtain the most information in the least amount of time. Design information for the three blades is given in figure 7.

The TF39 blade was developed by the General Electric Company under Air Force sponsorship for potential application in the engine powering the C5A airplane. It was of a solid composite construction having a design tip speed of 1050 feet per second. It had a span of 20 inches and a tip chord of 8 inches. Two material systems were evaluated. One utilized 4.0 mil filament in a 5505 boron/epoxy resin system. The other contained Type A graphite fiber in a PR288 epoxy resin system. The plies were layed up in a 0° , $+22^\circ$, 0° , -22° , etc. alternating arrangement. The lead-

ing edge protection scheme consisted of a type 316 stainless steel wire cloth (100 mesh) adhesively bonded to the leading edge of the blade with a precision nickel plating applied over the mesh.

The JT9D blade was developed by Pratt and Whitney Aircraft for evaluation in the engine which powers most 747 transports. It was also of a solid composite construction and was designed for 1450 feet per second tip speed. It was a considerably larger blade having a span of 32 inches and a tip chord of 12 inches. This blade was also tested using both a graphite/epoxy system and a boron/epoxy system. The graphite blades were made using Modmor II fiber in a BP-907 epoxy resin prepreg tape. The boron blades utilized 5.6 mil fiber/type 104 fiber glass scrim/BP-907 epoxy resin composite prepreg tape. The plies were layed up by placing a $\pm 45^\circ$ shell over a 0° core arrangement. The leading edges were protected by a 5 mil thick stainless steel sheath with a hard nickel plating added.

The 6-foot diameter Q-fan blade was designed and built by Hamilton Standard for possible STOL engine application. It was of a spar-shell design for 750 feet per second tip speed operation (see figure 8). It had a span of 20 inches and a tip chord of 13.5 inches. The construction utilized a shell made from type SP-292 (5.6) boron/epoxy prepreg tape over a titanium spar. All plies of the shell were layed up at a $\pm 45^\circ$ angle. The leading edge was protected by a relatively thick Inconel 625 sheath adhesively bonded to the boron/epoxy shell. The cavities between the shells forward and aft of the spar were filled with a foam-in-place rigid urethane foam to provide a light weight filler material.

4. FOD TEST CONDITIONS

All new commercial aircraft engines to be used in the United States must be certified in accordance with FAA foreign object ingestion requirements (fig. 9). The objects are classified in two general categories. Group I objects are relatively large including birds four pounds and over. The requirements for such objects are that the engine must not explode, disintegrate, or start an uncontrollable fire and that safe shutdown must be demonstrated. Group II objects include two inch diameter hailstones and birds under two pounds. The requirements for these objects are that the engine must continue safe operation without significant sustained power loss and that power recovery must be at least 75 percent.

With these requirements in mind, the blades were individually spin impact tested in whirling arm rigs. The impacting objects included gravel, small bolts and rivets, 2-inch diameter tempered ice balls, RTV foam and gelatin simulated birds, and real birds (fig. 10). The real birds used had previously been frozen but were thawed prior to test. At the time the tests were run, tip speeds on the order of 800 feet per second were being considered for the STOL engines in order to minimize noise suppression requirements. (Currently tip speeds nearer to 1000 feet per second are contemplated based on engine cycle and noise studies). Consequently, the tests were designed for an 800 feet per second tip speed, 80 knot takeoff condition, and an airfoil angle of attack based on STOL engine designs. The point of impact was selected to be 80 percent of span,

near the most common location shown by engine operating experience to sustain foreign object damage. The resulting local incidence angles between the airfoil chord and the object at the point of impact was 22° for the TF39 blade, 30° for the JT9D blade, and 35.8° for the 6 foot diameter Q-fan blade.

5. FOD TEST RESULTS

Five blades each of graphite/epoxy and boron/epoxy were tested for both the FT9D blades and the TF39 blades. Five blades of the 6 foot Q-Fan spar-shell blade design were also tested. Because of the large number of blades and the even larger number of tests (some blades were impacted more than once), only a few of the highlights of the test results will be discussed herein. For further information, references 1 through 3 contain complete details and photographs of all tests.

5.1 JT9D Blades

The JT9D blades were impact tested in an evacuated spin pit where they were spun about a vertical axis. Except for the gravel, which was dropped through a chute, the foreign objects were suspended from a string and allowed to free-fall into the blade. A timing mechanism was used to control the drop so the object would be struck approximately at its midpoint and thereby sliced in half. The remaining half attached to the string was retracted out of the way to avoid secondary impacts. A backup system was installed to catch the remaining portion of gelatin birds or

real birds if the string should fail. This consisted of barbed spikes located above the object drop location. High speed movies were taken of all tests to assure the validity of the results. In only one case was there a secondary impact.

The gravel impacts did nick, gouge, and unbond some of the leading edge sheath on the pressure side of the blades. Damage at the leading edge tip was negligible. A better bond between the sheath and blade was obviously necessary for the JT9D system tested.

The two-inch diameter ice ball did essentially no damage to the graphite blade while breaking off a chunk about one inch by five inches from the boron blade. High speed movies showed that the boron blade sliced the ball at the mid point. Based on these and other results, the graphite and boron blades are believed to have similar resistance to impact by large hailstones. The FOD threshold for ice for this blade is believed close to the ice ball weight of 2.6 ounces.

Blades were then impacted with 5.8-ounce and 11.2-ounce gelatin balls to simulate birds of similar masses. All four of these blades received moderate to severe damage (fig. 11). The leading edge had between 20 and 40 square inches of area removed for both graphite and boron blades. One blade of each material was then impacted with a starling weighing between 2.6 and 2.9 ounces. The blades passed this test with only slight tip delamination which appeared to be related to blade fabrication problems detected prior to the tests. Thus, the damage threshold level for both the boron/epoxy and graphite/epoxy JT9D blades as designed

and tested appears to be near the 3-ounce iceball and bird level. It should be remembered that this airfoil was designed for a much higher tip speed than the other blade designs tested. Thus the outer part of the span where the impacts occurred was much flatter and thinner with the maximum thickness aft of mid-chord and consequently was less resistant to foreign object damage. Also the incidence angle for the STOL impact conditions was higher than the blade would normally see in the engine application for which it was designed.

An interesting development from another contract being run by Pratt and Whitney for NASA-Lewis (ref. 4) was factored into a full-scale blade test. Figure 11 shows the very significant reduction in damage which took place as a result of simply adding two plies of 90° fibers to the surfaces of a boron/epoxy blade. The blades were tested under nominally identical impact conditions. It can be seen that adding chordwise stiffness considerably reduced the damage imposed by the six-ounce gelatin ball.

5.2 TF39 Blades

The TF39 blades were impact tested in an environmental chamber filled with helium to reduce horsepower requirements and temperature buildup. The blades were spun about a horizontal axis. The gravel and iceballs were dropped through a chute into the path of the blade. The real and simulated birds were fastened to a spring loaded injection mechanism which fired the objects into the path of the blade. The blade took a slice from the "bird" as it passed, leaving the remainder of the bird fastened to the injection

mechanism. The impact load on the blade is a function of the slice size, not total bird weight.

Neither the graphite nor the boron blade showed any damage from the gravel. Each of these blades was then impacted sequentially with three two-inch diameter ice balls dropped through the chute. The graphite blade showed no visible damage but a small debonded area along the leading edge sheath was detected using ultrasonics. The boron blade impacted by ice balls received more damage than the graphite blade similarly tested. It had a visible crack at the trailing edge protection sheath. In addition some delamination was detected at the root area of the blade.

Blades were next impacted with 6-ounce and 12-ounce slices of RTV foam. The blades which took the six-ounce slice sizes received significant damage. There was some splintering and delamination near the tip with delamination and cracking in the dovetail. However, little or no material was lost from either blade. Blades made of both materials were broken off at the root when an attempt was made to take a 12-ounce slice.

A TF39 blade of each material was then impacted with a real pigeon. The graphite blade took an eleven ounce slice with significant visible damage (fig. 12) but with little material lost. The blade was splintered at the tip with large delamination areas and severe root damage. The boron blade took a ten-ounce slice of a pigeon. This resulted in tip cracking and delamination throughout.

Although the composite TF39 blades received considerable damage from the rather large slices of real pigeons, it should be kept in mind that

even metal blades subjected to such large impacts normally receive significant damage. In addition the FAA requirement for one to two pound birds is power recovery to at least 75 percent. Thus the engine can sustain some damage and still be acceptable for this type of foreign object ingestion.

5.3 Spar-Shell Blades

The 6-foot Q-Fan spar-shell blades were impact tested in a sealed chamber which was partially evacuated to 9.5 inches of mercury absolute pressure to minimize power requirements, cell heatup and windage effects. These blades were also spun about a horizontal axis with the small media (gravel, rivets, nuts, bolts, and iceballs) dropped through a chute. The simulated and real birds were attached to a pendulum-type holding mechanism. The small media resulted in almost no damage in most instances, with slight leading edge denting (0.040 inch) resulting from a 100 percent iceball impact as determined from high speed photographs.

A nine-ounce slice of a gelatin simulated bird resulted in some damage to the leading edge sheath with considerable delamination in the shell toward the root with shell fractures in the inboard area of the blade on both the pressure and suction sides of the blade. An eleven-ounce slice of a simulated bird removed the entire shell from the spar.

A spar-shell blade then took a nine-ounce slice of a 18-ounce Chukar partridge. The leading edge sheath of the blade was bent locally (fig. 13), some interlaminar fracture between the spar and shell was found

and the shell had some cracking near the inboard area of the blade. However, no material was lost from the blade.

5.1 Other Results

In addition to the three full-scale blade programs previously discussed, an extensive program was run on subscale simulated blades (ref. 4). These specimens had a three-inch chord and an eight-inch span. They were doubly tapered from a maximum thickness of about one-quarter inch at mid-chord to an edge radius of 0.010 inch. Such blades were both ballistically impact tested in bench tests and spin-impact tested in a whirling arm rig using steel, gelatin and ice balls. Because these tests were relatively inexpensive compared to full-scale blade tests, many more parameters could be studied. Some of the conclusions from those tests were:

- Increased composite transverse tensile strength correlated well with improved resistance to delamination damage.
- Addition of S-glass and PRD-49 fibers to graphite composite resulted in increased impact resistance to cracking and delamination.
- Ultrasonic inspection and torsional modulus were the most effective measures of delamination type damage.
- Ply layups resulting in increased leading edge stiffness, such as obtained by the addition of 90° surface plies, were effective in reducing impact damage.

In addition to the results reported herein, full scale engine tests had previously been run where objects were ingested for FOD testing of full stages of composite fan blades. Those blades were made using fibers and resins different from the blades described herein but showed fairly similar damage. Also several nominally identical tests had previously been run on several surplus composite blades to verify the significance of single blade impact tests. The results of those tests showed that full scale engine tests correlate well with single blade tests for small bird impacts.

6. CONCLUSIONS

Some conclusions drawn from the work reported herein are:

1. RTV foam and gelatin are reasonably good simulations to real birds for FOD testing.
2. Graphite/epoxy blades and boron/epoxy blades have very similar FOD resistance.
3. Single blade FOD spin impact tests correlate well with full scale engine tests for small birds (less than about one pound). (Larger birds have not been used in engine evaluations of composite blades.)
4. Based on the test results described herein, all-graphite/epoxy and all-boron/epoxy blades as well as spar-shell blades can take 10 to 12 ounce slices of one to two pound birds with moderate damage.

7. REFERENCES

1. Premont, E. J., and Stubenrauch, K. R.: Impact Resistance of Composite Fan Blades. NASA CR-134515, 1973.
2. Steinhagen, C. A., and Salemm e, C. T.: Impact Resistance of Current Design Composite Fan Blades Tested under Short-Haul Operating Conditions. NASA CR-134533, 1973.
3. Graff, J.; Stoltz, L.; and Varholak, E. M.: Impact Resistance of Spar-Shell Composite Fan Blades. NASA CR-134521, 1973.
4. Friedrich, L. A., and Preston, J. L., Jr.: Impact Resistance of Fiber Composite Blades used in Aircraft Turbine Engines. NASA CR-134502, 1973.

FIGURE 1

TYPICAL TAKEOFF AND LANDING TRAJECTORIES FOR CTOL, STOL AND VTOL AIRPLANES

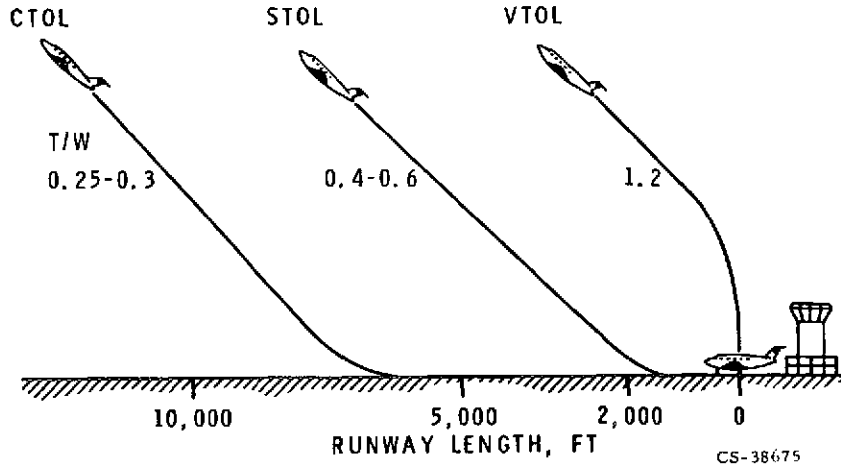


FIGURE 2

EXTERNALLY BLOWN-FLAP STOL AIRPLANE

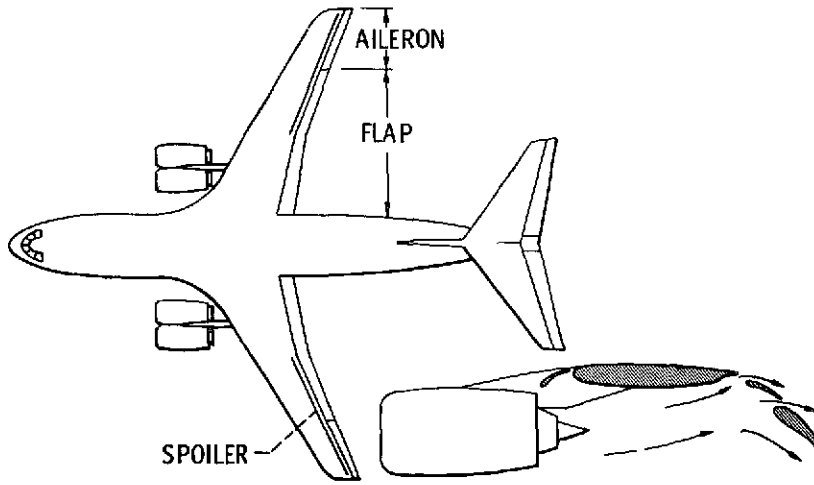




FIGURE 3. SHORT-HAUL ENGINE WITH VARIABLE PITCH FAN

FIGURE 4.

ADVANTAGES OF COMPOSITE FAN BLADES IN SHORT-HAUL ENGINES

1. REDUCED ENGINE WEIGHT
2. FAN BLADE CONTAINMENT IS EASIER AND LOWER COST.
3. MAKES VARIABLE PITCH FANS PRACTICAL RESULTING IN:
 - a. ELIMINATION OF CONVENTIONAL THRUST REVERSER WEIGHT, INITIAL COST, AND MAINTENANCE COSTS.
 - b. INCREASED SAFETY FOR LANDING AND GO-AROUND CAPABILITY.

FIGURE 5.

TYPICAL COMPOSITE FAN BLADE WEIGHT BENEFIT

24,000 LB. THRUST SHORT-HAUL ENGINE

(150 PASSENGER, 500 N. MI. RANGE, 4 ENGINE EBF AIRPLANE)

	<u>WEIGHT, LBS.</u>
VARIABLE-PITCH COMPOSITE FAN	W
FIXED-PITCH SOLID TITANIUM FAN WITH THRUST REVERSER	$W + 270$
VARIABLE-PITCH HOLLOW TITANIUM FAN	$W + 530$

FIGURE 6. COMPOSITE FAN BLADES

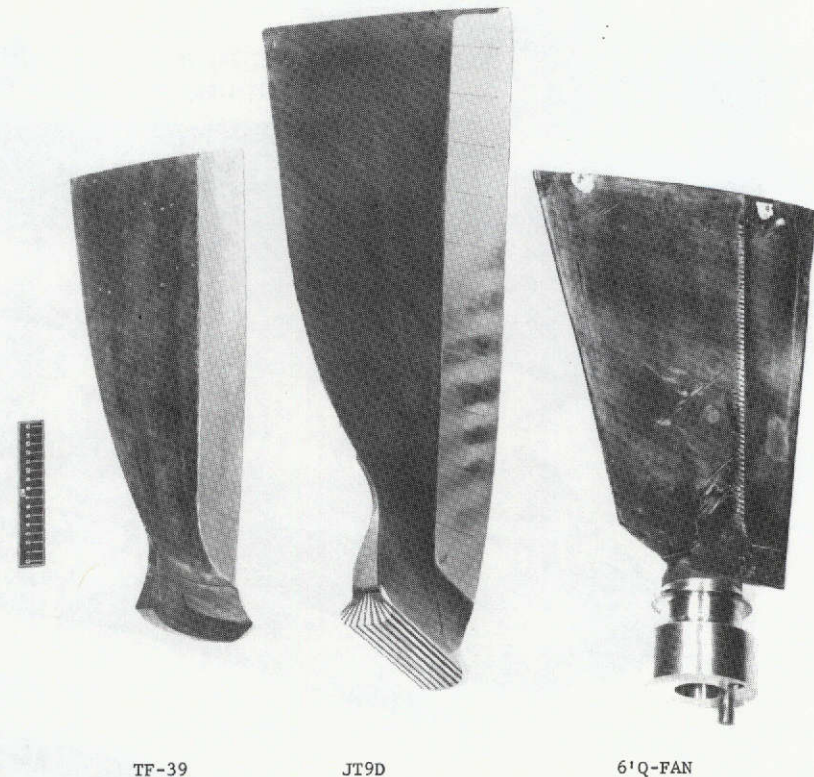


FIGURE 7.

BLADE DESIGNS SPIN-IMPACT TESTED

<u>BLADE</u>	<u>SPAN, (INCHES)</u>	<u>TIP CHORD, (INCHES)</u>	<u>DESIGN TIP SPEED,(FT/SEC)</u>	<u>CONSTRUCTION</u>	<u>MATERIAL</u>
TF 39	20	8	1050	SOLID COMPOSITE	GRAPHITE/EPOXY BORON/EPOXY
JT9D	32	12	1450	SOLID COMPOSITE	GRAPHITE/EPOXY BORON/EPOXY
6' Q-FAN	20	13.5	750	SPAR-SHELL	BORON/EPOXY SHELL TITANIUM SPAR

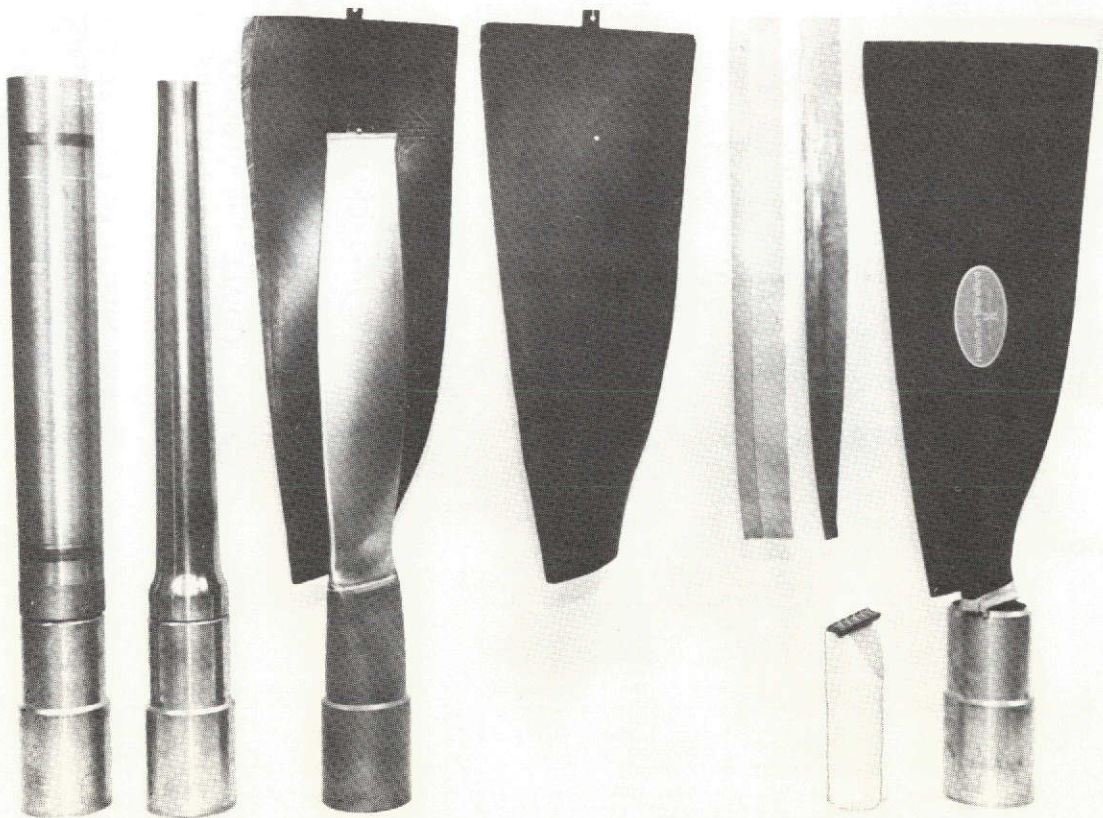


FIGURE 8. SPAR-SHELL BLADE ASSEMBLY SEQUENCE

FIGURE 9. FAA FOREIGN OBJECT INGESTION REQUIREMENTS
(CIRCULAR AC33-1B)

GROUP I OBJECTS

OBJECTS: CLEANING CLOTH
 MECHANICS HAND TOOL
 TYPICAL STEEL BOLT AND NUT
 AIRCRAFT TIRE TREAD
 FAILED BLADES
 BIRDS (4-POUNDS AND OVER)

REQUIREMENTS: ENGINE MUST NOT EXPLODE, DISINTEGRATE, OR START AN
 UNCONTROLLABLE FIRE. SAFE SHUTDOWN MUST BE DEMONSTRATED.

GROUP II OBJECTS

OBJECTS: WATER (4-PERCENT OF AIRFLOW WEIGHT)
 GRAVEL (1/4-INCH DIAMETER)
 SAND
 ICE (INLET DUCT AND LIP FORMATIONS)
 HAIL (1 AND 2-INCH DIAMETER)
 BIRDS (SMALL 1-4 OUNCES) (1/50)
 BIRDS (MEDIUM 1-2 POUNDS) (1/300)

REQUIREMENTS: ENGINE MUST CONTINUE SAFE OPERATION WITHOUT FLAMEOUT OR
 SIGNIFICANT SUSTAINED POWER LOSS. POWER RECOVERY MUST BE
 AT LEAST 75-PERCENT.

FIGURE 10. FOD TESTS

TIP SPEED - 800 FT/SEC

INCIDENCE ANGLES - 24° TO 36°

MEDIA

1/4" DIAMETER GRAVEL

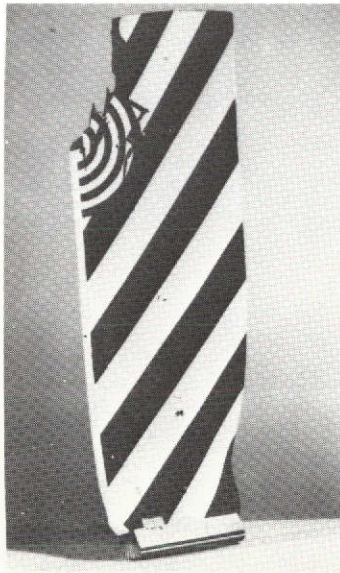
REPRESENTATIVE INLET HARDWARE (RIVETS, NUTS, AND BOLTS)

2" DIAMETER ICE BALLS

SIMULATED BIRDS (RTV FOAM AND GELATIN)

REAL BIRDS

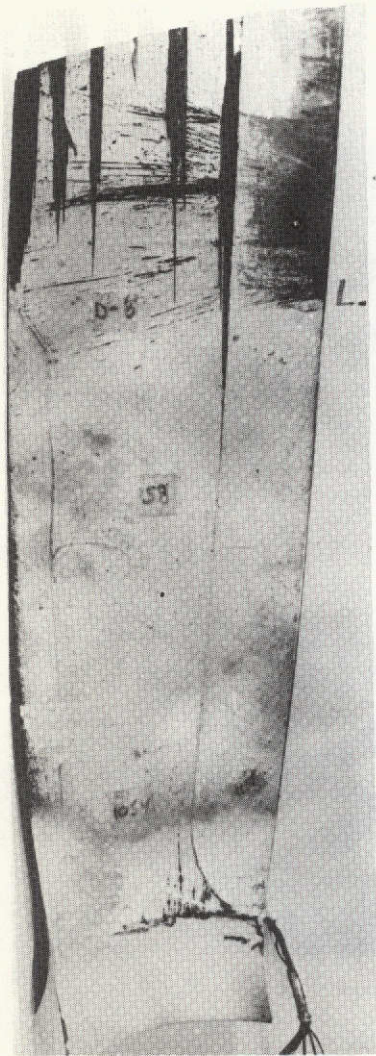
DAMAGE SUSTAINED BY BLADES



BLADE B-3, 6-OZ. GELATIN BALL

BLADE B-1X, 6-OZ. GELATIN BALL

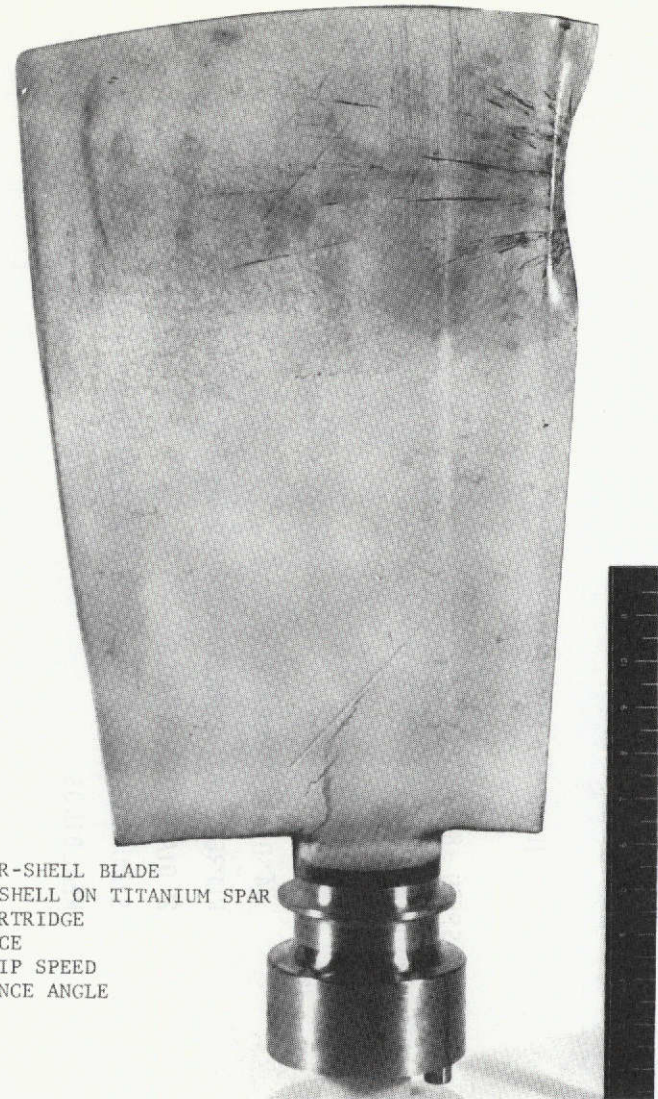
FIGURE 11. JT9D BORON/EPOXY COMPOSITE BLADES



TF39 IMPACT RESISTANCE TEST
 BLADE MATL: GRAPHITE/EPOXY
 FAN SPEED - 2760 RPM
 TIP SPEED - 800 FT/SEC
 REAL PIGEON
 WEIGHT OF PIGEON - 16 oz.
 WEIGHT OF SLICE - 12 oz.
 INCIDENCE ANGLE - 22°

NASA-Lewis

FIGURE 12. TF39 BLADE AFTER BIRD IMPACT



6' Q-FAN SPAR-SHELL BLADE
 BORON/EPOXY SHELL ON TITANIUM SPAR
 1.1 POUND PARTRIDGE
 10 OUNCE SLICE
 800 FT/SEC TIP SPEED
 35.5° INCIDENCE ANGLE

FIGURE 13. 6' Q-FAN BLADE AFTER BIRD IMPACT