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ENGINE INLET ICE PROTECTION AND COMPRESSOR CHANGES MADE TO RESIST ICE

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Introduction

Premise

Modern high technology turbine aircraft engines often employ high rotor speed compressors with thin advanced blading designs to achieve better performance. The engine designer is faced with a tradeoff between optimum compressor performance and on-wing durability. During the engine/ aircraft development stage, certain assumptions are made regarding the icing environment and the testing required to confirm compatibility with it. Often the true impact of the design trade-off is not realized until the engine is exposed to its service environment.

Despite successful engine test cell and aircraft natural icing certification tests, in 1984 General Electric Aircraft Engines Company began to experience an unacceptable level of foreign object damage (FOD) caused by ingested ice with its CT7-5/-7 family of turboprop engines.

Purpose

The purpose of this paper is:

(1) to address the issue of Stage 1 compressor rotor blade ice FOD in the CT7 engine,

(2) to explain the methods and techniques used in assessing the icing environment,

(3) to explain the lessons learned from test and analysis, and

(4) to define the final resolution of the compressor maintenance problem which simultaneously created accelerated performance deterioration for the engine.

The paper is divided into two parts, the first dealing with the airframe icing environment and its impact on the engine inlet system, and the second concentrating on the design improvement and durability testing of the Stage 1 compressor blade.

PART I

Basic Engine Design

The CT7 turboprop engine is a free-turbine modular design derivative of the T700 turboshaft engine. It employs a five-stage variable stator axial and single stage centrifugal compressor with a combined pressure ratio of 18:1.

The compressor operates behind an integral inertial particle separator (IPS). The separator system, shown in Figures I-1A and I-1B, is integrated into the power unit oil cooling system and provides airflow to cool the electronic engine control. Originally designed as a sand separator for the military helicopter environment, the system incorporated swirl and deswirl vanes to optimize efficiency. It has since been changed from a swirl concept to a straight axial bypass to reduce pressure loss and improve performance.

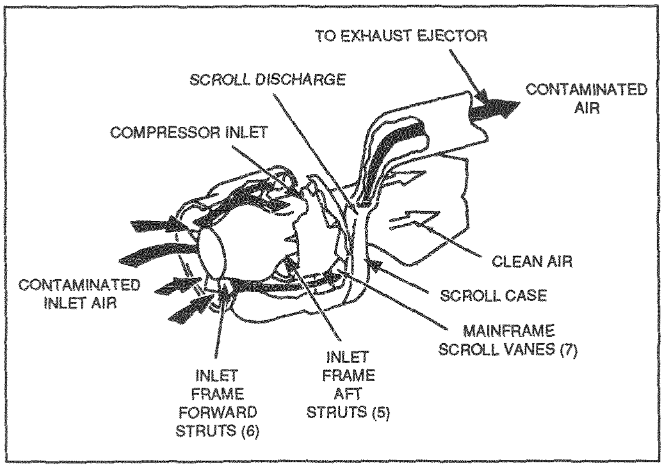


Figure I-1A Engine Inlet Flow Diagram

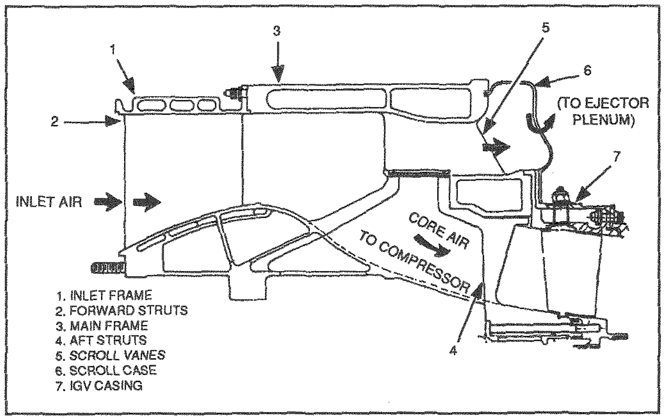


Figure I-1B Inlet Frame, Mainframe, IGV Casing Assembly

Inlet and Installed Icing Environment

The airframe-provided inlet design is a conventional S-duct with a throat area optimized to aircraft specifications. An inlet protection device (IPD) is incorporated to meet bird ingestion certification requirements.

Responsibility for inlet aerodynamics was assumed by the engine manufacturer. The airframer assumed responsibility for the mechanical design, structural integrity, anti-icing, test and procurement.

Other areas forward of the engine, which are subject to the icing environment are shown in Figure I-2. Propeller spinners on both applications are parabolic profile and unheated (neither anti-iced nor de-iced). Original ice-shed trajectory analyses showed no ingestion into either inlet design. Later analytical refinements reversed this finding for accumulations on the spinner nose. The two propellers used, were each 4-bladed with de-icing provided in alternating pairs. Propeller cuffs have been observed to accrete ice which was not shed with blade de-icing. In the upper inlet highlight-to-spinner boundary layer diverter area, one inlet, which is integral with the forward nacelle cowl, incorporates anti-icing. The other inlet, which moves relative to the forward nacelle cowl, is not anti-iced in this area. Both diverters have been observed to accrete ice.

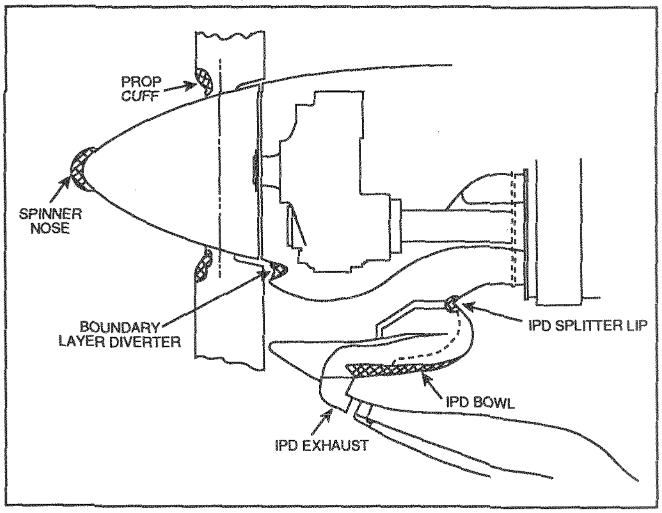


Figure I-2 Installation Ice Accretion

Certification Testing

The CT7 turboprop was successfully certified according to the requirements of FAR 33.67, FAR 25 Appendix C, and Advisory Circular 20-73 in January of 1983, at the General Electric Test Facility, Evendale, Ohio. Test conditions are shown in Table I-1. The Evendale facility is a sea level test cell capable of providing a controlled icing cloud from a free jet pipe 30 inches in diameter at a maximum velocity of 88 knots. Testing was conducted using an anti-iced bellmouth. No installation specific inlet testing was required or performed. During all phases of testing, engine surfaces remained ice-free and no discernible ice ingestion, causing either Stage 1 blade damage or parameter fluctuation, occurred.

Inlet ducts for both installations were certified at the inlet manufacturer's facility. This facility is a closed tunnel capable of simulating airspeed up to 195 knots and full Appendix C icing conditions to -30° C. No engine hardware was included in this testing.

ENGINE ICING CERTIFICATION TEST CONDITIONS (REF AC 20-73)

ENVIRONMENTAL ICING TEST CONDITIONS

Condition Number	1	2	3
Atmospheric Temperature, °F	29	23	-4
Liquid Water Content *(minimum), gram/meter* ^{3}	0.3	2.0	1.0
Mean Effective Drop Diameter, microns	40	25	15
Icing Condition Power Settings	Ground Idle	Flight Idle 50% Max Cont 75% Max Cont Takeoff	Flight Idle 50% Max Cont 75% Max Cont Takeoff
Duration at each of the power settings specified above, (minutes)	30	10	10

Table I-1

Inlet testing indicated fairly good results, however, the duct was not ice-free, as required by the engine manufacturer. Accretions up to 50 grams on the inlet to IPD splitter were noted. Testing was conducted under the conditions shown in Table I-2. Since both inlet and installation were subjected to significant natural icing certification flight tests, and not a single ice FOD event was observed, the CT7 entered revenue service in 1984. By the end of that year however, the ice FOD rate was 1.2/1000 EFH and considered unacceptable.

CONDITION	AIRSPEED (KTS)	TAMB (°C)	LIQUID WATER CONTENT (g/m^3)		DROP DIA (MICRONS)
			MAX CONTINUOUS	INTERMITTENT	
1.	195	−10	0.6	2.2	20
2.	195	−20	0.3	1.7	20

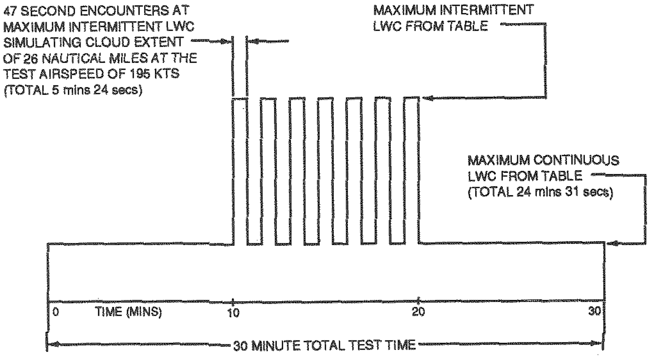


Table I-2 Flight Icing Encounter Pattern for Test Conditions 1 & 2

Engine Inlet System Development

Follow-on Icing Tests

From 1984 to 1988, six additional inlet tests and two engine tests were conducted to troubleshoot actual or suspected anomalies that might have caused ice FOD. Several of these tests were conducted on the initial prototype design. Later tests on production ducts revealed additional problems that required further optimization and proof tests.

Inlet component tests were run at the GE Evendale facility late in 1984 in an attempt to find a correlation between the engine certification testing conditions and those for the inlet at the inlet manufacturer's facility.

Because the GE open facility has limited viewing of the test specimen, a technique was developed to allow real-time remote viewing and recording through the inlet duct wall during the icing test. This technique proved useful in subsequent tests for viewing both of the IPD and engine face areas (See Figures I-3A and I-3B).

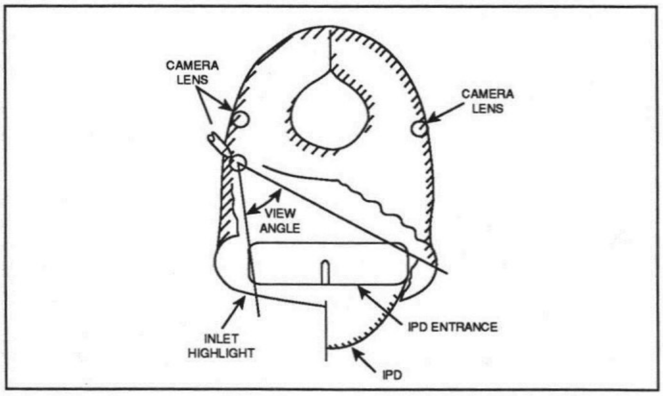


Figure I-3A Video Camera Angles - Looking Aft

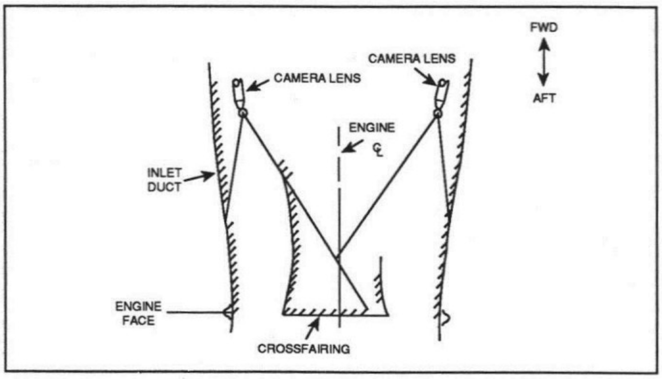


Figure I-3B Video Camera Angles - Plan Section

The icing was still apparent and a second test, paralleling the Evendale engine test conditions, was conducted in January 1985 at the inlet manufacturer's facility. Improvements made as a result of that testing were proof tested there later that year.

Although the ice FOD rate seemed to be coming down as additional fleet hours were accumulated (See Figure I-4), operators, particularly in the wet and cold winter climates (Sweden, Switzerland and Midwest U.S.), were still experiencing engine performance loss, associated with compressor blade maintenance and causing some premature engine removals. In addition reports of increased maintenance being required to keep the IPD from filling up with ice prompted more testing.

Late in 1985, at GE's outdoor crosswind test facility in Peebles, Ohio, an inlet icing test was conducted using an entire SAAB 340 aircraft (See Figure 1-5). The aircraft was tied down in front of a bank of 15 fans. These fans created an icing cloud that enveloped the entire propeller and spinner in the right-hand installation. However, the fans only provided 60 knots of ram airspeed. The underlying intent of the test was to see if propeller effects had any impact on ice accretion within the duct. While no new inlet ice was found, ice accumulated on both spinner nose (700 g max) and prop blade cuffs (20-30 g). These new sources prompted new analysis and efforts, described later, to reduce these potential threats.

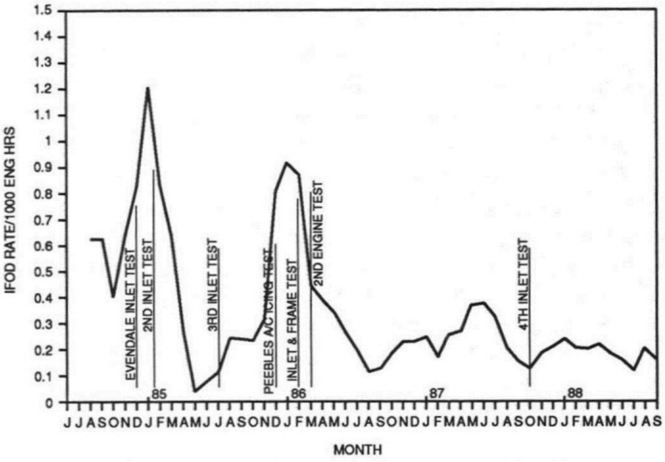


Figure I-4 Engine Ice FOD Rate 3 Month Rolling Average

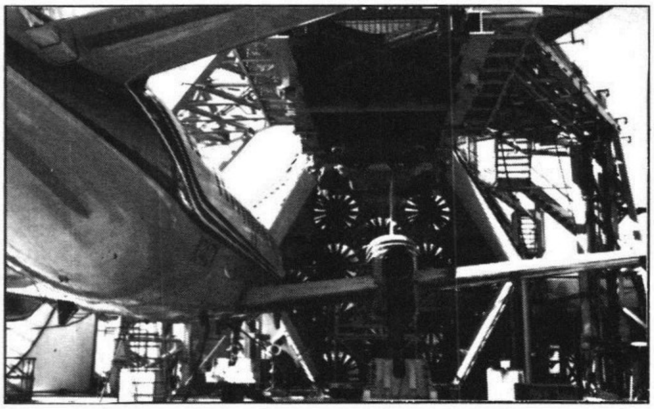


Figure I-5 Outdoor Crosswind Test Facility

Ground tests in heavy blowing snow were conducted in Cincinnati, Ohio and Erie, Pennsylvania in the same time period. These tests consisted of 30 minutes at ground idle followed by accel-to-takeoff power. No ingestion events occurred. Upon shutdown of the engines, little or no ice was found in the IPD, yielding no correlation to the field reports.

It was clear that the missing ingredient was airspeed and it was the inlet manufacturer's facility that was capable of testing airspeed along with ice crystals (simulated snow) and slush-like environments. Because the engine inlet and separator frame has a large frontal area of low velocity, like the IPD, a combined inlet and engine frame test was proposed in February 1986. The inlet facility, however, was not capable of running a CT7 engine. As a result, the test rig consisted of the inlet duct, inlet and separator frames, and the engine accessory gearbox, fitted with starter generator and IPS scroll casing (See Figure I-6).

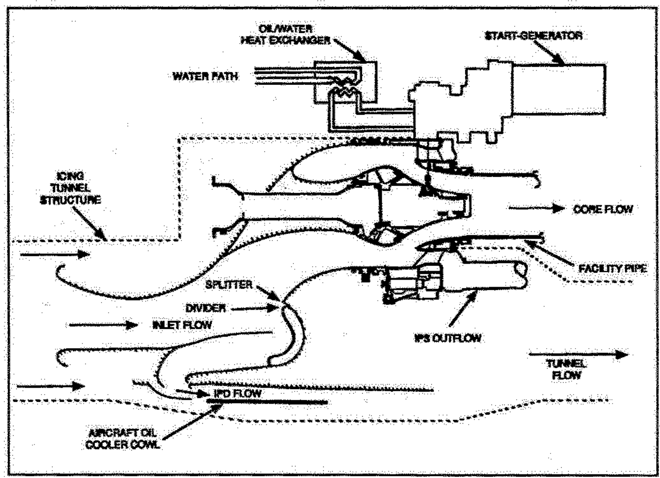


Figure I-6 Inlet/Frame Test Setup

Externally heated oil was supplied to the gearbox and circulated by motoring on the starter generator. This provided engine frame anti-icing for those surfaces normally protected by oil temperature. Hot air was generated externally to anti-ice those engine surfaces which rely on bleed air. Skin temperatures obtained from a simultaneous engine anti-icing test at Evendale were maintained to simulate anti-iced engine heat rejection.

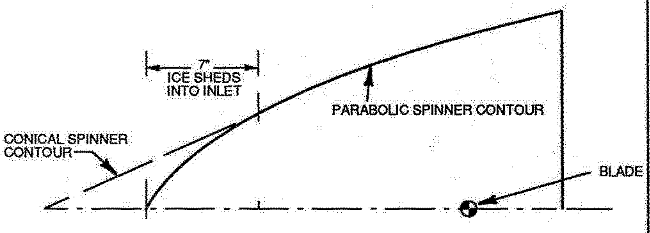
In addition to the ice crystal and mixed conditions, the standard test liquid water content (LWC) was factored up. This accounted for the additional water impingement created by the aircraft normal cruise speed of 260 knots vs the tunnel maximum speed of 195 knots. Three things were learned: (1) the engine frames did not ice or pack slush, (2) the IPD required additional flow-through ventilation to reduce packing of slush and aerodynamically assure that the slush would not enter the engine, and (3) the factored LWC put additional load on the inlet anti-icing system requiring further improvements. One of these improvements was a heated IPD exhaust chute.

During the above-mentioned second engine test at Evendale, this time with aircraft inlet installed, a single FOD event was observed. Using the inlet video cameras, the event was traced to ice build-up inside the inlet temperature sensor duct, from runback along the inlet frame. As the ice built up in the sensor duct, it gradually was sucked out by the compressor. A reworkable fix, demonstrated later in this test, was implemented immediately across the fleet and in production.

As duct improvements were gradually incorporated into the fleet the ice FOD rate stabilized at about 0.2/1000 EFH. This, however, was still an unacceptable performance and maintenance penalty for the small commercial operator. As a result, a target goal of .075/1000 EFH was established. While further inlet improvements continued to be addressed, the possibilities of ice FOD coming from additional sources, and measures needed to deal with these possibilities, were explored.

Other Approaches to Ice FOD Reduction

Turboprop spinner icing experience was reviewed and a conical spinner design was service evaluated in an effort to reduce accretions and thereby alter trajectories. There had been success in the past on turbofan applications for such designs; Figure I-7 depicts the turbofan test results upon which the turboprop service evaluation was based. The results of this survey yielded no improvement. Spinner coating experience was examined with no obvious benefit uncovered. A program to anti-ice the spinner nose was carefully reviewed, however, a shortfall of aircraft electrical power eventually ruled out such a program, as well as any potential for increased de-icing of propeller blades/cuffs.



Conditions	Relative Ice Accretion Elliptical	Conical
S.L.S-3°C, 2gm/m^3, 30μ	1.00	.06
5000 M .25 MACH -15°C 2.2 gm/m^3, 20μ	.43	.07
5000 M .25 MACH -20°C 1.7 gm/m^3, 20μ	.30	.05

Figure I-7 Spinner Ice Elimination/Reduction

Simultaneous to these source reduction/elimination efforts, GE embarked on an extensive program to evaluate and improve the effectiveness of the engine separator system for target size pieces of ice. Trajectory analyses, using the standard axi-symmetric model of the separator, were conducted for varying degrees of adverse particle preconditioning imposed by the turboprop S-duct. Baseline cases were correlated with factory test results for 3 gram pieces of ice (.75 inch dia).

Several flowpath modifications were analyzed for efficiency improvement and the most promising was selected for model testing (See Figures I-8A through I-8D). Modified inlet and separator hardware model testing was conducted in the GE Lynn component facility, using separator scavenge flows confirmed from flight test measurements. The mixed test results (see Figure I-9) showed no consistent net improvement in ice protection. It was concluded that the range of inlet duct exit trajectories is too broad to achieve substantial IPS performance gains within the confines of a compatible installation. While gains may be realized for a given preconditioned trajectory, a comparable loss is likely for another trajectory of equal probability. While inlet separators are effective in minimizing the number of damaging objects reaching the compressor, they are at best statistical devices which cannot be 100 percent effective. When faced with a steady input of instantaneous damage-producing objects (as opposed to a time dependant

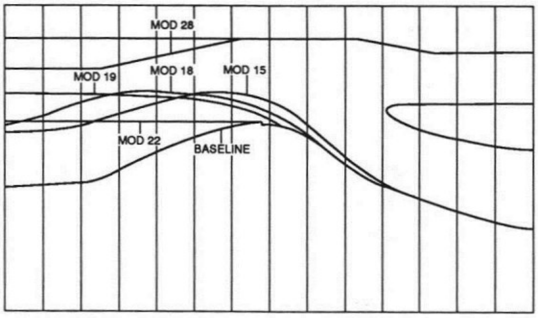


Figure I-8A

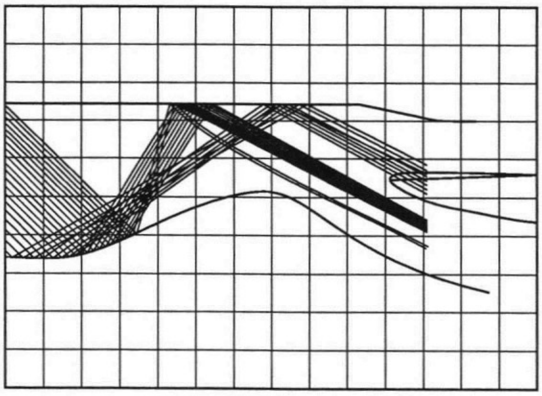


Figure I-8B

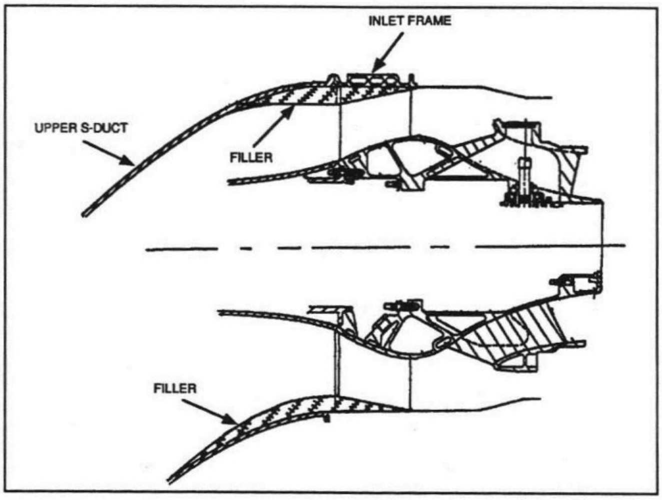


Figure I-8C

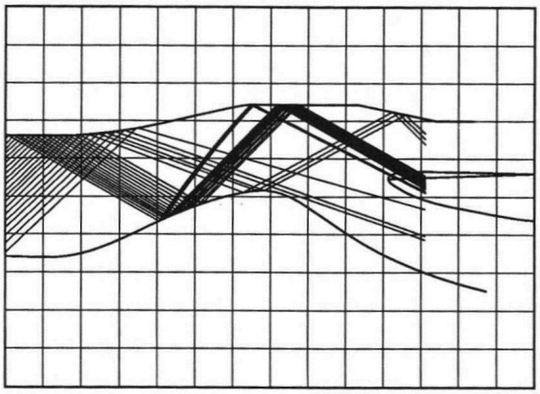


Figure I-8D

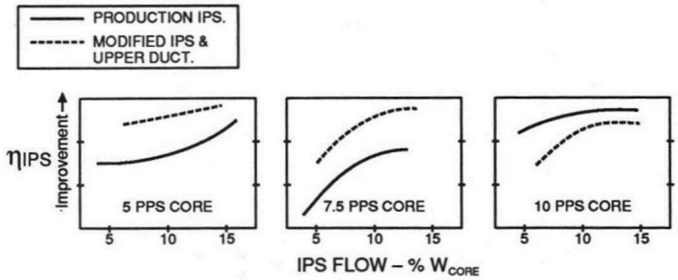


Figure I-9 Separation Efficiencies with Production Inlet

erosion process), separation efficiency improvements may be misleading. At this point, attention was turned to the Stage 1 compressor blades themselves.

Engine Inlet System Development Conclusions

1)To ensure a consistency in the application of icing test requirements, the aircraft inlet and engine should be tested together in the most severe environment available. This environment should include ice crystals and mixed conditions.

2)Successful operation in natural icing tests may not be sufficient to preclude in service icing problems.

3)Follow-up icing testing of the final Production inlet design is required to ensure proper implementation of prototype test results.

4)During the initial installation design phase, the complete inlet/propeller/spinner icing environment should be assessed as a system to ensure optimum distribution of anti-icing energy.

Part II

Ice FOD-Resistant Compressor Blade Development

Stage 1 Compressor Blade Clipping

Even with improved inlet ducts, the ice FOD rate requiring maintenance action for CT7-5 powered aircraft was about .20/1000 EFH; still beyond customer expectations. The FOD appeared as a curled stage 1 blade tip as shown in Figure II-1, and it caused an audible compressor whine and loss in engine temperature margin. The maintenance action required removal of an axial compressor casing half for access to the damaged stage 1 compressor blade(s); clipping the deformed blade material and a similar portion from an opposite blade to maintain rotor balance; and hand benching a leading edge on the clipped airfoils.

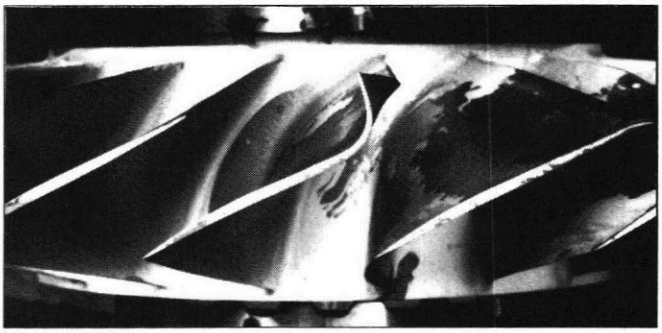


Figure II-1

This action eliminated the compressor whine but did not fully restore the engine's original performance level because the material removal adversely impacted compressor efficiency and airflow.

Test Set-up

A key part of developing a more rugged compressor blade was to determine the degree of the ice FOD which could result in Stage 1 blade damage. A rig was designed with a row of inlet guide vanes (IGV) ahead of the Stage 1 blisk driven by a high speed spindle at engine speeds (See Figure II-3). Due to the possibility of FOD wedging action between the blade and casing, a shroud over the blades was used to simulate the casing. A pneumatic gun was used to propel the FOD objects at various velocities up to 400 ft/sec (120 m/sec). The ice FOD tests however, were conducted at 85 - 90 ft/sec (27 m/sec), the highest possible velocities determined for ingested ice objects released during flight. It is possible that ice chunks impacting on the inlet S-duct could enter the compressor inlet at slower speeds, but the impact of these objects was considered less severe than the test simulation. The approximate ice velocity was calculated by equating the acceleration of a spherical ice mass to the drag of free stream flow using a drag coefficient of 0.55. Figure II-2 shows the calculated velocity at the Stage 1 blade as a function of ice ball size.

The ice objects used for the test were spherical in shape because the initial small right cylinders tumbled, causing erratic flight and inconsistent impact areas. The ice balls were targetted to pass cleanly between the IGV's and impact the blades as close as possible to the tip without contacting the shroud. A speed trap measured the object velocity just before entering the inlet casing. The largest ice chunk would be the circumferential space between the inlet guide vanes (about 1-inch at the casing) and would permit an 8 gram sphere to pass through when the vanes were fully open (i.e., axial at casing O.D.).

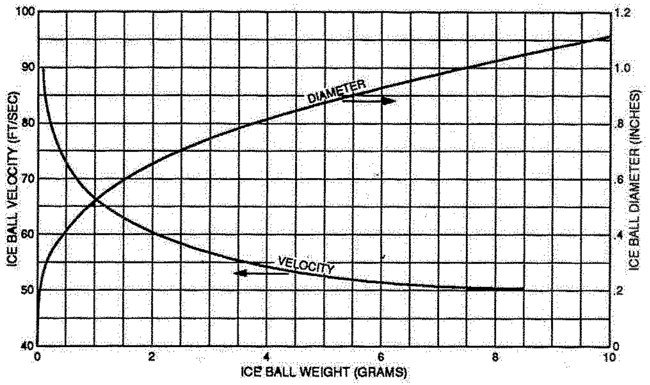


Figure II-2 Ice Ball Parameters at IGV Inlet

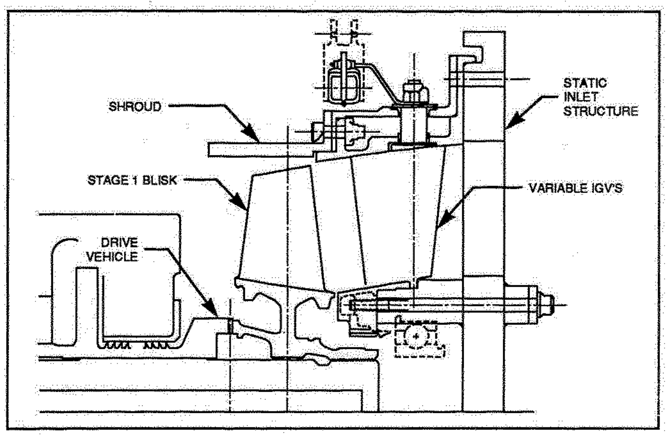


Figure II-3 Component Test Setup

The test events were recorded with a high speed camera system at 22,000 frames/second. This provided insight on the impact phenomenon and verified the impact area of the objects. High speed video (2500 frames/second), which had the advantage of instant replay to monitor testing, was used to verify the impact area and ice velocity. The test speed was 42,000 RPM, a typical altitude cruise speed at which most ice FOD events occur.

Results

The initial blisk testing was done on a CT7-5 blade. It was found that a 2.8 gram ice object caused initial bending, and a 4.5 gram ice object caused a single event blade tip curl similar to field damage (See Figure II-1). Smaller chunks of ice (i.e., 3 grams) can cause a blade curl from successive hits. Successive hits occur on a particular blade because it is bent forward of the plane of the other blades. The testing also determined the vulnerability of a blade which is adjacent to a clipped blade. A clipped blade allows more ice penetration prior to impact by the adjacent blade. This causes full tip curls from smaller ice objects. This correlated with field observations where compressors with clipped blades had higher rates of maintenance action after the first clip. The high speed photography also revealed that a large ice object can impact and bend a blade on its initial hit and then, due to a heavier impact on the protruding blade, cause a full curl on the next revolution. Large ice chunks (5 to 8 grams) were also fired at the pitch sections causing minor bulging. This was not typical of observed field damage. Therefore, it was concluded that the damaging ice objects were traveling along the outer casing wall and impacting in the blade tip area.

A sample of operator ice FOD data was evaluated to determine the extent and frequency of the blade curls (See Figure II-4). The data included the bend radius, since it is the amount of material removed prior to benching a new leading edge radius. About 75% of the events required a clip of 0.3 inches along the blade tip chord and 0.8 inches down the leading edge.

It was judged that a cutback of .25 inches along the tip and .65 inches down the leading edge along with a reshape of the leading edge to improve the aerodynamics would eliminate most of the problem associated with tip curls. Furthermore, a swept leading edge would present a more aerodynamic shape to minimize performance loss. This was called the "smart clip" (See Figure II-5) and is subject of a pending patent application. This "smart clip" was

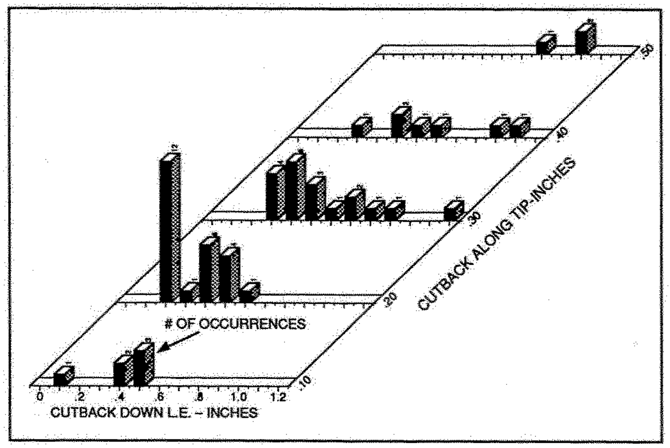


Figure II-4 Operator Ice FOD Data

evaluated in the test rig in steps of .12, .18, and .25 inches of tip cutback. The test results in Table II-1 show that the .25 inch cutback eliminates any damage that could be caused by an 8 gram iceball passing between the inlet guide vanes at 85 ft/sec. Although these larger objects travel more slowly when accelerating in an engine inlet, these tests were conservative because they held velocity constant at the upper limit of smaller objects.

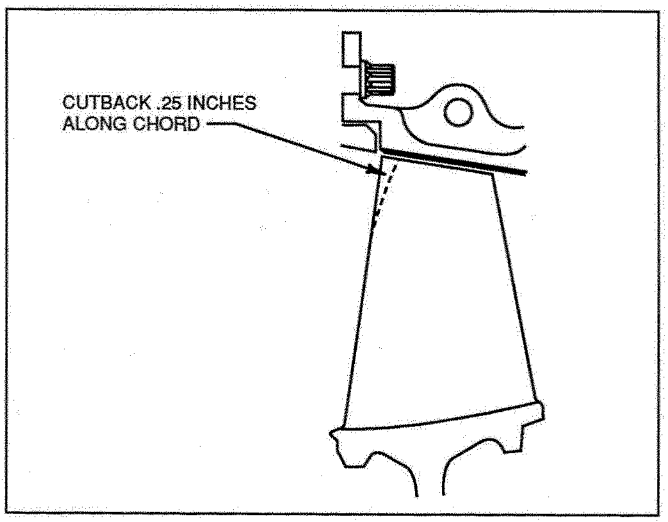


Figure II-5 "Smart Clip" Stage 1 Blisk

A significant reduction in the baseline blisk damage resistance was observed for a blade positioned next to a clipped blade. The results show that the initial damage threshold was reduced by objects from 2.8 to 1.5 grams. This is also where major curl damage was reduced by objects from 4.5 to 2.8 grams. Also, the .25 inch cutback showed initial damage occurring at 6.5 grams weight, whereas a uniformly cutback blisk was above 8 grams (See Table II-1).

TABLE II-1 TEST RIG ICEBALL FOD SUMMARY

Blisk Configuration	Object which Initiates Damage	Object which Causes Extensive Damage or Tip Curl
CT7-5A	grams	grams
Baseline	2.8	4.5
.12 Cutback	>4	5
.18 Cutback	6	>6
.25 Cutback	>8	>8
Baseline CT7-5A next to Field Clip	1.5	2.8
CT7-5A .25 Cutback next to Field Clip	6.5	>6.5
CT7-9 Cutback	>8	>8

Test Conditions:
Rotor Speed 42,000 rpm
Ice Ball Velocity 85 ft/sec
Impact Area @ Blade Tip

Initial blade cutbacks were carried out at the operator's shop or during on-wing maintenance that required access to the compressor. After the "smart" blade cutback, virtually all ice FOD problems were eliminated with that engine. As the field engine population increased in cutback compliance, corresponding reductions in maintenance action occurred (See Figure II-6). As of December 1989, the rate has been reduced by over 30 times to less than .005/1000 EFH with 98% compliance. The performance effect of the "smart clip" has been small particularly when carried out with other compressor refurbishment which, in itself, offsets the cutback Stage 1 blade performance loss.

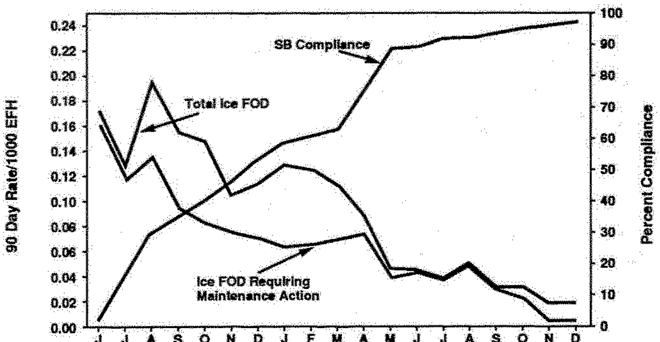


Figure II-6 CT7-5 Turboprop Ice FOD Reduction From "Smart Clip" Compliance

Additional ice testing and further review of the high speed films was done to understand whether blade leading edge thickness or sweep back geometry was influential in improving ice FOD resistance of the "smart clip" blade. Blade leading edge shapes of the test hardware were photographed, measured and correlated with the test results. This follow-on investigation which included tests of swept back blades with thin leading edges showed that good correlation could be obtained between damage resistance and thickness measured .04 inches back from the leading edge at a location 0.5 inches down from the blade tip. Figure II-7 is a plot of ice ball size and leading edge thickness showing a line of demarcation between damaged and undamaged airfoils. For this plot, damage was assumed to be any detectable plastic deformation of the blade leading edge. This plot points out the sensitivity of the damage resistance to blade leading edge thickness.

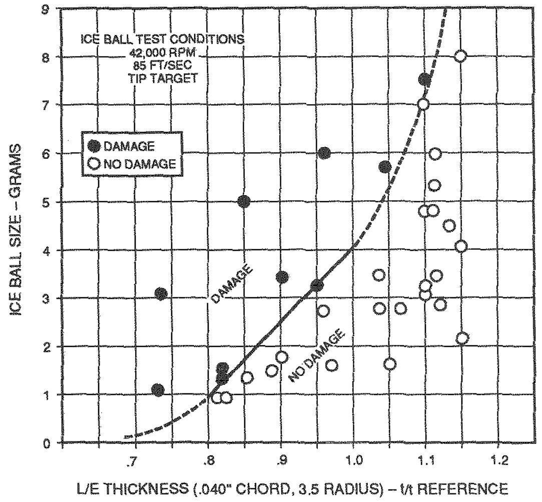


Figure II-7 FOD Resistance Correlates Well With L.E. Thickness

The blade leading edge thickness is felt to be critical since damage is initiated at this location. More dramatic blade curling occurs later due to the increased exposure of the blade because of the forward deformation of the leading edge. The high speed films show the ice ball is shattered by the initial blade impact which causes a significant load on the leading edge. However, blade curling is caused by the high loads imposed on the blade as it accelerates the ingested mass of ice up to wheel speed. The measurement location of .04 inches from the leading edge is somewhat arbitrary but does provide a quantitative measure of the lead edge bluntness where the initial ice impact occurs. Figure II-8 shows enlargements of the leading edge shape of two airfoils and how the relative thickness at .04 inches characterizes the leading edge shape. Velocities of the ice ball and blade are such that the ice is ingested at a rate of approximately .07 inches per blade at 80 feet per second. This adds further justification to a thickness measurement near the leading edge.

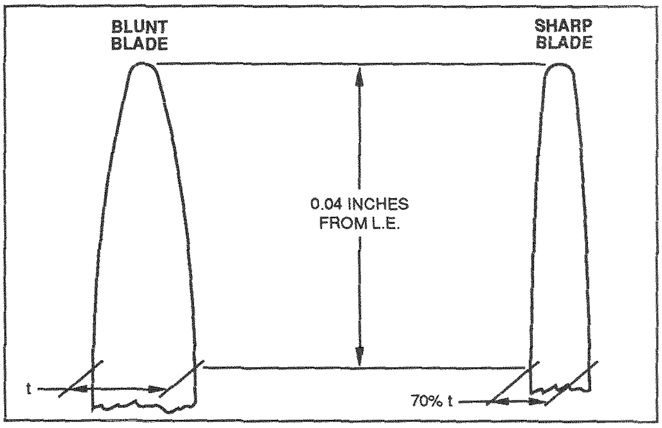


Figure II-8 Thickness at 0.04 Inches From L.E. Characterizes L.E. Bluntness

This investigation has demonstrated the importance of leading edge thickness in preventing ice damage to blades. It allows the engineer to design the best aerodynamic blade configuration including leading edge contour and assure good ice damage capability by controlling the leading edge thickness. This assumes that the remainder of the airfoil has sufficient strength to accelerate the ingested ice particles up to wheel speed without deformation.

Ice FOD-Resistant Compressor Blade Development

Conclusions

1)Blade leading edge thickness is the most important parameter for resisting ice FOD damage.

2)A full tip curl can be caused by a single large ice object, or by a succession of smaller objects which, initially, only partially deform the airfoil.

3)Airfoils which protrude forward of the plane of the other blades are likely to be hit repeatedly and more severely. Similarly, airfoils following more deeply cutback blades are more vulnerable to damage caused by deeper ice penetration prior to impact.

4)Increased ice velocity and size increase blade damage. However, larger particles accelerate slower and have lower velocity at blade impact.

5)As a rule to durability, the stage 1 compressor blades should be capable of withstanding impact from any piece of ice that can pass between the inlet guide vanes.

6)Cutback modification to the leading edge of the CT7-5 Stage 1 blade has an ice FOD resistance that will eliminate most field damage.