Delta Air Lines

SUBMISSION TO THE NATIONAL TRANSPORTATION SAFETY BOARD

UNCONTAINED ENGINE FAILURE
DELTA AIR LINES, FLIGHT 1288
MC DONNELL DOUGLAS MD-88, N927DA
PENSACOLA, FLORIDA
JULY 6, 1996

This submission contains Delta's analyses, findings, and recommendations derived from information developed during the investigation of this accident. This report is intended to be used as the basis for final recommendations to prevent this type of accident from occurring again. Areas addressed include: (1) the effects of abusive machining on titanium alloy material, (2) continued airworthiness certification criteria, (3) standardization and adequacy of guidance from original equipment manufacturers for the cleaning and processing of parts prior to visual inspection, and (4) supplemental inspection methods to ensure continued airworthiness.

CONTENTS

EXECUTIVE SUMMARY iv

1. FACTUAL INFORMATION 1

1.1 Flight History 1

1.2 Injuries 1

1.3 Damage 1

1.4 Engine Information 2

1.5 Fan Hub Information 2

1.5.1 Metallurgical Investigation 2

1.6 Hub Manufacturing Information 3

1.6.1 Coolant Channel Drill 3

1.6.2 Blue Etch Anodize Process 4

1.7 Hub Certification 4

1.7.1 Safe Life Certification 4

1.8 Operator Non-destructive Inspections 4

1.8.1 Cleaning 5

1.8.2 Media Blast 6

1.8.3 Fluorescent Penetrant Inspection 7

1.8.4 Post-Accident Observations 7

1.9 NTSB Recommendations 8

1.10 FAA Airworthiness Directives 8

2. ANALYSIS 9

2.1 Microstructure Damage from Machining 9

2.1.1 Microstructure Complexity 10

2.1.2 Machining Titanium 11

2.1.3 Titanium Drilling 13

2.1.4 Industry Data 14

2.2 Safe Life Certification 14

2.2.1 Safe Life Inspecion Requirements 15

2.2.2 Safe Life Certification Assumptions 15

2.2.3 Continued Airworthiness 17

2.2.4 Damage Tolerance Criteria 18

2.2.5 Certification Requirements - Summary 18

2.3 Operator Inspection Process 19

2.3.1 Part Drying 19

2.3.2 Plastic Media 20

2.3.3 OEM Guidance 20

2.3.4 FPI Effectiveness 21

3. CONCLUSIONS 21

3.1 Findings 21

3.2 Probable Cause 23

4. RECOMMENDATIONS 23

Figure 1 25

Figure 2 25

Figure 3 26

APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

EXECUTIVE SUMMARY

On July 6, 1996, Delta Air Lines flight 1288, a McDonnell Douglas MD-88, experienced an uncontained failure of the left engine during the beginning of the takeoff roll on runway 17 at the Pensacola Regional Airport, Pensacola, Florida. Subsequent investigation revealed that the first stage fan hub of the left JT8D-219 engine had fractured, resulting in an uncontained failure of the engine. Fragments from the engine penetrated the aft fuselage, causing fatal injuries to two passengers and substantial damage to the aircraft.

Investigation of this accident has revealed that the accident fan hub, which had accumulated approximately 14,000 cycles, fractured from an existing low cycle fatigue crack that had originated near an area of smearing, or "scuff marks", on the inner surface of a tie bolt hole. The surface anomalies were determined to be a microstructural deformation of the titanium alloy resulting from abusive machining (drilling) during the manufacturing process. A metallurgical examination of the fracture surfaces indicated that the crack had originated shortly after the fan hub was put in service. The certified safe life, or mandatory part replacement time, for the -219 fan hub is 20,000 cycles.

Delta has determined that the probable cause of this accident was the catastrophic failure of the left engine first stage fan hub as a result of a low cycle fatigue crack that originated from a microstructure defect created by abusive machining during the manufacturing process.

The safety issues in this report include the effects and detection of abusive machining on titanium alloy material, continued airworthiness certification criteria, standardization and adequacy of guidance from original equipment manufacturers for the cleaning and processing of parts prior to visual inspection, and supplemental inspection methods to ensure continued airworthiness.

Safety recommendations are included in this report, and are intended to be used as the basis for final recommendations to prevent this type of accident from occurring again.

1. FACTUAL INFORMATION

1.1 Flight History

On July 6, 1996, Delta Air Lines flight 1288, a McDonnell Douglas MD-88, experienced an uncontained failure of the left engine during the beginning of the takeoff roll on runway 17 at the Pensacola Regional Airport. The engines were just reaching peak thrust when the flight crew heard a noise and rejected the takeoff. The aircraft was brought to a stop on centerline approximately 1350 feet from the runway threshold.

Subsequent investigation revealed that the first stage fan hub of the left engine had fractured, resulting in an uncontained failure of the engine. Fragments from the engine had penetrated the aft fuselage, causing fatal injuries to passengers and substantial damage to the aircraft. One effect of the damage was a total electrical failure that precluded crew communication via either the interphone or public address system.

There were 5 crew members and 137 passengers on board at the time of the event. Passengers that occupied seats in the aft portion of the cabin were evacuated immediately from the aircraft; those forward in the cabin remained seated and were later deplaned via airstairs.

Emergency medical service (EMS) and airport rescue fire fighting (ARFF) personnel responded to the aircraft after being alerted by the airport tower.

1.2 Injuries

Two passengers, occupying seats in a row adjacent to the failed engine, were fatally injured. Another passenger, seated in the same row, was seriously injured. Two other passengers sustained minor injuries during the evacuation.

1.3 Damage

The uncontained failure of the left engine was caused by a fracture of the first stage fan hub, that in turn caused various components and other pieces to separate from the engine. Many fragments, including fan blades and a section of the fan hub, penetrated the aft fuselage and entered into the cabin. Other engine components, including the nose cowl, were scattered on the runway behind the aircraft starting from the point of failure about 385 feet from the threshold. Debris, including two large sections of the fan hub, was found in areas off both sides of the runway, at various distances from the centerline.

The aircraft sustained extensive skin and structural damage to the aft left side of the fuselage immediately adjacent to the engine fan section. Fragments penetrated the fuselage and passed through the aft cabin area, causing damage to interior furnishings. as well as to fuselage skin and structure on the right side.

An electrical power feeder bundle from the number 2 engine generator that runs above the cabin ceiling along the upper right interior of the fuselage was almost entirely severed.

The left engine was destroyed.

1.4 Engine Information

The MD-88 is equipped with the Pratt & Whitney JT8D-219 engine, which is an axial-flow front turbofan engine having a fourteen stage split compressor section. The engine fan, the first stage of the compressor section, consists of 34 blades attached to a titanium alloy fan hub.

The left engine had a total operating time of 7371.7 hours and 5905 operating cycles at the time of the accident. It had been installed on the accident aircraft on January 1, 1996, and had subsequently accrued 1528 hours and 1142 cycles.

1.5 Fan Hub Information

The fan hub weighs approximately 150 pounds, and is forged from the titanium alloy 6Al-4V, which contains 6% aluminum and 4% vanadium. The major portion of the hub consists of a disk forging that holds the fan blades in dovetail slots around the outer radius. Integral to the disk is a cone shaped nose piece that engages the front end of the hub to the inner race of the number 1 engine bearing. The aft end of the hub attaches to the following compressor component with 24 tie bolts that pass through holes in the rim of the disk just inside of the dovetail slots. Evenly spaced between each tie bolt hole are 24 stress redistribution holes. Each hole through the disk is approximately 3 inches in depth.

The accident fan hub had a total of 16,542 hours and 13,835 cycles at the time of the accident, and 1142 cycles since its last fluorescent penetrant inspection (FPI) and visual inspection by Delta Air Lines. Records indicate that the fan blades had been replaced prior to the engine being installed on the accident aircraft on January 1, 1996.

1.5.1 Metallurgical Investigation

Post-accident investigation revealed that the accident hub fractured in two places radially on the rim circumference as well as longitudinally in the cone area. One of the rim radial fractures emanated from a pre-existing fatigue crack in one of the tie bolt holes. According to the NTSB Metallurgist's Factual Report, the fracture contained fatigue striations that originated from points near the aft end of a tie bolt hole interior surface. Fatigue cracking had propagated approximately 1.5 inches radially inboard. Beyond that, fracture features were typical of an overstress separation.

A striation count on the fracture face using a scanning electron microscope (SEM) revealed the total number of fatigue striations was roughly equivalent to the total number of flight cycles for the fan hub. The number of striations, along with the appearance of the fracture surface, suggested that the crack was present on the aft face of the hub (0.46 inches) and along the wall of the tie bolt hole (0.9 inches) at the time the last fluorescent penetrant inspection (FPI) accomplished by Delta in December 1995.

The pre-existing fatigue crack originated near smearing, or "scuff marks", in the tie bolt hole. Small, shallow surface chips were noted in the smeared areas. The surface of the smeared areas, exhibited evidence of circumferential machining marks, probably from the boring operation during original part manufacture. The remainder of the hole surface away from the scuff marks exhibited a cross hatched pattern, typical of a honing operation.

Metallographic examination indicated that the microstructure of the metal along the surface of the hole wall adjacent to the fracture location was severely deformed and contained numerous secondary cracks.

1.6 Hub Manufacturing Information

Volvo Flygmotor in Trollhatten, Sweden, is the manufacturer of fan hubs for Pratt & Whitney JT8D-200 series engines. The accident hub was manufactured by Volvo in 1989; Pratt & Whitney subsequently received the hub and installed it on an engine that was delivered to Delta on April 27, 1990.

The -219 titanium fan hubs are forged in the United States and then delivered to Volvo where they are machined, finished, and inspected. During manufacturing, the tie bolt and stress redistribution holes in the disk rim are created using a three-phase process consisting of drilling, boring, and honing. After manufacturing is complete, the hubs undergo various dimensional and non-destructive tests to ensure Pratt & Whitney specifications are met.

1.6.1 Coolant Channel Drill

Manufacturing records for the accident hub indicate that a coolant channel drill in a computer controlled machining center was used to drill both the tie bolt and stress redistribution holes in the hub rim. A coolant channel drill permits coolant to flow into the hole just behind the carbide cutting edges during the drilling process. The coolant entering the hole serves as a drilling lubricant to reduce heat and as a flushing agent for removing drill chips from the hole.

According to manufacturing records[1], the request to change the manufacturing process to use a coolant channel drill was submitted by Volvo and subsequently granted engineering approval by Pratt & Whitney in February 1988. The Pratt & Whitney Process Approval Record indicated that the replacement of the drill type was considered an "insignificant" change.

According to Volvo, the change to the coolant channel drill was implemented because it permitted a straighter hole to be drilled, thus better maintaining drilling tolerances. However,

[1] NTSB Public Hearing, Exhibit 8G

the use of the coolant channel drill was discontinued shortly after 1989 reportedly due to hole oversizing.[2]

1.6.2 Blue Etch Anodize Process

After all machine work is completed on a hub, the part undergoes an inspection phase that includes the blue etch anodize (BEA) process. The BEA inspection is unique to titanium, and consists of a visual inspection of an anodized surface for unique patterns that indicate anomalies associated with certain microstructure changes in the parent metal.

Volvo manufacturing records of the accident hub indicate that when the BEA inspection procedure was accomplished, mechanical marks were detected inside the tie bolt hole where the fatigue crack originated. The BEA procedure in effect at the time the accident hub was manufactured did not have any failure criteria that would have identified the microstructural changes present in the tie bolt hole. Based on the BEA inspection results, the hub was referred to a visual inspection process, where, because the part satisfied all Pratt & Whitney inspection criteria, the marks were accepted.

Post-accident investigation identified seven fan hubs that were found to have various unusual conditions detected inside the holes during the Volvo BEA inspection process. These hubs, including the accident hub, entered service after being certified as meeting BEA and visual inspection criteria in effect at the time.

1.7 Hub Certification

The accident fan hub was certified by the FAA as meeting the requirements of FAR 33.14, Start-Stop Cyclic Stress (Low Cycle Fatigue) and FAR 33.4, Instructions for Continued Airworthiness, and supplemented by Appendix A33.4, Airworthiness Limitations Section.[3]

1.7.1 Safe Life Certification

The safe life limit (mandatory part replacement time) for the JT8D-200 series fan hub is 20,000 flight cycles in compliance with FAR A33.4. This information is found in the Pratt & Whitney JT8D Engine Manual, Chapter 05-10-00, entitled "Time Limits at Normal Take-off Thrust Rating".

1.8 Operator Non-destructive Inspections

According to Delta's maintenance records, the fan hub underwent a fluorescent penetrant inspection (FPI) at the base maintenance facility in Atlanta in October 1995 after removal from the engine for blade and restricted parts removal. FPI is a process involving the submersion of a part into a low viscosity fluorescent dye bath, followed by a pre-rinse, emulsified by washing with a high viscosity solution, and final rinsed. After the application of

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[2] NTSB Public Hearing transcript
[3] NTSB Public Hearing, Exhibit 8K

a developer, the fluorescent dye, which is retained by cracks and other surface defects through capillary action, luminesces under ultra violet (UV) light inspection. At the time of the FPI, the hub had accrued 12,693 flight cycles. Subsequent to the inspection, the hub was installed on the accident engine on December 29, 1995.

Delta's procedures for the cleaning, preparation and non-destructive inspection of parts are governed by standard practices that are based on procedural recommendations provided by the original equipment manufacturers (OEMs). For the titanium -219 hub involved in the accident, the Delta process standards and Pratt & Whitney service process operating procedures (SPOPs) pertaining to the cleaning and FPI processes are as follows:

Process	Delta Process Standard	Pratt & Whitney SPOP
Preclean	P.S. 900-1-1 No. 18, 4., D.	SPOP 209
Alkaline clean	P.S. 900-1-1 No. 18, 4., F.	SPOP 18
Plastic Media Blast	P.S. 900-1-1 No. 21	SPOP 19
FPI	P.S. 900-6-3 No. 02	70-33-00; SPOP 82,84

Delta's procedures pertaining to similar parts manufactured by different OEMs may vary because of differences in the OEM recommended procedures. That is, the procedures that cover the cleaning, processing and inspection of a given part manufactured by Pratt & Whitney may differ from the procedures that cover a similar part manufactured by General Electric or Rolls Royce. Delta's process standard may deviate from a particular manufacturer's recommendation when there is inconsistency or disagreement between the recommended procedures of the various OEMs on how to process a similar part. For example, consistent with the recommended procedures published by General Electric and Rolls Royce, Delta's process standard does not require a titanium part to be spray rinsed following a plastic media blast, even though a spray rinse is recommended, if necessary, by Pratt & Whitney. On occasions where Delta's process standard deviates significantly from the recommended procedures of the OEM, Delta will coordinate those differences with the OEM to ensure that the integrity of the process is not compromised. A summary comparison of Delta's process standards for cleaning, media blasting, and FPI with the recommended procedures from three OEM's is provided in Appendices C and D.

1.8.1 Cleaning

In preparation for the FPI, the hub was cleaned per Delta Process Standard (P.S.) 900-1-1, No. 18. The process standard covers the approved materials and procedures for cleaning dry film lubricant, and carbon removal and paint stripping of various aircraft and engine parts including aircraft wheels, landing gear parts, seat parts, and miscellaneous engine parts manufactured by Pratt & Whitney. The process standard is based on the original equipment manufacturer's (Pratt & Whitney) recommended procedures for cleaning titanium parts and specifies the sequence in which the parts are immersed in various alkaline solutions, rinsed, and dried prior to a plastic media blast and subsequent inspection. The specific alkaline solutions used and their concentrations, dwell times in the solutions, and rinse times used for the cleaning and drying of titanium parts are based on the manufacturer's recommended procedures.

The Delta cleaning process for titanium hubs manufactured by Pratt & Whitney in effect in October 1995 included three stages. First, the hub was placed in a wire mesh basket and dipped in light duty degreaser for a specified dwell time. It was then spray-rinsed with city tap water, followed by a cold water dip rinse. In the second phase, the hub was dipped in a more aggressive alkaline cleaner for a specified dwell time, after which it was spray-rinsed and dipped in a cold water rinse. Finally, the hub was dipped in a third alkaline solution which softens dry lubricant and anti-gallant compounds. Following this last alkaline solution dip, the hub was dipped in a hot water bath for "flash drying."

Flash drying is an evaporative drying technique that involves dipping a part in a hot water rinse until the part is heated to the same temperature as the surrounding water. When the part is lifted out of the water, the water on the surface quickly evaporates as a result of the high temperature. Delta's process standard 900-1-1 No. 18 states that the part should be immersed in hot water (150-200°F) until the temperature of the part equals the temperature of the water. Pratt & Whitney's Standard Practice SPOP 209, upon which Delta's process standard is based, states that the part should be immersed in hot water (150-200°F) until the temperature of the part is at the water temperature to flash dry. The cleaner relies on a visual inspection of the evaporation of water on the surface of the part to determine that a part is adequately dry. There is no published guidance or tools available to the cleaner to determine whether water that may be present in cracks or other surface anomalies has fully evaporated using the flash drying technique.

1.8.2 Media Blast

After the hub has been cleaned and flash dried, it is subjected to plastic media blast to remove anti-gallant per Delta P.S. 900-1-1, No. 21. Delta's P.S. 900-1-1, No. 21 covers the materials and procedures for cleaning aircraft and engine parts using dry plastic media (Exhibit 11S). The purpose of a media blast is to remove residual surface contaminants such as heat scale, carbon deposits, corrosion and rust. Delta's process standard for media blasting the hub involved in the accident is based on Pratt & Whitney Specification SPOP 19[4], which describes part preparation, air pressure and blasting technique to ensure the part is cleaned. Following the media blast, SPOP 19 and P.S. 900-1-1, No. 21 both state that the part should be blown clean with air. Delta's procedure then calls for an inspection of all surfaces and cavities to ensure no blasting media is entrapped or remaining on the part, followed by dipping the part in a rust preventive solution. Pratt & Whitney's procedure recommends the part be cleaned through a pressure spray rinse, if necessary, after the part is blown dry and before the corrosion inhibitor is applied. As noted earlier, Delta's procedure does not call for a water rinse following the plastic media blast.

[4] NTSB Public Hearing, Exhibit 11L

1.8.3 Fluorescent Penetrant Inspection

Once the titanium hub has been cleaned, it subjected to a multi-step process to prepare it for fluorescent penetrant inspection. The part is first dipped in a vat containing fluorescent penetrant dye for a minimum dwell time of 30 minutes. After the hub is removed from the dye vat, it is spray-rinsed with city tap water for a period of one to two minutes. The hub is then dipped in a vat containing emulsifier for a period of 30-90 seconds. The purpose of the emulsifier is to break down fluorescent dye that is present on the surface of the part, thereby enhancing the visual contrast of fluorescent dye that penetrates any surface defects. The dwell times in the dye penetrant and emulsifier solutions are specified in Delta's Process Standard P.S. 900-6-3 No. 02, and are based on recommendations from the original equipment manufacturer. Upon removal from the emulsifier, the part is spray-rinsed with city tap water for a period not longer than one to two minutes in any one area. The purpose of the emulsifier is to render the surface fluorescent water washable thereby enhancing the visual contrast of fluorescent dye that penetrates any surface defects. The hub is then placed in a drying oven at 140-160 degrees Fahrenheit to facilitate surface drying. After removal from the drying oven, the processor visually inspects the part to ensure that it is dry. Once it is determined that the part is dry, a dry powder developer is applied a low pressure through a hose nozzle. The developer is sprayed on the exterior and interior visible surfaces by sweeping the hose nozzle in various directions over the hub. After application of the developer, the hub is ready for inspection.

The fluorescent penetrant inspection takes place in a darkroom, called a "tent," that is enclosed by walls and a ceiling made of a heavy canvas material. The tent contains an overhead white light, overhead UV light, and hand-held incandescent and UV lights. The overhead white light and hand-held incandescent light are used to perform visual inspections prior to the UV inspection and in the event of a positive indication during the UV inspection. The UV lights are used to illuminate any fluorescent dye that is remaining on the surface of the part or that has penetrated surface defects through capillary action. A crack or similar defect on the surface of the part will appear under UV light as a "glowing" greenish-yellow indication. Magnifying lenses and mirrors are available to the inspectors for closer examination of potential positive indications picked up during inspection under UV or incandescent lighting.

1.8.4 Post-Accident Observations

During a visit to Delta's FPI line following the accident, the inspection of a titanium hub similar to the one involved in the accident was observed by the maintenance group representatives on two separate occasions. The first observation was accomplished with a regular shop FPI inspector performing the task. The second was done by the individual who gave the accident hub its last FPI. The FPIs observed by the group members were essentially the same except for the individual inspector techniques. The parts are placed on a set of plastic rollers that allow it to be moved relatively easy once in the tent. A round shaped work area having the same type rollers is the inspector's work area. The tent is provided with an overhead hoist and strap for manipulating the part during inspection. This tooling aid is used at the inspectors' discretion.

During the inspections, the group observed that the UV spotlight cannot effectively penetrate into the tie bolt holes when viewed from the top of the hub. The geometric design of the -219 hub, especially the conical front, and the size of the floodlight prevents the positioning of the spotlight in such a way that both (1) the light penetrates deeply into the tie bolt holes, and (2) the interior of the hole can be seen by the inspector if any developer was in the hole. On the bottom of the hub, proper alignment of the spot light in the bore holes can only be done if the inspector rotates the hub under a very specific frame of reference. Instead, the inspector was observed to rotate the hub in approximate 120 degree increments and then physically move his body and light along an arc to inspect the holes. During the visual inspection, the first inspector said that finding cracks in the bolt and balance weight holes is not really possible. The second inspector also stated to investigators that it was very difficult to see into the holes on the hub.

1.9 NTSB Recommendations

As a result of the initial investigation of this accident, in July 1996 the NTSB issued four recommendations for FAA action. In summary, the NTSB recommended that the FAA:

- Require (within 500 cycles) an eddy current inspection of JT8D-200 fan hub tie bolt and stress redistribution holes to be performed on those hubs that have accumulated more than 10,000 cycles.
- Require an FPI and eddy current inspection of JT8D-200 fan hub tie bolt and stress redistribution holes to be performed on all hubs by a fixed number of cycles, as determined by the risk of crack propagation from manufacturing flaws.
- Review and modify the processes by which Volvo and Pratt & Whitney permitted JT8D-200 series fan hubs to be placed in airline service following indication of mechanical damage in the tie bolt holes based on a BEA inspection.
- Review and revise, in conjunction with engine manufacturers and air carriers, procedures, training, and supervision of inspectors for performing FPI and other non-destructive testing of high energy rotating engine parts, with emphasis on the JT8D-200 series tie bolt and stress redistribution holes.

1.10 FAA Airworthiness Directives

The FAA issued a Priority Letter Airworthiness Directive (AD) in July 1996 that identified, and directed immediate removal from service, the remaining six JT8D-200 series fan hubs that had recorded indications of tie bolt hole surface anomalies found during the manufacturer's BEA inspection process.

In addition, another AD was issued in February 1997 that prescribed a continuing inspection program for tie bolt and stress redistribution holes in all JT8D-200 series fan hubs based on procedures outlined in a Pratt & Whitney Alert Service Bulletin issued in September 1996.

The program mandates that a combination of eddy current and FPI inspections to the hole areas must be accomplished using various inspection schedule options that are predicated on the number of total cycles accumulated on the fan hub.

2. ANALYSIS

2.1 Microstructure Damage from Machining

The Metallurgist's Factual Report indicates that the pre-existing fatigue crack originated at "scuff marks" or smearing in one of the fan hub tie bolt holes. Small, shallow surface chips were noted in the smeared areas. The surface of the "scuff marks", or smeared areas, exhibited evidence of circumferential machining marks, probably from the boring operation during original part manufacture. The remainder of the hole surface away from the scuff marks exhibited a cross hatched pattern typical of a honing operation.

A scanning electron microscope (SEM) examination revealed that the smeared area at the origin contained numerous parallel cracks (ladder cracks), parallel to the thumbnail area at the fracture origin. Also noted were small shallow chip outs that appeared to be associated with the ladder cracking.

Metallographic examination of a cross section through the fracture origin revealed that the microstructure along the tie bolt hole wall adjacent to the fracture location was severely deformed and contained numerous secondary cracks (previously mentioned ladder cracks). The metallographic examination disclosed that the layer of distorted microstructure adjacent to the fracture face consisted of two zones of depths .002 inches and .0035 inches respectively. The microstructure in the damaged zone closest to the hole surface "appeared unclear and heavily layered". This appearance is typical of alpha rich zones in titanium and is similar in appearance to the white surface layer caused either by extensive deformation and/or oxidation as reflected in published literature pertaining to the microstructure of titanium[5]. The microstructure in the second zone consisted of heavily deformed alpha and beta grains. The microstructure of the base material consisted of equiaxed alpha grains in a transformed beta mix, typical for a titanium base alloy processed below the beta transus temperature.

Abnormal Knoop hardness readings of 581 HK (52 HRC) were measured at a distance of .001 inch in the damaged microstructure area, compared to normal hardness readings of 347 HK (34 HRC) in the undamaged zone. This change in microhardness was much more severe than published literature indicated it should have been, indicating that previous research quantifying hardness abnormalities associated with "abusive machining" to date is inadequate.

(Abusive machining is defined as any process that deleteriously affects the microstructure of the parent metal.)

[5] Appendix A, 4

The surface damage (smearing) seen in this case, apparently caused by an improper machining operation, is remarkably similar in appearance and hardness to damage noted in the investigation of another fractured fan hub in 1982[6]. In both instances, the surface damage caused by the abusive machining eventually resulted in catastrophic fan hub break up, and uncontained engine failures. The serious nature of the problem is compounded by the fact that, although over a thousand articles have been published on various aspects of titanium and its alloys, there is comparatively little published work on the detailed effects of abusive machining on the microstructure of titanium alloys.

2.1.1 Microstructure Complexity

Ti-6Al-4V is a high-alpha, lean-beta alloy of titanium; the structure of the alpha phase is hexagonal close packed (HCP) while the beta phase is body centered cubic (BCC). In unalloyed titanium, only alpha exists below 1620° F while only beta exists above 1620° F. Alloying elements stabilize either of the two phases and so, by selecting suitable elements and proper heat treatment, both phases can be made to exist at room temperature.

The standard composition of Ti-6Al-4V (range or maximums)[7]:

	% Major Elements
Al	5.5 - 6.75
V	3.5 - 4.50
Fe	0.30
	% Interstitial Elements
O	0.20
C	0.10
N	0.05
H	0.015 sheet
	0.0125 bar

Aluminum stabilizes the alpha phase while vanadium and iron stabilize the beta phase. Oxygen, carbon and nitrogen which are considered impurities, form interstitial solutions and stabilize the alpha phase. With the above composition the beta transus temperature is 1825° F ± 25° F, but changes in the interstitial elements affect the beta transus temperature.

The interstitials also affect the alloy as follows:

- strength increases with interstitial content at intermediate temperatures up to 500° F without much loss of ductility, and strengthening effect decreases with increasing temperature,

[6] Appendix A, 5
[7] Appendix A, 1

- the beta to alpha transformation rate is accelerated by the presence of interstitials dissolved in the beta phase, and
- the notch sensitivity, especially at low temperatures, is increased with increasing interstitial content.

In general, the microstructures of Ti-alloys are manipulated by heat treatment and manufacturing process to give the desired strength and toughness from the following characteristics: (1) the relative amounts of alpha, beta, and transformed beta (alpha prime), (2) the morphology of the phases (equiaxed or acicular), (3) the texture of the grains, and (4) the sub-microstructural constituents (alpha 2 and omega) present in the primary alpha and beta phases. The formation and effects of these characteristics have been studied in detail[8] and are mentioned here to indicate the complexities involved in obtaining a desired composite property.

A review of literature[9] regarding titanium machining shows that relatively few studies have been conducted which examine and quantify the effects of machining, and drilling in particular, on the surface microstructure of titanium alloys (including Ti-6Al-4V).

2.1.2 Machining Titanium

The potential for microstructural changes during titanium machining can arise from the high cutting temperatures involved and the chemical reactivity of titanium. The high temperatures are mainly due to the tool-titanium high contact pressures, and the poor heat conductivity of titanium. The thermal conductivity of titanium is one third that of steel[10]. Hence the tool-chip interface temperatures when machining titanium are higher than they would be when machining steel. The temperature rise depends on the cutting speed and the tool material: for high-speed-steel tools and cutting speeds of 10-60 fpm, the temperature rise can range from 500° to 850° F, while for carbide tools at speeds from 10-220 fpm, the temperature rise can range from 400° to 1800° F. These measured temperatures may in fact be lower than the actual, instantaneous, temperature rise at the tool-workpiece interface. The high temperatures therefore are a potential source for microstructural changes in the titanium surface. Hence, any change in the tool material (e.g., from solid HSS to drills with carbide cutting edge inserts), feed rate, or speed of machining (as implemented by Volvo), should be considered as a *significant change*, and therefore require an extensive microstructural characterization[11] prior to implementation.

Compounded with high cutting temperatures is the strong chemical activity of titanium with the tool materials at elevated temperatures. This can macroscopically produce galling, welding, and smearing, since an alloy is continuously formed between the titanium chip and the tool material[12]. This alloy usually passes off with the chip but the potential for smearing on

[8] Appendix A, 6-14
[9] Appendix A, 2-4, 15-20
[10] Appendix A, 15
[11] Appendix A, 23
[12] Appendix A, 15

the workpiece also exists at very high temperatures. Such smearing has been observed during service experience of drilling the Ti-6Al-4V fan hub, but due to a lack of understanding, has been improperly characterized as machining marks.[13]

Oxidation is another problem at high temperatures due to the high chemical activity of titanium[14]. Typically, oxidation of the surface layers results in a large amount of the alpha phase [Figure 1], whose thickness (depth into the surface) increases with the temperature and the time held at that temperature [Figure 2]. However, since the kinetics of oxidation can also be affected by the applied stress (strain hardening), i.e. an Eyring type dependence on stress and temperature, the rate of oxide formation may be accelerated by high tool-workpiece stress and temperature. This aspect appears not to have been studied, specifically for titanium alloys.

To keep the cutting temperatures down, cutting fluid is used to minimize any tool-chip-workpiece friction and welding. Various types of cutting fluids such as water soluble emulsions, halogenated oils, and synthetic chemical are normally used for machining titanium. However, the use of chlorinated oils should be avoided since chloride residues from these oils may lead to stress corrosion cracking of the parts during high temperature service[15]. Any change in either the coolant type or in its delivery, should require a complete re-evaluation of the machining process including a study of the surface microstructure of the finished part[16]. For example, in the drilling operation of the Ti-6Al-4V fan hub, when changing the drill type from a regular HSS drill to a coolant channel drill, the process should not have been considered "approved" until a thorough evaluation of the finished surface had been completed. This was not done on a consistent basis[17], and is likely the root cause of the accident fan hub failure.

Cross-sectional hardness measurements on Ti-6Al-4V surfaces after machining operations like grinding have shown that if the operation has been gentle, the surface will exhibit a shallow white layer of hardness measured lower (by about 4 HRC) than the bulk material. But when the grinding has been abusive, the surface white layer will be distorted to a depth of 0.005 inches, and will measure an increased hardness (of about 4 HRC) compared to the bulk material[18]. Service experience gained from drilling of the JT-8D fan hub made from Ti-6Al-4V has shown that under abusive conditions, the white layer, or work affected microstructure, can extend to a depth of 0.025 inches and have a measured hardness increase of up to 21 HRC[19]. As a result, during normal operating stresses, surface cracks can initiate from this brittle layer caused by abusive machining. Such cracking has been observed[20], but it is not yet known if the cracks were initiated under service load application, or initiated during the abusive machining process.

[13] Appendix A, 24
[14] Appendix A, 1, 4
[15] Appendix A, 15
[16] Appendix A, 23
[17] Appendix A, 25
[18] Appendix A, 2, 3
[19] Appendix A, 5
[20] Appendix A, 5

Extensive surface deformation during abusive machining results in a highly strain hardened microstructure that, because of high machining temperatures, can undergo recovery and recrystallization. As seen from service experience[21], such recrystallization can result in a large, coarse grained microstructure in a thin surface layer. Because there have been no studies done, there is very little known about the recrystallization temperature and kinetics that lead to this deformed surface layer.

2.1.3 Titanium Drilling

During titanium drilling[22], thin chips flowing at high velocities are likely to fold and clog in the flutes of the drill, causing additional frictional temperature rise and smearing. These problems can be minimized by using short sharp drills, supplying cutting fluids to the cutting zone and using low speeds and positive feeds.

The accepted rule when drilling titanium is to keep the drill cutting and never allow the drill to ride in the hole without cutting metal. This is done to prevent temperature build-up, and the attendant oxidation that can occur. It could not be determined if this aspect was considered during the deep hole drilling of the accident hub, but it could account for the altered surface layer that resulted.

A sharp drill produces tight-curling chips, but as the drill dulls and the cutting temperature rises, feather-type chips are produced. This is a sign that the drill is dull. The appearance of discolored chips indicates that a drill has failed.

When drilling holes through a part, the general practice is to not drill all the way through on a continuous feed. The drill should instead be retracted and cleaned before breakthrough. The chips should be flushed from the hole before continuing to drill through the part. During coolant channel drilling, chips are flushed out by a coolant that is forced into the hole through a channel in the drill. However, when the drill breaks through at the exit side of the hole, there is no coolant backpressure to continue flushing the chips out. The trapped chips melt and can cause smearing or scuffing in the hole as there is now no coolant available to keep the drill-workpiece interface temperatures down.

A minor imperfection on the surface of the part, caused by a mildly abusive machining operation, can prove critical. Imperfections can serve as initiation sites for fatigue and/or stress corrosion, thereby drastically shortening the life of the part. In order to avoid such problems, all changes in manufacturing operations, including machining, should be thoroughly reviewed to determine the microstructural effects on the material, including strength and toughness. A review of this type is usually facilitated by the existence of sufficient data showing how changes in the process affect the material. The investigation of this accident reveals that such information is not readily available for certain machining operations on Ti-6Al-4V, including drilling.

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[21] Appendix A, 5

[22] Appendix A, 15

2.1.4 Industry Data

A lack of data exists pertaining to the issue of microstructure abnormalities caused by abusive machining (drilling) during the manufacture of titanium alloy parts, and specifically the susceptibility to microstructure damage from use of the coolant channel drill. Any study and collection of data regarding the effects of drilling on Ti-6Al-4V should include at least the following.

- Determine temperature rise with and without coolant, and, using the recommended drill types, at different speeds and feeds both in the recommended and abusive conditions. Sampling should include work pieces of varying thicknesses within the extremes of deep hole geometries usually encountered in the manufacture of titanium aircraft and engine components. Additionally, tool-workpiece force/pressures should be measured during the cutting operation.
- Conduct hardness tests, and characterize the morphology, composition, plastic deformation and any micro-cracking of the near-surface cross-section by optical microscopy, SEM and TEM and X-ray diffraction methods.
- Study and document post-drilling properties to include tensile strength, number of cycles needed to initiate a fatigue crack of set length as a function of cyclic stress, and time to initiate a stress-corrosion crack of pre-determined length in a NaCl solution as a function of stress.
- Correlate measured properties of strength, fatigue life and stress corrosion susceptibility with surface characterization, and thus with the type of drilling operation.

Currently there is no comprehensive database that contains the effects of drilling changes on the microstructure and properties of Ti-6Al-4V; i.e. data that can be used as evaluation criteria for certification and approval when changes in the machining process (drilling) are proposed. The investigation of this accident reveals that changes to the machining and tooling process should always be considered "significant changes", and approval should be substantiated on the basis of equivalency with a rigorously established industry baseline.

2.2 Safe Life Certification

The 20,000 flight cycle safe life limit for compliance with A33.4 was established by applying a 20% life reduction factor to the analytically established "B0.1" (risk factor of 0.1 or less, or for a safe life component, it is estimated that the chance of the strength falling appreciably below the design ultimate value is about 1 in 1000) statistical design life goal of 25,000 flight cycles for crack initiation, with no credit for crack propagation[23].

Safe life certification is based on the assumption that the part will remain crack free during the service life. It is assumed that the number of cycles to failure (with failure defined as fatigue crack initiation) are related to the "average" strength of the part. The NTSB Metallurgist's factual report[24] indicates that fatigue crack initiation in the accident hub began during the first

[23] Appendix B, 1
[24] NTSB Public Hearing, Exhibit 15B

244 cycles of the service life of the part. The possibility also exists that, due to residual stresses associated with the damaged microstructure and a severe hardness gradient[25], the crack may have initiated prior to the part being put into service. This is obviously contrary to the certification requirement of no fatigue crack initiation during the entire life of the part.

As discussed in the analysis above, early fatigue initiation in the accident hub was caused by abusive machining (drilling) during the manufacturing process that resulted in a material defect (deleteriously altered titanium microstructure) going undetected by the supplier's (Volvo) quality assurance program, thus allowing a defective part to enter service. The consequence is that the fatigue endurance limit that was determined by the fan hub certificate holder (by applying a life reduction factor) was grossly exceeded. This indicates the need for additional validation of life reduction factors, or the establishment of a fatigue probabilistic reliability standard for safe life determination.

Such a life reduction factor had been proposed by a commenter during the review of FAR 33.14, and described in Amendment 33-10, Dec. 16, 1983. The commenter had suggested that a fixed percentage of the predicted life be established as the "initial service life". The suggestion was not incorporated because it was thought that the existing methodology of predicting low cycle fatigue life was adequate, and that adoption of a reduced initial life would "place undue burden on the applicant (engine manufacturer) with no commensurate safety benefit".

2.2.1 Safe Life Inspection Requirements

Since the accident hub was certified using safe life criteria, no fixed interval inspections were required by regulation to ensure continued airworthiness. The Pratt and Whitney Overhaul Manual (OHM) specifies only "opportunistic inspections", consisting of FPI to detect "large flaw" defects during shop visits. The accident hub was inspected only once, by Delta using FPI, during a single shop visit after 12,693 flight cycles[26]. An existing fatigue crack, extending 0.9 inches into the tie bolt hole, and 0.46 inches across the aft face of the hub adjacent to the tie bolt hole, was not detected during the single inspection opportunity.

2.2.2 Safe Life Certification Assumptions

The 20% life reduction used to determine hub safe life limit (20,000 cycles) does not account for any initial material or manufacturing induced flaws in the hub, i.e. flaws that are not present in the fatigue test sample coupons. Merely increasing the hub design ultimate stress does not guarantee an increase in its safe life unless the life reducing effects of any initial flaws are fully accounted for. The hub design and continued airworthiness certification criteria, based on FAR 33.14 and 33.4 respectively, do not account for the effect of these flaws on fatigue life.

[25] Metallurgist's Factual Report
[26] NTSB Docket No. SA-515, Exhibit 110

For example, the existing -219 fan hub safe life cycle limit ("L1") is predicated on takeoffs at normal take-off thrust. Based on FAR 33.14, it should be necessary to determine a design minimum fatigue life ("L2") predicated on start-stop cycles at *maximum power and thrust ratings*.

The determination of design minimum fatigue life should also consider the scatter factor associated with the S-N (stress life prediction) curve of the hub material. The fatigue life scatter factor does not take into account the variations in the manufacturing quality of the hub, and the possible existence of induced 'initial' flaws. Currently it is assumed that initial flaws will be detected during the manufacturer's inspection process. There is no provision made for flaws that may pass undetected, or that may be detected but then not be recognized as significant. Currently there are no provisions for characterizing manufacturing flaws in terms of location, size, orientation and distribution. In calculating a reliable safe life, such characterizations should be quantified into an *initial fatigue quality parameter*[27] that accounts for growth characteristics of the initial flaw population, and consequently causes a further reduction to minimum fatigue life ("L3"). Initial flaws can typically be grouped into three categories: (1) defects during initial forming, such as voids and inclusions, (2) random flaws induced during normal machining and handling, such as sharp notches, and (3) improper heat treatment or machining-induced flaws in the material's microstructure in the form of inhomogenities and cracks. In the accident hub, cracks induced from an improper machining operation and altered microstructure contributed to the failure.

A safe life criterion that includes initial flaws (e.g. cracks, notches) that have passed undetected into service implies that the crack growth rate in fatigue must initially be stable, predictable, and the life of the part must be exceeded before the crack becomes unstable. In the accident fan hub, a fatigue striation count on the fracture surface indicated that the crack growth was initially stable till around 9000 cycles. After that it became unstable and finally failed around 14,000 cycles, as shown in Figure 3. Theoretical predictability of crack growth appears possible based on an initial analysis using NASGRO[28] material data for the Ti-6Al-4V alloy and crack growth equations, and estimated maximum cyclic stress. The size of the initial flaw in the accident hub was taken to be the depth of the high alpha content and high hardness microstructure found in the smeared area of the tie bolt hole surface, and measured as 0.017 inches. Based on fractography the crack was assumed to have been a corner crack with an aspect ratio of 2.35. Using these initial flaw sizes, the predicted crack size as a function of fatigue cycles was plotted using NASGRO. Figure 3 shows that there is an excellent correlation between the theoretical and actual crack growth rate. This correlation therefore suggests that analytical determination of cycles-to-failure can be obtained with good accuracy if the initial damage/flaw is known and properly characterized.

For cases where the initial flaw size can be characterized as a short fatigue crack whose initial growth rates are not well defined,[29] additional work characterizing growth rates must be accomplished. The cycles to transition from a short crack to a crack that can be described by

[27] Appendix B, 3
[28] Appendix B, 4
[29] Appendix B, 5, 6

linear elastic fracture mechanics should be determined. This is necessary to correctly assess the impact of the distribution of crack sizes likely to be found on the total fatigue life of the hub.

Thus, characterization of initial flaws in a hub after manufacturing will allow prediction of the minimum life to fatigue failure ("L3") based on crack growth considerations. In other words, the "L3" life is the damage tolerance based limit for Paris Law behavior, during which the crack growth rate is predictable. "L3" can be considered equivalent to the "initial service life" that had been proposed, but not accepted, by the commenter during the FAR 33.14 review. At that time no quantitative means of establishing this initial life was proposed. A clearly defined, quantitative approach, is proposed in this report that aims at removing any arbitrariness in defining the initial life "L3".

2.2.3 Continued Airworthiness

Continued airworthiness is contingent upon the enactment and application of minimum certification standards, and also the interdependence of the original equipment manufacturer delivering a "defect free" part that meets the type design certification basis, coupled with the operator performing inspections during the service of the life of the part that will detect rogue flaws, accidental damage and environmental damage.

Current continued airworthiness certification of the -219 fan hub does not include a schedule of inspection intervals based on the application of damage tolerance methodology.

There is also no provision for identification of the critical stressed area of the part coupled with a characterization of initial flaw size or material quality index. The material quality index must be linked to the manufacturer's ability to detect manufacturing defects of the type and extent experienced on the accident hub. The material quality index must not be dependent on the subjective interpretation of visual inspection techniques such as BEA, but instead must be characterized by the use of new high frequency eddy current inspection techniques capable of detecting the types of titanium microstructure deficiencies found during the investigation of this accident (see Section 1.5.1). The current certification basis of the -219 fan hub does not include a fixed interval inspection schedule based on analytically predicted stable growth rates (validated by tests) of low cycle fatigue cracks that emanate from rogue manufacturing flaws .

Current continued airworthiness certification does not require the application of supplemental non-destructive testing methods, such as high frequency eddy current inspection, for the critical stressed areas (tie bolt holes) of the fan hub. Under current certification guidelines, the same "large flaw" inspection technique, i.e. FPI, is used to detect damage in all areas of the hub, including both high and low stress areas.

These issues are considered inadequacies in the current safe life continued airworthiness certification process.

2.2.4 Damage Tolerance Criteria

The application of damage tolerance criteria provide several advantages (as opposed to a reliance on safe life limits) to the effective management of continued airworthiness during the service life of the part. A damage tolerance continued airworthiness certification program:

- Requires that the reliability of inspection procedure is quantified (example 90% probability of detection with a 95% confidence level).
- Increases confidence in being able to predict both the rate of growth of a small defect (crack), and the critical crack size at which failure will occur under specified loads.
- Provides repeat inspection opportunities to detect a crack prior to failure (required to achieve 95% confidence level).
- Addresses initial material quality (such as microstructure damage present in the accident fan hub), defined as a distribution of intrinsic microstructural anomalies that might lead to failure.[30] This concept quantifies the effect of defects below designated NDE capability.
- Requires more analysis and testing (enhanced reliability) than the low cycle fatigue based systems certified under safe life requirements.
- Less scatter (enhanced reliability) in the measurement of fracture mechanics properties than in low cycle fatigue life determination.
- Failure prediction is based on the presence of damage (material defects, manufacturing defects, environmental and accidental damage).

All of these aspects combine to yield inspection size versus remaining life predictions for specific material and applications, which in total form a quantitative basis of damage tolerant design and life prediction approach.

2.2.5 Certification Requirements - Summary

Safe Life determination using life reduction factors must be rigorously substantiated by analysis and test. In addition, life reduction factors must account for manufacturing defects, material defects, accidental damage and environmental damage that may go undetected in the part's service life. Research is needed that establishes validation criteria for the use of life reduction factors that can be applied to safe life certification.

Not all factors affecting fatigue crack initiation (manufacturing defects, material defects, accidental and environmental damage) can be accounted for in the service life of critical engine rotating parts. Initial fatigue design data is subject to considerable statistical variability. Significant scatter is observed in published S-N fatigue data. Conventional safe-life design acknowledges statistical scatter qualitatively through the use of life reduction factors, but it does not quantify the resulting level of reliability[31]. Safe life certification must be supplemented by continuous airworthiness limitations based on rigorously applied damage tolerance criteria[32].

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[30] Appendix B, 8
[31] Appendix B, 9
[32] Appendix B, 10, 11

The damage tolerance analysis should account for manufacturing damage and material defects using an initial flaw assumption. Analysis should not be based on fatigue crack initiation (threshold credit). Additional research is needed to determine an equivalent initial crack size and shape, but validation of initial flaw size should be part of the continued airworthiness certification process.

2.3 Operator Inspection Process

Maintenance records indicate that the -219 fan hub had been cleaned, processed and subjected to fluorescent penetrant inspection in accordance with Delta's standard practices pertaining to titanium engine parts manufactured by Pratt & Whitney. Nevertheless, metallurgical analyses of the failed hub revealed that at the time of the last FPI in December 1995, the crack was present on the aft face of the hub (0.46 inches) and along the wall of the tie bolt hole (0.9 inches); yet, the crack was not detected and the fan hub was returned to service. This calls into question two safety concerns with regard to FPI: the integrity of the existing cleaning and/or FPI processes, and the adequacy FPI as an inspection method for critical rotating parts.

The first concern focuses on the possibility that the cleaning or inspection process was compromised, resulting in a contamination of the region of the part that contained the crack. This explanation is bolstered by the fact that the metallurgical examination of the crack surface failed to detect the presence of trace elements of the fluorescent dye penetrant. Although it cannot be conclusively determined from this that no dye penetrated the crack during the FPI, the absence of trace elements on the surface of the crack in combination with the failure of the inspector to detect a crack nearly half an inch in length on the aft face of the hub suggests that it is highly unlikely that fluorescent dye had penetrated the crack during the FPI processing.

2.3.1 Part Drying

One possible source of contamination is the presence of water in the crack that would preclude penetration by the fluorescent dye. Delta's process standard for titanium parts utilizes a flash drying technique at the end of the alkaline cleaning procedure, except for certain Roll Royce parts[33]. This technique involves immersing the part in a vat of hot water until the temperature of the part equals the temperature of the water. When removed from the hot water, the part dries through evaporation. However, it is apparent from observation of the drying process and from the testimony of witnesses at the public hearing on this accident that there are no tools available to cleaning personnel for determining whether the temperature of the part equals the water temperature; or that the part has been adequately heated to ensure the evaporation of water that may be present in cracks or other surface defects. It is therefore possible that the part progressed beyond the flash drying stage of the cleaning process with water still present in the crack. Because dye penetrant is essentially oil-based, it will be repelled by any water present in the crack.

The cleaning personnel responsible for drying the part must rely on the prescribed water temperature and dwell time requirements for flash drying stated in the process standard,

[33] Rolls Royce Overhaul Manual

followed by a visual inspection of the evaporation of water on the surface. It was noted during the public hearing that the recommended temperature and dwell times for flash drying were developed to facilitate the evaporation of water on the surface of the part and do not account for possible water present in deep cracks or other surface anomalies. There is no way for cleaning personnel to know whether or where a crack may exist in order to assess whether water has fully evaporated from the crack.

The use of oven drying has been raised as a possible solution to the deficiencies of flash drying. Of the three OEMs of titanium engine parts used by Delta, only Rolls Royce specifically requires oven drying of Group A parts and compressor and turbine blades. Nevertheless, whether a part is dried through flash drying or oven drying, *time* is the critical variable for ensuring the complete evaporation of water on the surface or in a crack. A single standard for determining the sufficient time at an elevated temperature is therefore needed whether the part is dried in an oven or flash dried.

2.3.2 Plastic Media

A second possible source of contamination is plastic media. Delta's process standard provides guidelines to cleaning personnel on the proper technique for blasting a part with plastic media to prevent the media from becoming entrapped or from masking potential defects on the surface of a part through peening or material displacement. A number of expert witnesses in the public hearing advocated rinsing the part after subjecting it to media blast to loosen and remove potential media contamination. Delta's process standard calls for blowing the part with compressed air following the media blast, and the recommendations from the OEM's differ on this point. Only Pratt & Whitney's recommended procedure refers to a pressure spray rinse to remove plastic media, *"if needed"*; however, no guidance is provided by Pratt & Whitney as to whether a rinse is needed or not. Neither Rolls Royce nor General Electric recommend the use of a spray rinse on titanium parts after plastic media blasting.

2.3.3 OEM Guidance

As noted by a number of expert witnesses in the Safety Board's public hearing on this accident, FPI is a highly process-dependent activity. That is, for FPI to be an effective tool for detecting and rejecting critical parts with flaws that exceed tolerance limits, cleaning, preparation and inspection procedures must be closely followed. The fact that there is inconsistency or disagreement in the various OEM recommended procedures for similar parts is therefore a serious concern. A single set of procedural standards for cleaning and inspecting similar parts should be developed. It should incorporate the best scientific information available for enhancing the effectiveness of the cleaning and inspection processes. It is recommended therefore, that a task force comprising representatives from government and the industry be convened to review the adequacy of existing original equipment manufacturer procedures for cleaning and processing critical parts prior to visual inspection, and develop standardized procedures for cleaning and processing.

2.3.4 FPI Effectiveness

The second safety concern focuses on whether FPI is an effective inspection method for critical engine parts like the -219 hub; parts that are characterized by complex geometries or areas that are difficult to inspect visually, such as tie bolt holes. In this particular case, at the time of the 1995 inspection the crack had propagated on the aft face of the hub to a length that should have been detected through FPI. However, the crack initiated and was detectable in a tie bolt hole many cycles before it emerged on the aft surface. Had the FPI been conducted earlier (prior to its emergence on the aft face), it is likely that the probability of detecting the crack would have been much lower given the difficulties faced by inspectors in adequately conducting a 360° visual inspection of deep holes. Although tools such as mirrors, boroscopes and pen lights are available to inspectors in the FPI tent, difficulties in inspecting the tie bolt and stress redistribution holes were noted by inspectors during the investigation, and were observed firsthand by investigators.

Following the accident, Delta worked with Pratt & Whitney and the FAA to develop an eddy current inspection technique for use as a supplemental inspection of the tie bolt and stress redistribution holes on the -219 hub. The eddy current procedure was adopted in an AD issued in February 1997 that mandates a combination of eddy current and FPI inspections at regular intervals throughout the safe life of the fan hub. There is concern that there are other critical rotating parts characterized by complex geometries or deep holes for which visual inspection techniques are not well suited. It is therefore recommended that a task force comprising government and industry representatives be convened to identify critical areas of component parts for which existing visual inspection procedures may be unsuited to detecting existing flaws, and develop alternative or supplemental inspection techniques that increase the probability of detecting such flaws to acceptable limits.

3. CONCLUSIONS

3.1 Findings

1. A severe microstructural deformation of the titanium on the wall of the tie bolt hole of the accident hub, adjacent to the origin of the fracture, was caused by abusive machining during the manufacturing process.

2. The non-destructive inspection and evaluation processes used during manufacturing were not effective in assessing the microstructural deformation on the part caused by abusive machining, and in making a determination to reject the part for service.

3. A change in the machining process that involved drill replacement (to a coolant channel drill) in the manufacture of JT8D-200 fan hubs was classified as an "insignificant change", and given engineering approval by the manufacturer without adequate research as to potential abusive effects of the replacement drill on the microstructure of the titanium.

4. High temperatures resulting from manufacturing machining processes, particularly drilling, have the potential for affecting, or changing, the microstructural characteristics of titanium alloys.

5. Relatively few studies have been conducted, and little data is available, that quantify the potential effects of machining, and drilling in particular, on the surface microstructure of titanium alloys.

6. Assumptions used to determine and certify the safe life limit for the JT8D-219 fan hub do not account for life reducing initial flaws that might exist when the part comes out of the manufacturing process.

7. The certification of the -219 fan hub does not include development of an initial fatigue quality parameter that accounts for growth characteristics of cracks that might develop as the result of manufacturing flaws.

8. Damage tolerance criteria are not included in the certification of the -219 fan hub; there is no requirement for any inspections that ensure continued airworthiness of the part to the life limit.

9. The procedures that cover the cleaning, processing, and inspection of a given part manufactured by one original equipment manufacturer (OEM) may differ from the procedures that cover a similar part manufactured by other OEMs.

10. Cleaning personnel rely on a visual inspection of the evaporation of water on the surface of the part to determine that a part is adequately dry. There is no published guidance or tools available to the cleaner to determine whether water that may be present in cracks or other surface anomalies has fully evaporated prior to the application of fluorescent penetrant dye.

11. During two observations of FPI inspections, it was observed that an ultraviolet spotlight does not effectively penetrate into the tie bolt holes when viewed from the top of the hub. From the bottom of the hub, proper alignment can only be done if the inspector rotates the hub under a particular frame of reference. One inspector said that finding cracks in the bolt and balance weight holes is not really possible. A second inspector also stated to investigators that it was very difficult to see into the holes on the hub.

3.2 Probable Cause

The probable cause of this accident was the catastrophic failure of the left engine first stage fan hub as a result of a low cycle fatigue crack that originated from a microstructure defect created by abusive machining during the manufacturing process. Contributing to this accident was:

- the failure of the manufacturer to adequately evaluate changes to the approved drilling process, and the effects of those changes on the microstructure of titanium,
- the failure of the manufacturer to adequately assess visual abusive machining damage indications, and to effectively utilize a non-destructive method to evaluate these findings,
- the absence of an effective standard for rejecting parts with known abusive machining defects detected through Blue Etch Anodize inspection methods during the manufacturing process,
- the failure of the certification process to adequately account for factors that can preclude critical parts from reaching their safe life limit,
- the absence of standardized guidance for air carriers for cleaning and processing of critical parts during the fluorescent penetrant inspection process used by operators, and
- the absence of an effective visual inspection method suitable for detecting flaws in critical rotating parts with complex geometries and deep holes.

4. RECOMMENDATIONS

As a result of the findings from this investigation, it is recommended that:

1. To the FAA: Convene an industry task force to identify critical machining processes, especially drilling, and associated potential deleterious effects on the microstructure of titanium; and recommend requirements for the evaluation of these practices, and subsequent changes to certified tools and methods.

2. To the FAA: Sponsor an industry/academia research effort to develop additional non-destructive testing methods, such as the new application of high frequency eddy current inspection, that will detect defective microstructure surface layers (interstitial oxygen stabilized alpha) in critical rotating engine parts; and to establish a certification requirement for the reliable detection of such damage.

3. To the FAA: Charter an industry task group to review and recommend revisions to current certification procedures for safe life engine rotating parts to require the validation of life reduction factors, or as an alternative, to establish a minimum fatigue probabilistic reliability standard to ensure that premature failure is extremely remote; and to require that

continued airworthiness of safe life parts be managed by damage tolerance criteria as a supplement to safe life determination.

4. To the FAA: Convene an industry/government task force to review the adequacy of existing original equipment manufacturer procedures for cleaning and processing critical parts prior to visual inspection, and develop standardized procedures for cleaning and processing.

5. To the FAA: Convene an industry/government task force to identify critical areas of component parts for which existing visual inspection procedures may be unsuited to detecting existing flaws, and develop alternative or supplemental inspection techniques that increase the probability of detecting such flaws to acceptable limits.

Figure 1. Micrograph of the near-surface region of an oxygen contaminated Ti-6Al-4V alloy, showing a large amount of alpha phase (white areas). [Appendix A, Ref. 1].

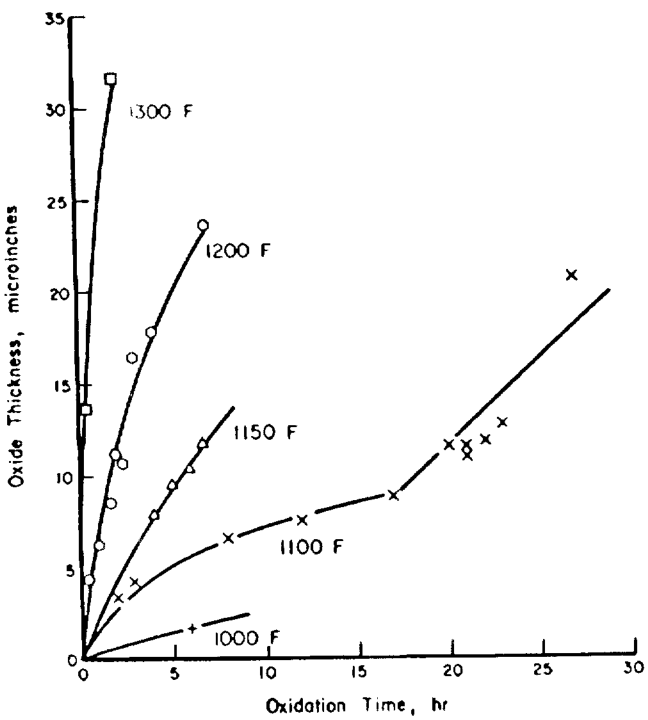

Figure 2. Thickness of the oxide layer formed on Ti-6Al-4V alloy as a function of time at different temperatures [Appendix A, Ref. 1]

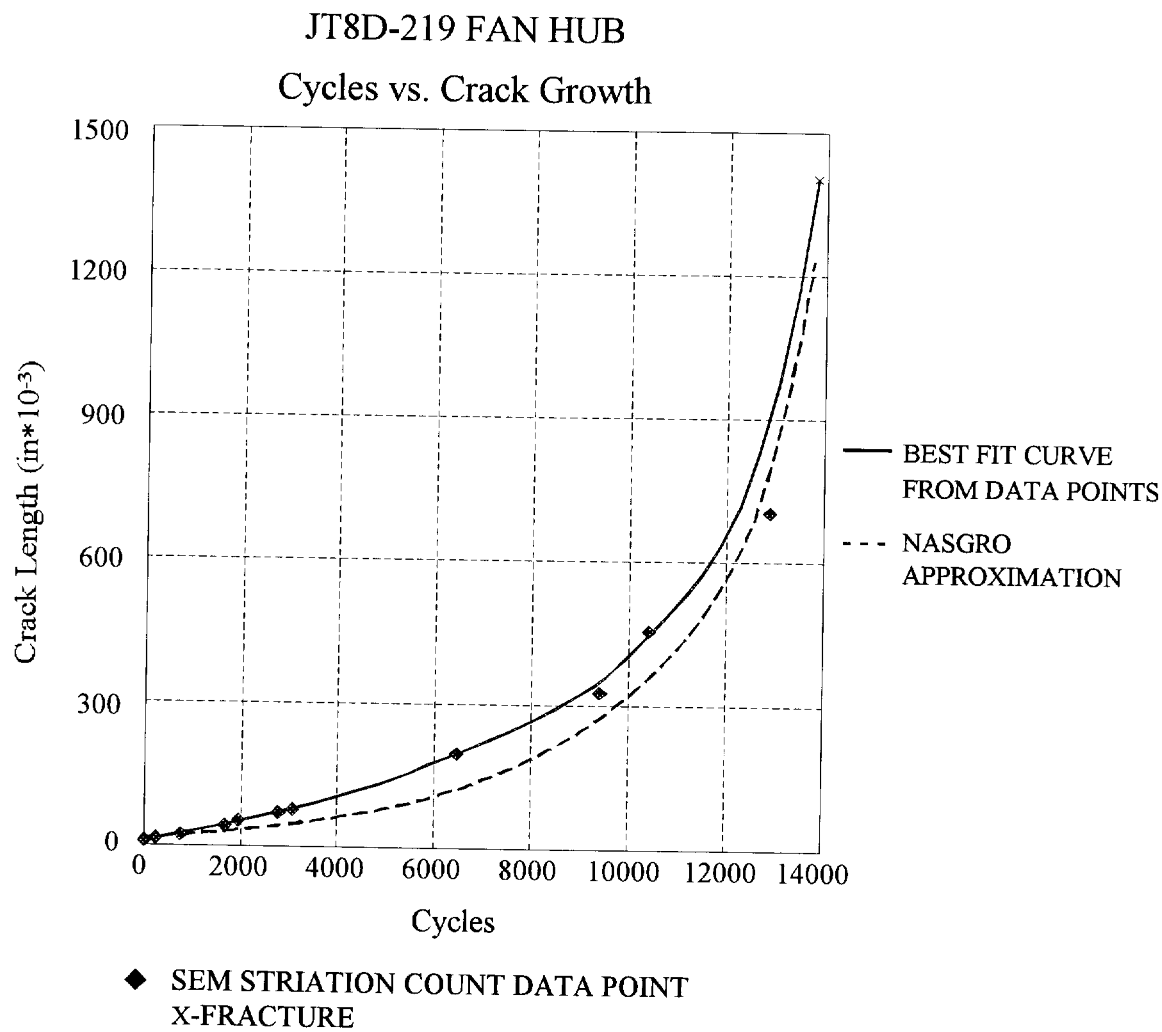
JT8D-219 FAN HUB
Cycles vs. Crack Growth
1500
1200
900
600
300
0
Crack Length (in*10-3)
0
2000
4000
6000
8000
10000
12000
14000
Cycles
BEST FIT CURVE FROM DATA POINTS
NASGRO APPROXIMATION
SEM STRIATION COUNT DATA POINT
X-FRACTURE

Figure 3.

APPENDIX A

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APPENDIX B

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APPENDIX C

PROCESS COMPARISON
DELTA vs. OEM's
CLEANING AND BLASTING

PROCESS OVERVIEW

The purpose of this chart is to illustrate the procedures performed by Delta on a titanium part compared to what is specified by the original equipment manufacturers (OEM's). The blue text indicates differences.

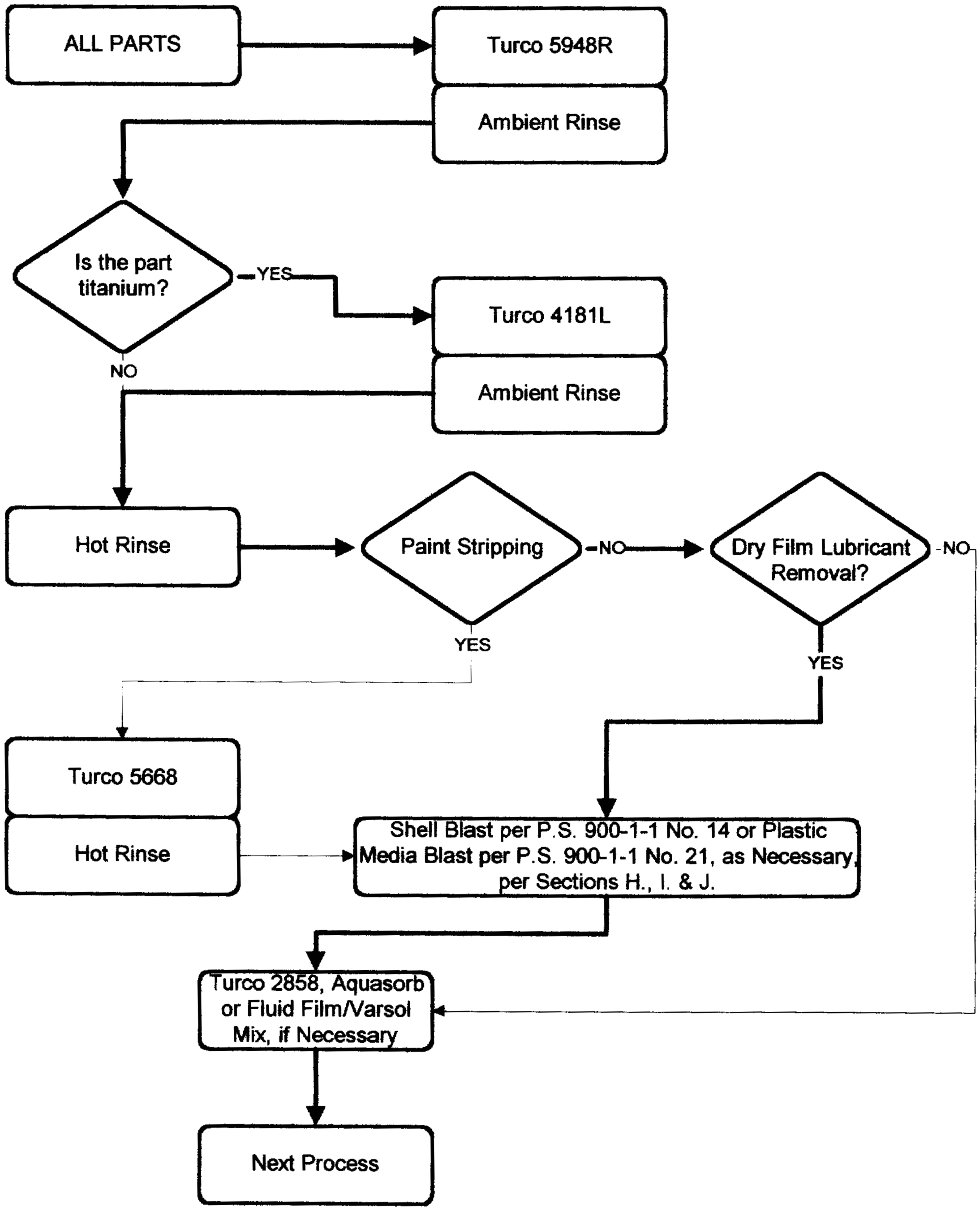
DELTA'S STANDARD HUB/DISK PROCESSING (Titanium)	PRATT & WHITNEY'S PROCEDURES FOR: JT8D-219, Hub, 1st Stage (Titanium)	GENERAL ELECTRIC'S PROCEDURES FOR: Disk, Stage 1, (Ti-6AL-4V) ①	ROLLS ROYCE PROCEDURES FOR: Low Pressure Compressor Disc, (Titanium)
Preclean - P.S. 900-1-1 No. 18, 4.,D.	Preclean - SPOP 209	Preclean - Solvent clean, shop practices, Not Required	Preclean - O.P. 102
Alkaline Clean - P.S. 900-1-1 No. 18, 4., F.	Alkaline Clean - SPOP 18	Alkaline Clean - 70-21-09	Alkaline Clean - O.P. 136, Not Required
Plastic Media Blasting - P.S. 900-1-1 No. 21 - Alternate for Shell.	Plastic Media Blasting - SPOP 19	Plastic Media Blasting - 70-21-04, Not Specified	Plastic Media Blasting - O.P. 104-005
Shell Blasting - P.S. 900-1-1 No. 14 - Alternate for Plastic.	Shell Blasting - SPOP 8, Not Specified	Shells and Rice Hulls - 70-21-04, Not Specified	Fruitstone Blasting - O.P. 104-004

① This disk is sent for outside repair (not associated with the differences identified).

PROCESS COMPARISON
DELTA vs. OEM's
CLEANING AND BLASTING

PARTS PROCESSING FLOW CHART

The purpose of this chart is to illustrate the processing sequence of titanium parts requiring dry film lubricant removal per P.S. 900-1-1 No. 18.



PROCESS COMPARISON
DELTA vs. OEM's
PRECLEANING - AQUEOUS

The charts that follow illustrate the differences between Pratt & Whitney's, General Electric's and Rolls Royce's procedures and Delta's replacement procedures.

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 209		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-22		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 102	
Solution Makeup & Maintenance - Preclean							
Step 4., C., (1)	Mix 5948R Solution one part cleaner to four parts water. (25%)	Oper. 1	Mix 5948DPM per SPS 105, 25% by volume	Step 3., A.	Mix 5948R per S1142, 20%	Step 3. A., (3)	Mix 5948R Solution to 20-40% by volume
	Maintain tank temperature 145-155°F.		Maintain solution to 140-180°F.		Maintain solution to 160-180°F.		Maintain solution to 113-140°F.
	No solution maintenance required. Dump when effectiveness decreases.		Dispose of solution when cleaning can no longer be accomplished within the time specified.		Use procedures recommended by Turco.	Step 3. B.	Maintain solution concentration by titration. Control chloride content by the Volhard method.

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 209		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-22		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 102	
Part(s) Processing - Preclean							
Step	Immerse parts for 5-	Oper.	Immerse parts and let	Step 4.	Immerse parts, allow	Step 6.	Immerse parts for 30

PROCESS COMPARISON
DELTA vs. OEM's
PRECLEANING - AQUEOUS

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 209		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-22		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 102	
Part(s) Processing - Preclean							
4., D., (1)	30 minutes.	1	soak for 5-30 minutes.		to dwell for 15-60 minutes.		minutes.
	Remove parts, drain and spray rinse over tank. Immerse in ambient tank with mild agitation until all soap is removed.		Flush over tank with air-assisted cold water. Immerse in warm water (90 - 100°F)		Remove parts, spray rinse and dip in ambient water.		Remove parts, wash in cold water. Pressure wash with air/water gun.
	If necessary, Scrub part with non-metallic bristle brush and flush with water.		If necessary, Scrub part with a soft non-metallic bristle brush. Flush part with air assisted spray gun.		Not Specified		Not Specified
	If further wet processing is to be accomplished, hot water rinsing can be omitted.		Not Specified		Not Specified		Not Specified
	Immerse in hot water (150-200°F) until part equals the temperature of the		Immerse in hot water (150-200°F) until temperature of the part is at the water		Rinse part by dipping in hot water (140°F or higher)		Immerse parts in clean, hot water at a minimum of 176°F.

PROCESS COMPARISON
DELTA vs. OEM's
PRECLEANING - AQUEOUS

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 209		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-22		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 102	
Part(s) Processing - Preclean							
	water.		temperature to flash dry.				
	Not Specified		Not Specified		Repeat as necessary		Repeat as necessary
	Remove & drain. Use clean, dry compressed air or vacuum to remove trapped water as necessary.		Not Specified		Dry parts with clean dry compressed air or by dwell time in an oven at 140°F minimum.		Dry using a clean, dry, air blast.

PROCESS COMPARISON
DELTA vs. OEM's
CLEANING - ALKALINE

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 18		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-09		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 136	
Solution Makeup & Maintenance - Alkaline Clean							
Step 4., F.	**Mix alkaline solution (4181L) 11-14% by volume. Maintain between 11-14% by titration and additions.**	Oper. 2., b.	Mix per SPS 158-12 (SPMC 116, 4181L) to 12-20% by volume. Maintain by manufacturer's instructions	Step 3., A.	Mix per S1003, (C04-009, 4181) to 12 oz/gal. Maintain between 60-90 g/l by titration and additions.	Step 9. B. (1)	Mix OMAT 173, to 50 g/l. Maintain by manufacturer's instructions.
	Maintain temperature between 180-190°F.		Maintain temperature between 160-170°F.		**Maintain temperature between 180-190°F.**		Maintain temperature between 185-203°F.

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 18		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-09		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 136	
Part(s) Processing - Alkaline Clean							
Step 4., F.	**Immerse parts for 10-15 minutes.**	Oper. 2., b.	Immerse parts between 15-30 minutes.	Step 4.	Immerse parts between 10-20 minutes.	Step 9. B. (1)	Immerse parts for 30 minutes maximum.
	Pressure spray or dip rinse in water.	Oper. 3.	Pressure spray rinse over alkaline solution, Dip in cold water and spray rinse with cold water.		Rinse by immersion in water. Spray rinse with hot water (140°F)	Step 9., C.	Wash parts in cold water and air/water pressure blast.

PROCESS COMPARISON
DELTA vs. OEM's
CLEANING - ALKALINE

DELTA'S PROCESS STANDARD 900-1-1 No. 18		PRATT & WHITNEY'S STANDARD PRACTICE SPOP 18		GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-09		ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 136	
Part(s) Processing - Alkaline Clean							
			water.				
	Not Specified		Not Specified		Rinse by immersion in deionized water, ambient temperature.		Not Specified
	Rinse with hot water rinse (135-200°F)	Oper. 4.	Immerse in hot water (150-200°F) until part is at the water temperature to flash dry.		Not Specified	Step 9., D.	Immerse in hot water (176°F minimum), remove and use clean dry air blast.
	Not Specified		Not Specified		Not Specified	Step 9., E.	Oven dry at 302-392°F for one hour if further processing is not required. Note: may be carried out just prior to NDT.
	Not Specified		Not Specified	Step 5.	Visually inspect for complete removal of oil and dirt.		Not Specified

PROCESS COMPARISON
DELTA vs. OEM's
PLASTIC MEDIA BLASTING

DELTA'S PROCESS STANDARD 900-1-1 No. 21, Plastic	PRATT & WHITNEY'S STANDARD PRACTICE SPOP 19, Plastic	GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-04, Plastic	ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 104, Plastic
Pre-blasting Processes			
Preclean per P.S. 900-1-1 No. 09 or 900-1-1 No. 11 as applicable	Preclean with SPOP 209	Part must be free from oil and grease.	Clean as instructed in Engine Manual to remove grease and dirt.
Mask to prevent media entrapment and coating damage	Mask as necessary to prevent media entrapment, Mask plasma coated air seals.	Mask all surfaces, if required, as indicated in the Engine/Shop manual.	Blank off the areas not to be blasted.
Blasting Parameters			
Nozzle Pressure: 40 psi, pressure type machine	Machine pressure: 30-40 psi	Machine pressure: 25-40 psi	Blast pressure 10-15 psi
Grit Size: 16-20	Grit Size: 12-20	Not Specified	Not Specified
Grit Size: 30-40	Grit Size: 20-40	Grit Size: 20-40	Mesh Size: 30/40
Nozzle distance from part: 6-8 inches.	Nozzle-to-part distance: 3-4 inches.	Nozzle-to-part distance: 4-8 inches.	Nozzle-to-work distance: 4 inches minimum.
Nozzle angle to part: Not specific, just sufficient to sweep across part.	Nozzle angle to part: 45-60°	Nozzle angle to part: 30-80°	Nozzle angle to part: 30-40°
Not Specified	Not Specified	Nozzle diameter: 0.3-0.5 inches	Nozzle diameter: 0.375 inches
Not Specified	Not Specified	Not Specified	Flow rate: 550 g/min at 10 psi and 650 g/min at 15 psi.

PROCESS COMPARISON
DELTA vs. OEM's
PLASTIC MEDIA BLASTING

DELTA'S PROCESS STANDARD 900-1-1 No. 21, Plastic	PRATT & WHITNEY'S STANDARD PRACTICE SPOP 19, Plastic	GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-04, Plastic	ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 104, Plastic
Blasting Process			
Blast parts with Polyplus 30-40 supplied Nonstock, U.S. Technology Corp.	Blast parts with PMC 3300, Polyplus-Blast Type II, 20-40 U.S. Technology Corp.	Blast parts with C04-153 Polyplus 20/40 mesh, supplied by U.S. Technology Corp.	Blast parts with OMAT 1/247 or alternative MIL-P-85891 Type II, 30-40 mesh, U.S. Technology Corp.
Blast parts with Plasti-Grit 30-40 supplied Nonstock, Composition Materials	Not Specified	Not Specified	Not Specified
Blast parts with Polyplus 16-20 supplied under Delta part number (027201493), U.S. Technology Corp.	Blast parts with PMC 3300, Polyplus-Blast Type II, 12-20 U.S. Technology Corp.	Blast parts with C04-153 Polyplus 20/40 mesh, supplied by U.S. Technology Corp.	Not Specified
Blast parts with Plasti-Grit 16-20 supplied under Delta part number (027201493), Composition Materials	Not Specified	Not Specified	Not Specified
Not Specified	Specified Later	Remove Applied Masking.	Specified Later
After Blasting, blow clean with air.	Blow clean with air.	Remove any residue or media using clean, dry air.	Remove all media with clean, dry air blast and or soft brush.
Not Specified	Not Specified	Not Specified	A vacuum cleaner can be used.
Not Specified	If necessary, clean by SPOP	Not Specified	Not Specified

PROCESS COMPARISON
DELTA vs. OEM's
PLASTIC MEDIA BLASTING

DELTA'S PROCESS STANDARD 900-1-1 No. 21, Plastic	PRATT & WHITNEY'S STANDARD PRACTICE SPOP 19, Plastic	GENERAL ELECTRIC'S STANDARD PRACTICE 70-21-04, Plastic	ROLLS ROYCE ENGINE OVERHAUL MANUAL O.P. 104, Plastic
Blasting Process			
	209 and pressure spray rinse with hot water to remove plastic media.		
Not Specified	Remove masking.	Specified Earlier	Remove blanking plugs, masking tape, or mask.
Inspect all part surfaces and cavities to ensure complete removal of media.	Not Specified	Visually check that part(s) has been evenly cleaned and all residues and media have been removed.	Inspect the part to ensure complete removal of abrasive.
Dip part in Aquasorb as required.	Apply corrosion inhibitor with SPOP 5, as necessary.	Not Specified	Dip steel parts in temporary protective coating, O.P. 340 if necessary.

References: Pratt & Whitney's Standard Practice, 70-21-00, SPOP 18, 19 & 209
Rolls Royce's 594J Engine Overhaul Manual, 70-00-00, O.P. 102, 104 & 136
General Electric's Standard Practices, 70-21-00, Method 04, 09, & 22
Delta Air Line's Process Standard Manual, 900-1-1 No. 18 & 21

PROCESS COMPARISON
DELTA vs. OEM's
SHELL BLASTING

This process comparison is included due to shell blasting being accomplished in lieu of plastic media blasting on Roll Royce's fan disc.

DELTA'S PROCESS STANDARD 900-1-1 NO. 14 - Shell Blasting	ROLLS ROYCE'S ENGINE OVERHAUL MANUAL O. P. 104 - Fruitstone Blasting
Pre-blasting Processes	
Preclean per P.S. 900-1-1 No. 09 or 900-1-1 No. 11 as applicable	Clean as instructed in Engine Manual to remove grease and dirt.
Mask to prevent media entrapment and coating damage	Blank off the areas not to be blasted.
Blasting Parameters	
Nozzle Pressure: 60-100 psi, pressure type machine	Not Specified
Nozzle distance from part: 6-8 inches.	Not Specified
Nozzle angle to part: Not specific, just sufficient to sweep across part.	Not Specified
Blasting Process	
Blast parts with Mil-G-5634A Type 1 or 3, "Soft Grit" walnut shells, supplied by Delong Equipment Co.	Blast parts with OMAT 196B, Walnut Shells
Blast parts with Mil-G-5634A Type 1 or 3, "Carboblast" supplied by Turco	Blast parts with OMAT 1/17, Lignocellulose grit, "Carboblast" supplied by Turco.
After Blasting, blow clean with air.	Remove all media with clean, dry air blast and or soft brush.
Not Specified	A vacuum cleaner can be used.
Inspect all part surfaces and cavities to ensure complete removal of media.	Inspect the part to ensure complete removal of abrasive.
Dip part in Aquasorb as required.	Dip steel parts in temporary protective coating, O.P. 340 if necessary.

APPENDIX D

PROCESS COMPARISON
DELTA vs. OEM's
FLUORESCENT PENETRANT INSPECTION

DELTA PROCESS STANDARD 900-6-3 No. 02	PRATT & WHITNEY'S STANDARD PRACTICE 70-33-00; SPOP 82,84	GENERAL ELECTRIC'S STANDARD PRACTICE 70-32-02	ROLLS ROYCE ENGINE OVERHAUL MANUAL 70-00-00; O.P. 210
4. C. Surface Preparation - Clean to a water break free surface	Same	Parts must be thoroughly cleaned prior to inspection.	Adequate pre-cleaning is essential for successful operation of penetrant inspection.
4. D. High & Ultra-High Post-Emulsifiable Penetrant Application - Apply penetrant by immersion, spraying, brushing, flowing, or electrostatic spraying. Allow 15 min. drain time. If not processed within 1 hr. re-wet with penetrant. Max. of 2 hrs. may lapse before water washing. If process is interrupted more than 2 hrs. clean and reprocess part.	Penetrant Application - Same Drain Time - 10 to 60 mins. Rewetting Time - Same Max. Time Before Water Wash - Same. Max. Time Before Reprocessing - Same	Penetrant Application - Same Drain Time - 15 min. Class A&B, 30 min. Class C Re-wetting time - Same Max. time before water wash - Same Max. time before reprocessing - same	Penetrant application - Same Drain time - Not less than 10 min. Rewetting time - Same Max. time before water wash - Same Max. time before reprocessing - Not specified
4. D. (3) Pre- Rinse Penetrant - Coarse water spray 30 psi to 40 psi max., 12 in. from part where possible. One min. max. in one area. Water temp. 50°F to 100°F. Shop air pressure max. 25 psi.	Water Spray - same Distance from part - same Time in one area - same Water temp. - 50°F to 90°F Shop air pressure - same	Water Spray - Same Distance from part - Same Time in one area - Not Specified Water Temp - Ambient Shop air pressure - Same	Water spray or in agitated bath. Distance from part - Same Time in one area - Not specified. Max. Water temp. - 95°F Max. water pressure - 25 psi Shop air pressure - Same

PROCESS COMPARISON
DELTA vs. OEM's
FLUORESCENT PENETRANT INSPECTION

DELTA PROCESS STANDARD 900-6-3 No. 02	PRATT & WHITNEY'S STANDARD PRACTICE 70-33-00; SPOP 82,84	GENERAL ELECTRIC'S STANDARD PRACTICE 70-32-02	ROLLS ROYCE ENGINE OVERHAUL MANUAL 70-00-00; O.P. 210
4. D. (5) Emulsifier Application - Apply by spray or immersion. If immersion, agitate solution. 5% concentration. Rinse with water to stop emulsification. Water spray 30 to 40 psi. 12 inches from part. Maximum rinse time in one area I min. for Class 1 and 1.5 for Class 2. Water temp. 50 ° to 100°F. Shop air pressure max. 25 psi.	Application - same Agitate solution - same Solution concentration - same Water psi - same Maximum rinse time - same Water temp. - 50°F to 90°F Shop air pressure - same	Application - Same Agitate solution - Same Solution concentration - Same Water psi - Same Maximum rinse time - 2 min. Water temp - ambient Shop air pressure - Same	Application - Same Agitate solution - Same Solution concentration - Same Water pressure - 25 psi Maximum rinse time - same Max. Water temp - 95°F Shop air pressure - 25 psi
Drying of parts - Air dry at room temp. or in hot air oven max. temp. 160°F. Don't allow parts to dry any longer than necessary.	Start to dry parts within 30 min. No air dry statement Oven temp. - same Drying limit - 30 min.	No air dry statement Oven temp - Same Length of drying time - Same	Immerse parts in hot water (176 to 194°F), air blast (25 psi), place in oven (140 to 176°F) 20 min. max.
Developer Application - Allow 10 min. for developer to absorb penetrant before inspection. Part must be inspected within 2 hrs.of developing, if not clean it and reprocess. Consider indications found after I hr to be questionable.	Developer absorption time - Same Inspect within 4 hrs. or clean and reprocess. |	Developer absorption time - Same (10 min) Inspection within 4 hrs. or clean and reprocess	Developer absorption time - same Inspection within 3 hrs. or reprocess

PROCESS COMPARISON
DELTA vs. OEM's
FLUORESCENT PENETRANT INSPECTION

DELTA PROCESS STANDARD 900-6-3 No. 02	PRATT & WHITNEY'S STANDARD PRACTICE 70-33-00; SPOP 82,84	GENERAL ELECTRIC'S STANDARD PRACTICE 70-32-02	ROLLS ROYCE ENGINE OVERHAUL MANUAL 70-00-00; O.P. 210
Inspectors eye accustom to darkness - 1 to 3 min. if entering from shop area, up to 5 min. if entering from bright sun.	Start inspection not less than I min. after entering booth.	Eye accustom to darkness not specified	Eye accustom to darkness not specified
Inspect with ultraviolet light	Same	Same	Same
Inspecting questionable indications - Wipe with solvent using cotton swab or fine-hair brush. Do not use solvent containing halogen on titanium. Apply dry developer by dusting or from bulb-type applicator to suspected areas. Inspect under ultraviolet light. Indications that reappear after 5 min. shall be considered valid.	Same	Wipe with cotton swab or absorbent material damp with solvent. Titanium solvent caution - Same Indications that appear after 2 min. shall be considered valid.	Use a cotton bud moistened with solvent wipe the indication, allow to dry. Apply NAD, inspect immediately for repeat indication. Wait 10 min. then reinspect.

PROCESS COMPARISON
DELTA vs. OEM's
FLUORESCENT PENETRANT INSPECTION

DELTA PROCESS STANDARD 900-6-3 No. 02	PRATT & WHITNEY'S STANDARD PRACTICE 70-33-00; SPOP 82,84	GENERAL ELECTRIC'S STANDARD PRACTICE 70-32-02	ROLLS ROYCE ENGINE OVERHAUL MANUAL 70-00-00; O.P. 210
Removal of developers and penetrants - Remove developer by water washing or scrubbing with brush and water. Remove penetrants by cleaning with solvents. For titanium and titanium alloys use only solvents which contain on halogens. Removal of inspection material residues is necessary only if detrimental to subsequent operations or components intended function.	Same	Unless otherwise directed all parts shall be cleaned to remove penetrant and developer after inspection. Titanium solvent caution - Same	Remove all developer using clean, dry air blast.
4. K. Process Control Penetrant test - Fluorescence, brilliance, and color. - Weekly Brightness test for penetrant - Quarterly. Dry Developer - Weekly Emulsifier test - Fluorescence, contamination and concentration. - Weekly Tam Test Panels - Daily TAM 14640 Magnaflux PSM-5 Sherwin P&W P/N 198055	Penetrant test - Same Emulsifier concentration test - monthly Dry developers - each shift TAM Test Panels - each shift	Recommended that a process control check be established to check materials and equipment on a regular basis. Penetrant test - Same TAM Panels - Same Ultraviolet light - Same Dry Developer - Same Emulsifier - Same	Penetrant test for brightness - same Water washable penetrant water content - same Ultraviolet light - monthly Dry developer - same Emulsifier - same TAM Panels - Each shift

PROCESS COMPARISON
DELTA vs. OEM's
FLUORESCENT PENETRANT INSPECTION

DELTA PROCESS STANDARD 900-6-3 No. 02	PRATT & WHITNEY'S STANDARD PRACTICE 70-33-00; SPOP 82,84	GENERAL ELECTRIC'S STANDARD PRACTICE 70-32-02	ROLLS ROYCE ENGINE OVERHAUL MANUAL 70-00-00; O.P. 210
Ultraviolet Light - Weekly Water content of water washable penetrants - Monthly			