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# MD-88 Has Uncontained Engine Failure on Takeoff Roll Following Fan-hub Fracture

***A defect in the fan hub was not detected by blue-etch anodize inspection following manufacture, nor was the resulting fatigue crack detected in a fluorescent penetrant inspection during maintenance at the airline facility.***

*FSF Editorial Staff*

Delta Air Lines Flight 1288, a McDonnell Douglas MD-88 bound from Pensacola, Florida, U.S., to Atlanta, Georgia, U.S., underwent an uncontained engine failure while taking off on July 6, 1996. Debris from the no. 1 (left) engine penetrated the passenger cabin, killing two passengers and seriously injuring another. Cabin crew initiated an evacuation, during which another passenger was seriously injured.

As the MD-88 began its takeoff roll on Runway 17 at Pensacola Regional Airport, the throttles were advancing in the autothrottle mode when the flight crew heard a "loud bang" and passengers and flight attendants in the aft cabin experienced a "concussion or blast-like sensation." The captain, who was the pilot-not-flying, took control and the aircraft was stopped on the runway.

The no. 1 engine had suffered an uncontained failure of its front compressor-fan hub. Seeing no indication of a fire, the captain decided not to order an evacuation. But because electrical power failed for a period following the engine failure, the flight crew was unable to contact flight attendants in the aft cabin; the aft-cabin flight attendants initiated an evacuation, and about 30 passengers left the aircraft using the tailcone and overwing emergency exits.

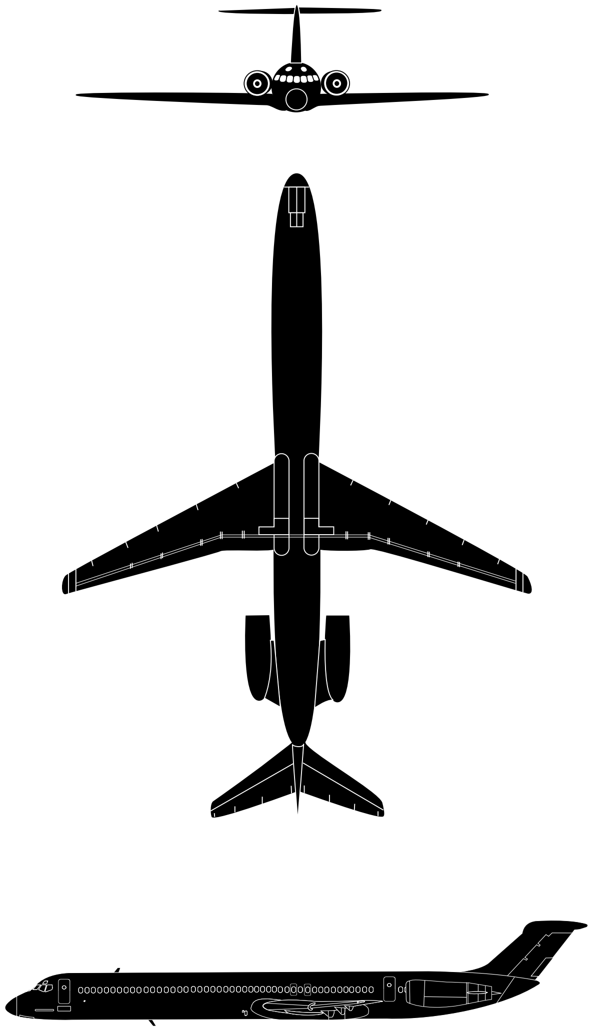
The accident occurred in daylight visual meteorological conditions.

The U.S. National Transportation Safety Board (NTSB), in its final report on the accident, said that the probable cause was "the fracture of the left engine's front compressor-fan hub, which resulted from the failure of the Delta Air Lines' fluorescent penetrant inspection [FPI] process to detect a detectable fatigue crack initiating from an area of altered microstructure that was created during the drilling process by Volvo for Pratt & Whitney and that went undetected at the time of manufacture.

"Contributing to the accident was the lack of sufficient redundancy in the in-service inspection program."

Flight 1288's crew included two pilots and three flight attendants. Two nonrevenue passengers, a Delta pilot and a Delta flight attendant, were aboard, the pilot in the cockpit jumpseat and the flight attendant in the aft-cabin jumpseat.

At 1330 local time, the first officer began a preflight inspection. After the captain arrived at 1345, the first officer told the captain, "There's oil coming out of the bullet [nose of the left



## McDonnell Douglas MD-88

The MD-88 is the fifth in a series that began with the MD-80 in 1979. The MD-88 was certified by the U.S. Federal Aviation Administration (FAA) on Dec. 9, 1987.

The twin-turbofan medium-range airliner combines two Pratt & Whitney JT8D-219 engines with an electronic flight instrumentation system (EFIS), onboard wind-shear detection, computer flight management system and greater use of composite structural materials than its predecessors. Other avionics include color weather radar.

The redesigned cabin interior has five-abreast seating, wider aisles and newly designed overhead bins. The cabin typically seats 142 passengers: 14 in first class and 128 in coach.

The MD-88 has a maximum takeoff weight of 149,500 pounds (67,800 kilograms) and a maximum landing weight of 130,000 pounds (59,000 kilograms). It cruises at Mach 0.76 and has a range of about 3,100 miles (5,000 kilometers) with a full load of fuel.♦

Source: *Jane's All the World's Aircraft*

engine] now." The first officer also informed the captain of two rivets missing on the left wing.

"He and the captain discussed these items in the cockpit … and the captain told the first officer to log the missing rivets in the airplane's logbook," said the report. "The captain told [NTSB] investigators that he and the first officer concluded, based on the amount of oil the first officer reported seeing, that the airplane was airworthy and that he therefore elected to depart without notifying maintenance. The captain told [NTSB] investigators that he based his decision on the first officer's report that the oil was not dripping, stating, 'You know, this was two drops out of 14 quarts.'

"He stated that Delta policy called for captains to determine when maintenance irregularities affecting airworthiness should be reported to maintenance personnel for guidance. Delta did not operate a maintenance facility at Pensacola, but contract maintenance was available."

The engines were started, and the flight crew later said that both engines started normally and that there was no unusual vibration during taxi. Flight 1288 was cleared for takeoff at 1423.

The first officer, who was the pilot flying, moved the throttles and called for the autothrottles to be set when the engine-pressure ratio reached 1.35. The throttles were advancing in autothrottle mode when, at a speed of about 40 knots (74 kilometers per hour [kph]), the no. 1 engine failed.

The report said, "The captain took control of the airplane and retarded both throttles to idle. He applied manual brakes and brought the airplane to a gradual stop on the runway. The captain did not command reverse engine thrust, and the ground spoilers were not deployed. There were no cockpit indications or warnings of fire."

The aircraft stopped, about 1,350 feet (412 meters) down Runway 17, with the left tire of the right-main landing gear near the runway centerline.

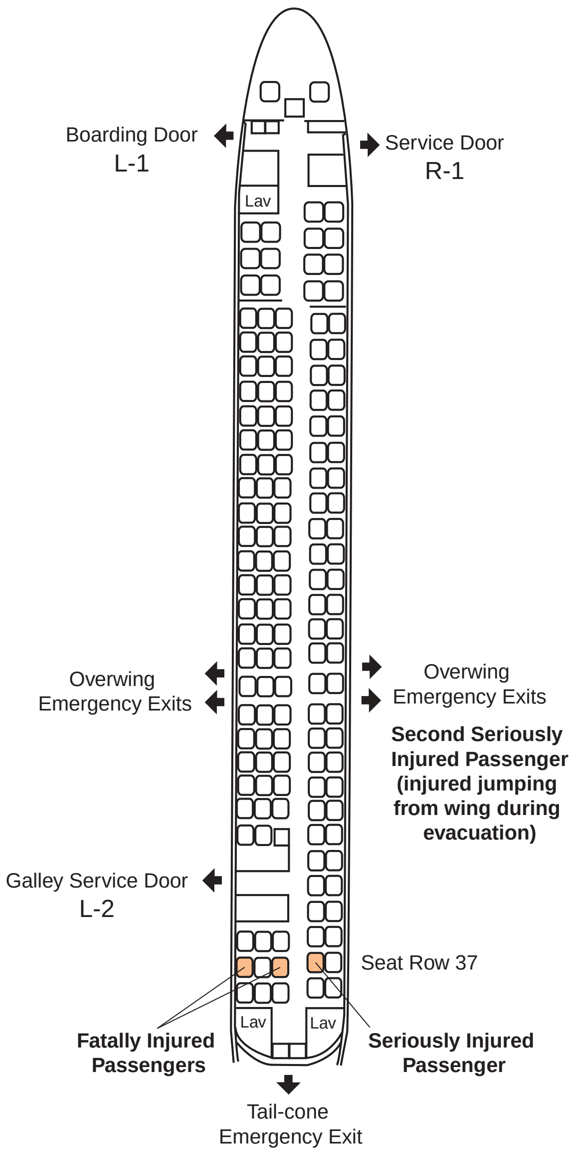
"Engine debris was found on both sides of Runway 17's centerline along the airplane's path," said the report. Several impact gouges were on the runway left of the centerline. The entire left-engine nose inlet cowl was found on the runway 563 feet [172 meters] from the runway threshold. The nose bullet was found on the runway about 20 feet [6.1 meters] to the left of the nose cowl.

"The fan hub and blade assembly were separated from the left engine, and the surrounding engine outer case and cowl were ruptured, with torn and missing sections. The forward part of the stage-1.5 compressor disk was missing. The hub was separated at a 360-degree circumferential fracture located just forward of the stage-1.5 disk bore."

After the MD-88 stopped, the first officer attempted to contact the tower and the flight attendants, but the loss of electrical power had made the radio and cabin interphone inoperative. The flight crew activated emergency power from the aircraft's battery, contacted the tower and declared an emergency at 1425.

The L-1 (left-forward; Figure 1) flight attendant entered the cockpit to ask whether to evacuate the cabin, and the captain said that because there was no cockpit indication of fire, an evacuation should not be initiated. According to witnesses outside the MD-88, fire was visible in the left-engine cowling area for about 20 seconds following the engine failure. When firefighters arrived at 1427 they did not see smoke or fire, although one firefighter reported smelling smoke. NTSB investigators later determined that there was fire damage to the engine from the 6 o'clock position to the 9 o'clock position, as seen from aft looking forward, on the exterior of the cowling.

**MD-88 Passenger Cabin, Delta Air Lines Flight 1288**




Source: U.S. National Transportation Safety Board

**Figure 1**

"The flight attendant used a portable megaphone to tell passengers to remain seated," said the report. "The first officer stated that he made a similar announcement on the public-address system after power was restored and that he again attempted to contact the flight attendants with the interphone but was not successful."

The nonrevenue Delta pilot in the cockpit jumpseat went to inspect the aft cabin, and the captain directed the first officer to inspect the cabin. The first officer discovered that the overwing exit windows had been removed.

The report said, "A male passenger, who was seated in an overwing emergency-exit row (row 26), told [NTSB] investigators that during the takeoff roll he heard a 'pop' and that passengers then began unbuckling their seat belts, running and screaming for him to open the exit. He said that he opened the overwing exit while the airplane was still moving about 30 miles per hour [48 kph] even though he was not certain that this was the proper action to take. He later told investigators that he wished he had been given some guidance for when to open the exit. According to his statement, he stepped out onto the left wing and jumped off the front leading edge after seeing fire coming from the left engine. Other passengers came out of the window exit 'frantically,' and he said he helped people off the wing until they stopped coming."

The first officer immediately returned to the cockpit to notify the captain to shut down the engines. After doing so, the captain radioed the tower that the airplane was shut down on the runway and said, "Be advised we have passengers [standing] on the runway." At 1427, the captain again radioed the tower to request medical assistance and fire-fighting personnel to inspect the airplane exterior for fire.

"The first officer started back toward the aft section of the cabin again, passing the cockpit jumpseat passenger who was returning to the cockpit to brief the captain on the structural damage and injuries to passengers," said the report. "As the first officer moved aft through the cabin, he saw that the aft (tail-cone) exit and left-aft (L-2) door were open. He advised passengers to remain seated and briefly exited the airplane to restrain a passenger who was attempting to jump off the wing, advising her that it was safer to remain on board. The first officer estimated that about half of the passengers had already evacuated the airplane, most of them from seats aft of the wings' leading edges."

*The fan hub and blade assembly of no. 1 engine were separated from the engine in the accident. Debris from the engine penetrated the cabin, killing two passengers and seriously injuring another in the row adjacent to the failed engine.* (Photo: U.S. National Transportation Safety Board)

After hearing the first officer's report of injuries, structural damage to the aircraft and the evacuation, the captain pulled the left-engine fire handle, which shut off fuel and hydraulic-fluid supply to the left-engine pumps and armed the fire extinguisher. The captain and first officer again assessed the situation, and the captain reiterated his instruction to the L-1 flight attendant not to evacuate the aircraft.

"The flight attendants who were in the aft cabin had initially initiated an evacuation (based on the serious airframe damage and passenger injuries) after attempting unsuccessfully to contact the flight crew by interphone," said the report. "The flight attendants in the aft cabin began the evacuation using the tail-cone slide. Three passengers and an infant evacuated using that slide. The L-2 flight attendant then opened the L-2 door and pulled the evacuation slide's manual inflation handle. After pulling the inflation handle, the flight attendant saw fire on the left engine's forward cowling and immediately blocked the exit and redirected passengers forward.

"The L-1 flight attendant told [NTSB] investigators that she saw 'a hole in the aircraft and lots of blood.' She advised the captain that 'we had an emergency situation and possibly two dead.'"

The two passengers seated on the left side of the airplane in the window and aisle seats of row 37, adjacent to the left engine, died from massive head injuries. A passenger seated in row 37 on the aisle on the right side sustained head and other injuries caused by engine debris. Another passenger sustained a fractured ankle when she jumped from the left wing during the evacuation. In total, there were two fatalities, two serious injuries and three minor injuries among the 137 passengers.

At 1427, emergency medical technicians and firefighters arrived at the accident scene, and two minutes later were supplemented by additional emergency personnel

"The first officer and firefighters on the ground disconnected the tail-cone slide (which had earlier been deployed by the aft flight attendants) and lowered the ventral stairs to evacuate the injured," said the report. "A medical-treatment (triage) area was set up along the side of Runway 17, and a landing zone was designated for an emergency-medical-evacuation helicopter that was used to transport the most seriously injured passenger to a local hospital at 1442."

The captain requested portable stairs so that the passengers who had remained aboard could exit.

"The aft left fuselage and interior of the airplane in the vicinity of the no. 1 engine were substantially damaged by debris from the engine," said the report. "A total of 16 holes, punctures or tears were documented on the left fuselage skin." There were seven exit holes, punctures and tears on the right fuselage skin.

"The cabin interior was substantially damaged near seat row 37, next to the left engine," said the report. "Debris from the left engine's fan hub and fan blades had penetrated the left cabin wall and overhead bin vertically from the lower-left passenger window through the overhead bin and ceiling panel. Engine-fan components had also pierced the side and ceiling of the right cabin wall."

The Pratt & Whitney JT8D-219 turbofan engine that had failed was destroyed.

Weather at the time of the accident was: wind, 210 degrees at 12 knots (22 kph); visibility seven miles (11.3 kilometers); temperature 90 degrees Fahrenheit (F) (32 degrees Celsius [C]); and towering cumulus clouds reported in all quadrants. The report said, "Weather was not a factor in the accident."

The captain, the first officer and the three on-duty flight attendants were on the second day of a three-day flight sequence when the accident occurred.

The captain, 40, was hired by Delta in 1979 after flying for a commuter airline. After serving as a flight engineer on the Boeing 727 and as a first officer on the Douglas DC-9, B-727, Boeing 757 and Boeing 767, he transitioned to the MD-88. He held an airline transport pilot (ATP) certificate with multi-engine land rating and was type rated in the DC-9. His U.S. Federal Aviation Administration (FAA) first-class medical certificate included the limitation that he wear corrective lenses for distant vision.

The captain had 12,000 hours of flight time, with 2,300 hours as pilot-in-command (PIC) of the MD-88. A records search found no FAA enforcement actions, accidents, incidents or company disciplinary actions in the captain's work history. He had completed a Delta crew resource management (CRM) course as part of recurrent training in March 1996.

The first officer, 37, had flown Cessna A-37s and Fairchild Republic A-10 Thunderbolts for the U.S. Air Force before being hired by Delta in 1990. After flying as a flight engineer on the B-727 and the Lockheed L-1011, he was upgraded to first officer on the Boeing 737 and transitioned to the MD-88 about a year before the accident. His FAA first-class medical certificate had no limitations.

The first officer had 6,500 hours of flight time, of which 500 hours were in the MD-88. A records search found no FAA enforcement actions, accidents, incidents or company disciplinary actions in the first officer's work history.

The three on-duty flight attendants and the nonrevenue-passenger flight attendant were qualified on the MD-88 and had received Delta initial and recurrent training on emergency-evacuation procedures.

"The flight attendants and flight-crew members had completed joint emergency-procedures training, which included CRM methodology, during their initial and recurrent training at Delta," said the report.

The NTSB accident investigation concentrated on the left-engine compressor-fan hub's manufacture and maintenance.

The titanium-alloy fan hub (Figure 2) was forged by Ladish Co., Milwaukee, Wisconsin, U.S., and finished and inspected for Pratt & Whitney by Volvo Aero Corp., Trollhattan, Sweden, in January 1989.

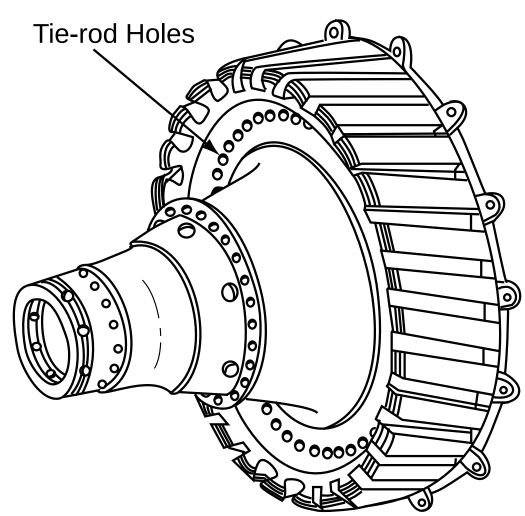
"The hub consisted of a disk forging that held 34 fan blades in dovetail (interlocking-joint) slots," said the report. "The aft end of the hub attached to the stage-1.5 disk with 24 tie rods that passed through 0.5175-inch [1.3-centimeter] diameter tie-rod holes drilled in the hub rim just inside of the dovetail slots. The 2.91-inch [7.4-centimeter] deep tie-rod holes were located around the circumference of the hub bore and alternated with 24 smaller-diameter stress redistribution (SR) holes."

The fan hub had been installed in two other engines prior to the accident engine. It was removed from the previous engine in September 1995 after having accumulated 12,693 cycles. Pratt & Whitney assigned a service life of 20,000 cycles for this type of fan hub, based on extensive material testing.

The hub assembly was subjected to "heavy maintenance" on Oct. 27, 1995, in conformance with Delta's JT8D-219 engine-maintenance-management plan.

"The maintenance included [an FPI] and visual nondestructive testing (NDT), a blade-slot dimensional inspection and

**Pratt & Whitney JT8D-200 Series Engine Fan Hub**




Source: Pratt & Whitney

**Figure 2**

*A flight attendant inflated the evacuation slide at the L-2 position, but saw fire on the no. 1 engine's forward cowling and immediately blocked the exit. Evacuating passengers were then directed forward.* (Photo: U.S. National Transportation Safety Board)

blade-slot shotpeening at Delta's maintenance facility in Atlanta, Georgia," said the report.

[FPI is a method for detecting surface fractures. The report said, "The technique involves applying a penetrant fluid (a low-viscosity penetrating oil containing fluorescent dyes) to the surface after it has been cleaned and allowing it to penetrate into any surface cracks. Excess penetrant is then removed and a 'developer' is applied to act as a blotter and draw the penetrant back out of any surface cracks. This produces a fluorescent indication of cracks or anomalies when viewed under ultraviolet lighting."

[Shotpeening involves firing shot, or hardened balls, onto a metal surface to increase the metal's resistance to fatigue cracking.]

Following the FPI and NDT, the fan-hub assembly was installed on the accident engine on Dec. 29, 1995, and the engine was installed on the accident aircraft on Jan. 1, 1996. The fan hub accumulated a further 1,142 cycles between the installation and the accident. There were no reported anomalies related to the fan hub or engine in the accident aircraft's logbook.

The NTSB subjected the fractured components of the fan hub to metallurgical examination.

"The fan hub had fractured radially in two places," said the report. "One of the radial fractures contained a fatigue crack that originated at two locations on the inboard side of a tie-rod hole. The two origins were located within the tie-rod hole at distances of 0.307 inch [0.78 centimeter] and 0.553 inch [1.4 centimeters] from the aft edge of the hole. Fatigue-fracture features extended a maximum of about 1.5 inches [3.8 centimeters] radially inboard (towards the center of the engine) from the origins.

"About 12,887 fatigue striations were found in the fatigue-fracture region, roughly equivalent to the number of the hub's flight cycles."

The NTSB concluded that, because the number of fatigue striations found in the fatigue-fracture region was about the same as the number of cycles undergone by the fan hub, the fatigue cracks had begun propagating about the time that the hub was first installed in an engine in 1990.

The metallurgical examination also showed an area of the tie-rod-hole wall where the surface was darker than the surrounding area at each fracture origin. Within these darker areas were many small, parallel surface cracks, known as ladder cracks.

"Metallurgical examination of the microstructure underlying the surface of the tie-rod hole (closest to the hole-wall surface) in the [crack-]origin areas determined that the material was severely deformed and hard," said the report. "The location and appearance of the accident hub's altered microstructure indicated that the deformation was formed by a tool used in creating the tie-rod hole."

At the Volvo finishing facility, the 24 tie-rod and SR holes were produced by a computer-controlled coolant-channel drill, bored to enlarge the hole and finished by honing. That type of drill has two internal borings that convey coolant to the drill tip, just behind the cutting edges.

"The coolant served as a lubricant and flushing agent to remove [titanium] chips from the hole," said the report. "Volvo employees stated that the flushing was important because titanium chips can be easily compacted in hole-drill interface areas, and this can cause friction and elevated temperatures in holes."

Volvo conducted test drillings after the accident to attempt to replicate the conditions found in the tie-rod hole on the accident fan hub. Holes were drilled without the normal coolant and at higher revolution and feed speeds to promote drill breakage and metal-chip accumulation in the hole.

The report said, "According to Volvo, the hole with the defect features that most resembled those of the accident hub had a microstructure that was 'heavily deformed' and had a hardness that corresponded 'with the values for the failed hub.' An analysis determined that the layer of deformed microstructure contained ladder-type cracking and 'a high concentration of iron from the drilling operation.'

"Because the high temperature (at least 1,200 degrees F [649 degrees C]) required to form the altered microstructure could not have existed if coolant were flowing freely over the area, the [NTSB] considered the possibility that the coolant-channel drill malfunctioned. However, because a complete cessation of coolant flow over the hub would have been readily noticeable by the drill operator, the loss of coolant to the area of the altered microstructure was more likely caused by a brief obstruction to the coolant reaching that particular area, such as would result from chip packing or broken pieces of a drill bit.

"Therefore, chip packing or wedging, leading to a temporary, localized loss of coolant, most likely contributed to the creation of the altered microstructure. Thus, the [NTSB] concludes that some form of drill breakage or drill breakdown, combined with localized loss of coolant and chip packing, occurred during the drilling process, creating the altered microstructure and ladder cracking in the accident hub."

***"About 12,887 fatigue striations were found in the fatigue-fracture region, roughly equivalent to the number of the hub's flight cycles."***

In February 1988, Pratt & Whitney gave Volvo permission to use a coolant-channel drill, rather than a standard drill that is removed during drilling to remove chips from the hole.

The report said, "This change was approved because Pratt & Whitney's engineering data indicated that changes in drilling operations were 'insignificant' as long as subsequent boring and honing operations were carried out to a depth of at least 0.010 inch [0.25 millimeter] to remove material (including defects) created by the drilling phase. The total depth of material removed from the tie-rod hole after drilling on the accident hub was about 0.0185 inch [0.47 millimeter]. Metallurgical examinations conducted by the [NTSB] after the accident indicated that the total depth of the altered microstructure created by the drill was about 0.024 inch [0.6 millimeter], more than twice the depth anticipated by the 0.010-inch limit set by Pratt & Whitney."

At Volvo, the accident hub had been subjected to the same tests as other completed hubs. The tests consisted of a dimensional inspection, to check the location, concentricity, diameter and perpendicularity of holes; a visual inspection, to check the surface finish; FPI, to check for defects such as cracks, voids or porosity; and a blue-etch anodize (BEA) inspection.

[The report said, "The BEA inspection process, which is unique to titanium, involves a visual inspection of the surface after it is anodized (the part surface is electrochemically oxidized) for anomalies associated with microstructure changes in the metal.

[“The BEA process, which is performed after all machine work is completed, includes three steps: etching in an acid/salt solution to clean the surface, anodizing in a trisodium phosphate solution and etching again in a nitric/hydrofluoric acid solution. The anodizing step produces a dark-blue oxide coating on the part. The etching in the nitric/hydrofluoric acid solution removes some of the blue surface coloration, creating a contrast between anomalies and the normal surface indication (the amount of coloration removed differs between anomalies and the normal surface). Before the accident, Pratt & Whitney provided BEA inspectors with six color pictures of rejectable defects, referred to as templates, to help identify anomalies.”]

Volvo records indicated that during the inspection of the accident fan hub, a BEA inspector noted “manufacturing marks” in the tie-rod hole analyzed by the NTSB after the accident.

“There was no further description in Volvo’s manufacturing records of the accident-hub ‘manufacturing marks’ or where they were located in the hole,” said the report. “Volvo visual-inspection and supervisory personnel subsequently determined that the fan hub met Pratt & Whitney’s manufacturing criteria, and the component was sent to Pratt & Whitney for installation.”

In testimony at the NTSB hearing about the accident, a Volvo fan-hub quality inspector said that the BEA inspector who noted the manufacturing marks intended to alert the visual inspector to the condition.

“According to the Volvo manager, the indication did not match any of the templates used by Volvo to identify anomalies at the time and ‘was not a blue-etch indication,’” said the report. “[It was] an observation he made on the surface.”

***“The [NTSB] recognizes that the BEA inspection process places interpretive demands on inspectors, that identification of rejectable conditions may still not be complete and that templates of defect indications are added when they are encountered and identified.”***

The NTSB concluded that although the anomaly in the accident hub tie-rod hole would have been detectable by BEA inspection, Volvo did not identify the anomaly as grounds for rejection because the appearance of the tie-rod hole did not correspond to any of the templates supplied at that time by Pratt & Whitney.

“The failure of the manufacturer’s BEA inspection to detect and identify a rejectable condition in the accident hub after the drilling process at Volvo resulted in the postaccident development and addition of four new templates to assist in identifying microstructural defects similar to [those on] the accident hub for use by BEA inspectors,” said the report. “The [NTSB] recognizes that the BEA inspection process places interpretive demands on inspectors, that identification of rejectable conditions may still not be complete and that templates of defect indications are added when they are encountered and identified.

“The [NTSB] concludes that although the additional templates will assist BEA inspectors in detecting potential defects similar to the one that existed on the accident hub, this accident suggests that there may be additional rejectable conditions that have not yet been identified.”

The NTSB concluded that the crack on the hub surface adjacent to the tie-rod hole was large enough to have been detected during the fan hub’s FPI inspection at the Delta maintenance facility in October 1995.

The report said, “Postaccident metallurgical examinations conducted by the [NTSB] indicated that based on the striation count, at the time of the last FPI the crack … was about 0.46 inch [1.2 centimeters] long and that this crack extended about 0.90 inch [2.3 centimeters] within the tie-rod hole, for a total surface length of 1.36 inches [3.5 centimeters]. The FAA’s review of FPI processes at Delta concluded that based on reliability data collected by the Nondestructive Testing Information Analysis Center, a visible crack of this size should have been detectable with both a probability of detection and confidence level exceeding 95 percent.”

“Fan-hub FPIs were conducted in accordance with Pratt & Whitney’s *Overhaul Standard Practices Manual* (*OSPM*) inspection procedures and Delta standards, both of which were accepted by the FAA,” said the report.

Following the accident, the NTSB observed the procedures used in a Delta fan-hub FPI. The FPI involved three phases: cleaning, processing and inspection.

The fan hub first went through a series of soakings in solvents and strippers, interspersed by rinsings. For the next step, the *OSPM* stated, “Put part fully in hot water at 150 [degrees F] to 200 degrees F [66 degrees C to 93 degrees C] until the temperature of the part is at the water temperature to flash dry [after the part is removed from the water].”

“Delta’s director of compliance and quality assurance testified at the public hearing that flash drying may not be effective in areas where water is trapped, in areas ‘that you can’t readily see or flaws … ,’” said the report. “[A] witness from a company that provided Delta with chemicals for the FPI process stated that the effectiveness of flash drying depends on the depth of the crack. 'If it's a fairly deep crack … it's doubtful whether you're going to remove that [water] from a fatigue crack,' the chemical company witness stated."

Another witness, the general manager and director of technical services for a company that provided hardware used in FPIs, also discussed flash drying.

The report said, "He noted that after the hot rinse 'we will without fail recommend the use of some dryer, some hot forced-air dryer. … Penetrant is basically an oil. And if there is water in the defect, then the water will repel that penetrant and make it difficult if not impossible for [penetrant] entry to occur.' He added, 'If you've got water in a defect, a lot of it, penetrant won't get in … . And you'll also impede your ability to determine the depth of the crack.'

"Although it could not be conclusively determined whether water trapped in the crack at the time of the FPI rendered the crack undetectable by this method, the [NTSB] is concerned that a number of experienced practitioners in the field believe that such a potential exists when flash drying is the only drying method used. The [NTSB] concludes that significant questions exist about the reliability of flash drying in removing water from cracks."

Following flash drying, the fan hub was subjected to plastic-bead (media) blasting to remove any oil remaining on the hub after the final washing, and then soaked in dye penetrant for about 30 minutes. "The hub was spray-rinsed with water after being removed from the dye vat and then placed in an emulsifier for up to 90 seconds," said the report. "The hub was spray-rinsed again and placed in a drying oven … . After the fan hub was removed from the dryer, dry developer powder was sprayed on using a spray gun."

[Developer powder, or dust, draws the dye from surface cracks or defects, making the defect visible as a fluorescent green indication.]

"The [NTSB] is concerned that when only a spray-gun applicator was used, the powder did not cover the hole walls along the full depth of the hole," said the report. "The [NTSB] is further concerned that even using a more focused application tool, such as a squeeze bulb, the geometry of the hub may be such that full coverage of the hole walls may never be possible. … The [NTSB] concludes that better techniques are needed to ensure the fullest possible coverage of dry developer powder, particularly along hole walls.

"The time between application of the developer and inspection must be controlled to maximize the brilliance of indications (which increases over time), and yet ensure that sufficient dye penetrant remains in the defect for diagnostic activities. Delta inspectors described a method for part tracking in which they coordinated with processors to control the flow of parts so that the time limit [between application of the developer and inspection] would not be exceeded. This informal system would have been vulnerable to error from the difficulty of estimating how long an inspection of the part will take inside the booth, worker distraction and the potential for the loss of collective knowledge during shift turnover.

"Thus, there is no assurance that the accident hub was inspected within the limits set forth in the process standard. Although it could not be conclusively determined whether this played a role in the nondetection of the crack in the accident hub, the [NTSB] concludes that the absence of a system that formally tracks the timing of the movement of parts through the FPI process was a significant deficiency."

[The NTSB noted that after the accident, Delta initiated a formal procedure to track parts and adherence to time requirements. But the board expressed concern that other repair facilities might not have an adequate procedure.]

NTSB investigators observed FPIs by two different inspectors. The report said, "Parts to be inspected were placed on plastic rollers that allowed them to be moved more easily … . Parts were moved by hand."

Hubs were placed on plastic disks, aft side facing down, to insulate them from the rollers. Inspectors lifted and turned the hubs by hand to reach the hubs' aft sides and interiors.

"During these lifting actions, it would have been difficult for personnel to ensure that they were not touching the hub in an area with an indication [of an anomaly], particularly on the aft face," said the report. "FPI experts testified at the public hearing that penetrant could be rubbed off during handling. … The [NTSB] concludes that FPI indications remain vulnerable to manual handling, and fixtures used to support the part during inspection may obstruct inspector access to areas of the part."

[After the accident, Delta began encouraging its FPI inspectors to use support equipment, such as an overhead hoist, for handling hubs.]

"The [NTSB] concludes that one or more procedural deficiencies in the cleaning, drying, processing and handling of the part might have reduced or prevented the effectiveness of Delta's FPI process in revealing the crack," said the report. "The [NTSB] also concludes that the potential deficiencies identified in the Delta FPI process may exist at other maintenance facilities and [may] be, in part, the reason for the failure to detect cracks in other failed engines identified in this investigation."

The NTSB acknowledged that despite the procedural deficiencies that its investigators noted, it was possible that the steps leading up to the visual inspection phase of the FPI for the accident hub had been accomplished well enough for the crack to have been detectable. If that were so, the inspector's failure to detect the problem meant that he did not observe the crack or observed the crack but did not realize its significance.

The NTSB considered the human factors related to inspector performance.

"The inspector who conducted the FPI on the accident hub was in good health, had passed company vision examinations three months before the inspection and had been assigned stable work hours at the time of the inspection," said the report. "The inspector was trained in accordance with company policy, and was qualified to document the results of his inspection on the part's shop traveler [the record-keeping form] without the work being signed off by a supervisory inspector. The FPI shop foreman described the inspector as capable and competent. Therefore, the [NTSB] concludes that no personal or physical factors would have prevented the inspector from detecting a visible crack on the accident hub."

The NTSB investigated other possible reasons that the FPI inspector did not reject the defective fan hub.

"Systematic visual search is difficult and vulnerable to human error," said the report. "Research on visual inspection of airframe components, for example, has demonstrated that cracks above the threshold for detection are missed at times by inspectors because they fail to scan an area of a component.

"Interruption is an inherent part of the FPI process, and the inspector would have interrupted his visual search several times to conduct diagnostic evaluations on detected indications and to reposition the hub. It is possible that the inspector failed to resume his search at the last location examined and that he was not aware of this because of the size and complexity of the part.

"It is also possible that the inspector detected an indication at the location of the crack but forgot to diagnose, or reinspect, the location. If inspectors had a method to document examined areas and locations requiring follow-up diagnosis, the inspector's dependency on memory would be reduced. A system in which an inspector could insert plastic markers into holes that have been inspected and found to be defect-free would serve as a mechanical checklist for the inspector, and document the progress of the inspection across the part."

The NTSB considered whether the inspector's low expectation of discovering a crack in the fan hub had led to decreased vigilance.

"The inspector who inspected the accident hub stated that he could not recall ever having detected a crack on a -219 hub, and the inspector's supervisor stated that he was not aware that cracks had ever been found on a -219 hub at Delta," said the report. "Therefore, the inspector's experience diagnosing indications on -219 hubs consisted of a series of false indications. Although the inspector stated that he approached a part as if it had a crack to detect, his experience with indications on -219 hubs most likely biased his expectation of confirming that an indication was a crack, especially if the indication was not clearly defined."

The inspector of the accident fan hub said that an FPI inspection of a -219 fan hub could require as much as two hours. He described the FPI process as "tedious" and "monotonous."

The report said, "Research on vigilance suggests that performance decreases with increasing inspection time. However, data to support this conclusion in the aviation inspection domain are inconclusive. … No evidence from this investigation exists to evaluate how inspection duration and the adequacy of breaks (the inspector stated he took frequent breaks) affected the inspection of the accident hub.

"The [NTSB] concludes that the duration of inspections and the amount and duration of rest periods may indeed affect inspector performance, but this potential has not been adequately studied in the aviation domain."

The FAA had reviewed Delta's FPI facility in August 1996 and recommended that written and proficiency exams be given during inspector recertification.

"Delta responded to the recommendation by requiring that inspectors pass a written examination on FPI procedural knowledge and receive training to proficiency on a practical examination on a set of 10 sample parts," said the report.

The NTSB agreed with the FAA that more frequent evaluation of inspectors was needed to ensure proficiency, but added that written examinations and practical examinations on a limited number of parts required supplementation.

The report said, "The effectiveness of an inspection involving visual search, like FPI, depends on the inspector's skills in visual search and detection, which cannot be adequately evaluated using written exams and practical tests that do not evaluate the ability of an inspector to detect indications using a sample of representative parts with and without defects.

"The [NTSB] concludes that because of the potentially catastrophic consequences of a missed crack in a critical

***"Systematic visual search is difficult and vulnerable to human error. Research on visual inspection of airframe components, for example, has demonstrated that cracks above the threshold for detection are missed at times by inspectors because they fail to scan an area of a component."***

rotating part, testing methods that evaluate inspector capabilities in visual search and detection and document their sensitivity to detecting defects on representative parts are necessary. Such methods would require an inspector to examine several parts, some containing defects and some without, that are representative of those tested on the line. In addition, the defects provided should range in size from small, at the threshold for the inspection method, to large and well within the method's capabilities."

Despite the concerns that the NTSB raised about Delta's FPI procedures, the board was unable to assign one specific reason for the nondetection of the crack in the accident fan hub.

"The [NTSB] concludes that Delta's nondetection of the crack was caused either by a failure of the cleaning and FPI processing, a failure of the inspector to detect the crack or some combination of these factors," said the report.

Based on both the Delta accident at Pensacola and other accidents investigated by the NTSB that involved failed engine parts, the NTSB said, "Manufacturing and in-service inspection processes currently being used do not provide sufficient redundancy to guarantee that newly manufactured critical rotating titanium engine parts will be put into service defect-free and will remain crack-free through the service life of the part."

The report discussed four safety recommendations issued by the NTSB to the FAA, on July 29, 1996, based on the NTSB's preliminary investigation. The recommendations and the FAA responses were:

- "**A-96-74**. Require that, within 500 cycles of FAA approval of an engine 'on-wing' eddy-current inspection process for Pratt & Whitney JT8D-200 series engine fan-hub tie-rod holes, this inspection be performed on those hubs that have accumulated more than 10,000 cycles since new (CSN); and prioritize the inspections to ensure that the fan hubs most at risk (data suggest those hubs with 10,000 [CSN] to 15,000 CSN) are inspected first. This inspection can be superseded by the redundant inspection urged in safety recommendation A-96-75."

FAA response: The FAA agreed that an eddy-current inspection of the fan-hub tie-rod holes was needed, but said that SR holes should be included as well. The FAA did not believe that an eddy-current inspection could be performed "on-wing" and instead proposed that certain fan hubs considered to be at the greatest risk be removed from engines and subjected to eddy-current inspections and FPI.

*"The [NTSB] concludes that Delta's nondetection of the crack was caused either by a failure of the cleaning and FPI processing, a failure of the inspector to detect the crack or some combination of these factors."*

The FAA reviewed manufacturing records and divided hubs into three risk categories. Category 1, the highest-risk group, consisted of eight hubs that were found, through a search after the Pensacola accident, to have had inspection indications when inspected after manufacture. Category 2, the next-highest risk category, represented 779 fan hubs with tie-rod holes and SR holes created by coolant-channel drills. Category 3, with the lowest risk, included 2,262 fan hubs whose holes had been created by standard drills.

All Category-1 hubs were ordered removed from service by Airworthiness Directive (AD) 96-15-06. Pratt & Whitney Alert Service Bulletin (ASB) A6272 set forth initial inspection and reinspection intervals for Category-2 and Category-3 fan hubs, and the NTSB agreed that repetitive eddy-current inspections and FPI at the intervals specified in ASB A6272 for Category 2 were acceptable in lieu of on-wing inspections. The NTSB classified safety recommendation A-96-74 "Open — Acceptable Alternate Response."

- "**A-96-75.** Require an inspection of all Pratt & Whitney JT8D-200 series engine fan-hub tie-rod and SR holes by means of FPI and eddy current by a fixed number of flight cycles based on the risk of crack propagation from manufacturing flaws."

FAA response: See A-96-74. Because the FAA did not provide for any initial inspection of Category-3 fan hubs, the NTSB classified safety recommendation A-96-75 "Open — Unacceptable Response."

In a March 24, 1997, letter to the NTSB, the FAA said that it had reviewed all fan-hub records and identified as a "new suspect population" any fan hubs with notations about burned drills, marks on tools, broken drill tools, chatter, surface finish or dimensional anomalies. That suspect population included 253 fan hubs, of which 113 were coolant channel–drilled and 140 were standard-drilled. "The FAA has determined that these fan hubs must be inspected with a more aggressive field-management program," said the FAA letter.

Safety recommendations A-96-74 and A-96-75 have been superseded by safety recommendation A-98-19, included in the final accident investigation report and listed in this article among the report's recommendations. Safety recommendations A-96-74 and A-96-75 are now classified by the NTSB as "Closed — Unacceptable Action/Superseded."

- "**A-96-76**. Review and modify the processes as necessary by which Volvo and Pratt & Whitney permitted JT8D-200 series fan hubs to be placed in airline service following indications of mechanical damage in the tie-rod holes based on the [BEA] inspection."

FAA response: In a Feb. 27, 1997, letter to the FAA, the NTSB said, "The [NTSB] notes that the 'standard masters' [templates] that [further broaden rejectable BEA] conditions … are being revised for disks, hubs, couplings, blade retainers, rotating air seals and rotating spacers. Also, Pratt & Whitney is expanding the Materials Control Laboratory Manual to include photographs as examples of abusive machining. Finally, fan hubs currently in production are inspected to the new standard. Because the FAA's actions are responsive to the intent of the recommendation, the [NTSB] classifies safety recommendation A-96-76 'Closed — Acceptable Action.'"

- "**A-96-77**. Review and advise, in conjunction with the engine manufacturers and air carriers, the procedures, training (including syllabi and visual aids) and supervision provided to inspectors for performing FPI and other nondestructive testing of high-energy rotating engine parts, with particular emphasis on the JT8D-200 series tie-rod and SR holes."

FAA response: The report said, "Pending review of final FAA action, the [NTSB], in its February 1997 letter, classified safety recommendation A-96-77 'Open — Acceptable Response' after the FAA stated that it had 'conducted an inspection review of the Delta Air Lines facility … and is satisfied that Delta Air Lines has the proper guidance for training and qualifying personnel in nondestructive testing methods and the performance of FPI.' The FAA also stated, 'Additionally, the FAA is developing a six-month action plan to conduct an evaluation of other facilities that do FPI and other nondestructive testing of high-energy rotating parts.' Based on the FAA's March 1997 letter, the [NTSB] continues to classify safety recommendation A-96-77 'Open — Acceptable Response.'"

The NTSB examined the actions of the crewmembers in the accident.

The first officer had reported, following the preflight inspection, "two or three drops" of oil on the nose bullet and two missing rivets on the left wing. The captain had decided to depart without notifying Delta Air Lines maintenance.

"The oil that was found on the bullet nose could not have been related to the hub failure, and the missing rivets were from an outboard section of the wing," said the report. "Therefore, the [NTSB] concludes that these were not factors in the subsequent engine failure.

"However, the [NTSB] is concerned that the flight crew did not request maintenance action before departure from Pensacola and that flight crews may generally be reluctant to request maintenance at airports without company maintenance facilities because the reporting process and arranging for contract maintenance may result in delays.

"In this instance, the captain's deferral of a maintenance check of the oil leak until after arrival in Atlanta and his failure to ensure that maintenance action was taken on the missing rivets appear to have been contrary to guidance contained in Delta's FOM [flight operations manual], which required flight crews to notify Delta maintenance personnel of maintenance irregularities, or fluid leaks, at the gate. However, the flight crew's decision was later supported by Delta management. This suggests that Delta management does not agree that fluid drops on the bullet nose or two missing rivets constitute maintenance irregularities.

***" …The [NTSB] is concerned that the flight crew did not request maintenance action before departure from Pensacola and that flight crews may generally be reluctant to request maintenance at airports without company maintenance facilities because the reporting process and arranging for contract maintenance may result in delays."***

"Thus, the [NTSB] concludes that there is a lack of clarity in written guidance in the FOM to Delta flight crews on what constitutes maintenance 'discrepancies' and 'irregularities' and when to contact maintenance personnel and to log anomalies."

Although there were fatalities and injuries in the aft cabin and passengers were evacuating following the fan-hub failure, the captain did not immediately shut down the engines. The NTSB said that the captain's actions were correct based on the knowledge he had at the time.

"The interphone system was inoperative at the critical moment when decisions were being made by the aft flight attendants to evacuate and by the captain not to evacuate," said the report. "Thus, neither of these decisions, nor the information on which they were based, could be immediately communicated to crewmembers at the opposite end of the airplane.

"The [NTSB] concludes that neither the aft flight attendants' decision to evacuate nor the captain's decision not to evacuate was improper in the light of the information each of them had available at the time. However, the [NTSB] is troubled by the lack of communication among crewmembers in the front and back of the airplane."

The NTSB said that every airliner operating under U.S. Federal Aviation Regulations (FARs) should have a reliable means of communicating an evacuation decision to all crewmembers.

"The [NTSB] believes that the FAA should require that all newly manufactured passenger-carrying airplanes … be equipped with independently powered evacuation-alarm systems operable from each crewmember station. The FAA should also require carriers operating airplanes so equipped to establish procedures, and provide training to flight and cabin crews, regarding the use of such systems."

The NTSB expressed concern that emergency exits had been opened without the knowledge of the flight crew.

"It is important for cockpit crews to know that exits have been opened for any reason, so that appropriate measures can be taken to minimize the resulting … hazards to passengers who may be departing the airplane through those exits," said the report. "The [NTSB] is aware that some airplanes, including the MD-88, are equipped with cockpit indicators showing open exits, but the [NTSB] concludes that safety could be enhanced if all cockpit crews were immediately made aware of when exits are opened during an emergency. … The FAA should require that all newly manufactured airplanes be equipped with cockpit indicators showing open exits, including overwing-exit hatches, and that these cockpit indicators be connected to emergency power circuits."

The NTSB discussed passenger-instruction issues related to the passenger who had opened an emergency exit while the MD-88 was still moving.

The report said, "The [Delta MD-88 passenger-information card] illustrates how to open the exits, and states that persons seated in emergency-exit seats must be able to 'assess whether opening the emergency exit will increase the hazards to which passengers may be exposed.' However, the card does not specifically state when the exit should be opened or describe the conditions under which doing so might increase the hazards to which passengers might be exposed. Nor does the card state that the exit should not be opened until the airplane has come to a stop."

The NTSB conclusions included the following findings:

- "The flight crew was properly certified and trained for the flight, and was in compliance with federal flight and duty-time regulations;
- "The airplane was properly certificated and maintained in accordance with applicable federal regulations, including an [FAA]-approved airworthiness maintenance program;
- "Visual meteorological conditions prevailed, and weather was not a factor in the accident;
- "The oil observed preflight by the first officer came from the no. 1 bearing housing and, therefore, was not a precursor to the accident;
- "Some form of drill breakage or drill breakdown, combined with localized loss of coolant and chip packing, occurred during the drilling process, creating the altered microstructure and ladder cracking in the accident fan hub;
- "Fatigue cracks initiated from the ladder cracking in the tie-rod hole and began propagating almost immediately after the hub was put into service in 1990;

***"Although the altered microstructure in the accident-hub tie-rod hole was detectable by BEA inspection methods, Volvo did not identify it as rejectable because the appearance of the tie-rod hole did not match any of the existing inspection templates showing rejectable conditions."***

- "Although the altered microstructure in the accident-hub tie-rod hole was detectable by BEA inspection methods, Volvo did not identify it as rejectable because the appearance of the tie-rod hole did not match any of the existing inspection templates showing rejectable conditions;
- "Although the additional templates will assist BEA inspectors in detecting potential defects similar to the one that existed on the accident hub, this accident suggests that there may be additional rejectable conditions that have not yet been identified;
- "Drilling damage in this accident hub extended much deeper into hole sidewall material than previously anticipated by Pratt & Whitney;
- "The crack was large enough to have been detectable during the accident hub's last FPI at Delta;
- "Significant questions exist about the reliability of flash drying in removing water from cracks;
- "Better techniques are needed to ensure the fullest possible coverage of dry developer powder, particularly along hole walls;
- "Although it could not be conclusively determined whether this played a role in the nondetection of the crack in the accident hub, the absence of a system that formally tracks the timing of the movement of parts through the FPI process was a significant deficiency;
- "FPI indications remain vulnerable to manual handling, and fixtures used to support the part during inspection may obstruct inspector access to areas of the part;

- “One or more procedural deficiencies in the cleaning, drying, processing and handling of the part might have reduced or prevented the effectiveness of Delta’s FPI process in revealing the crack;

- “The potential deficiencies identified in the Delta FPI process may exist at other maintenance facilities and [may] be, in part, the reason for the failure to detect cracks in other failed engines identified in this investigation;

- “No personal or physical factors would have prevented the FPI inspector from detecting a visible crack in the accident hub;

- “An inadvertent failure of the inspector to systematically search and complete follow-up diagnosis when necessary on all surfaces of the hub might have caused the FPI inspector to overlook the crack;

- “A low expectation of finding a crack in a -219 series fan hub might have caused the FPI inspector to overlook or minimize the significance of an indication;

- “The duration of inspections and the amount and duration of rest periods may indeed affect inspector performance, but this potential has not been adequately studied in the aviation domain;

- “Because of the potentially catastrophic consequences of a missed crack in a critical rotating part, testing methods that evaluate inspector capabilities in visual search and detection, and document their sensitivity to detecting defects on representative parts are necessary;

- “Delta’s nondetection of the crack was caused either by a failure of the cleaning and FPI processing, a failure of the inspector to detect the crack, or some combination of these factors;

- “Manufacturing and in-service inspection processes currently being used do not provide sufficient redundancy to guarantee that newly manufactured critical rotating titanium engine parts will be put into service defect-free and will remain crack-free through the service life of the part. Further, all critical rotating titanium engine components are susceptible to manufacturing flaws and resulting cracking and uncontained engine failures that could potentially lead to catastrophic accidents;

***“Because of the potentially catastrophic consequences of a missed crack in a critical rotating part, testing methods that evaluate inspector capabilities in visual search and detection, and document their sensitivity to detecting defects on representative parts are necessary.”***

- “Although during the preflight inspection the first officer found a small amount of oil on the bullet nose of the left engine and two missing rivets, these were not factors in the subsequent engine failure;

- “There is a lack of clarity in written guidance in the flight operations manual to Delta flight crews on what constitutes maintenance ‘discrepancies’ and ‘irregularities’ and when to contact maintenance personnel and to log anomalies;

- “The captain shut down the engines in a timely manner when he became aware of conditions in the aft cabin;

- “Neither the aft flight attendants’ decision to evacuate nor the captain’s decision not to evacuate was improper in light of the information each of them had available at the time;

- “Every passenger-carrying airplane operating under [FARs] Part 121 should have a reliable means to ensure that all crewmembers on board the airplane are immediately made aware of a decision to initiate an evacuation;

- “Safety could be enhanced if all cockpit crews were immediately made aware of when exits are opened during an emergency; [and,]

- “Guidance provided to passengers on Delta Air Lines MD-88s regarding when emergency exits should and should not be opened is not sufficiently specific.”

The NTSB made the following recommendations to the FAA:

- “Form a task force to evaluate the limitations of the BEA and other postmanufacturing etch processes, and develop ways to improve the likelihood that abnormal microstructure will be detected (A-98-09);

- “Inform all manufacturers of titanium rotating engine components of the potential that current boring and honing specifications may not be sufficient to remove potential defects from holes and ask them to re-evaluate their manufacturing specifications and procedures with this in mind (A-98-10);

- “Establish and require adherence to a uniform set of standards for materials and procedures used in the cleaning, drying, processing and handling of parts in the

FPI process. In establishing those standards, the FAA should do the following:

- "Review the efficacy of drying procedures for aqueously cleaned rotating engine parts being prepared for FPI (A-98-11);
- "Determine whether flash drying alone is a sufficiently reliable method (A-98-12);
- "Address the need to ensure the fullest possible coverage of dry developer powder, particularly along hole walls (A-98-13);
- "Address the need for a formal system to track and control development times (A-98-14); and,
- "Address the need for fixtures that minimize manual handling of the part without visually masking large surfaces of the part (A-98-15);

- "Require the development of methods for inspectors to note on the part, or otherwise document during a nondestructive inspection, the portions of a critical rotating part that have already been inspected and received diagnostic follow-up to ensure the complete inspection of the part (A-98-16);
- "Conduct research to determine the optimum amount of time an inspector can perform nondestructive-testing inspections before human-performance decrements can be expected (A-98-17);
- "In conjunction with industry and human-factors experts, develop test methods that can evaluate inspector skill in visual search and detection across a representative range of test pieces, and ensure [that] proficiency examinations incorporate these methods and are administered during initial and recurrent training for inspectors working on critical rotating parts (A-98-18);
- "Require that all heavy rotating titanium engine components (including the JT8D-200 series fan hubs) receive appropriate nondestructive testing inspections (multiple inspections, if needed) based on probability-of-detection data at intervals in the component's service life, such that if a crack exists, but is not detected during the first inspection, it will receive a second inspection before it can propagate to failure; assuming that a crack may begin to propagate immediately after being put into service, as it did in the July 6, 1996, accident at Pensacola, Florida, and in the July 19, 1989, United Airlines accident at Sioux City, Iowa [U.S.] (A-98-19)";

[In the Sioux City accident, there was a catastrophic failure of the no. 2 tail-mounted engine of a DC-10-10 during cruise flight. The discharge of fan-rotor assembly parts ruptured three hydraulic systems, leaving most flight controls inoperable. The flight crew was able to maneuver the airplane to the Sioux City airport. During the landing, the airplane cartwheeled and broke apart. One crewmember and 111 passengers were killed in the accident; 10 crewmembers and 174 passengers survived.]

- "Require, as an interim measure, pending implementation of safety recommendation A-98-19, that critical rotating titanium engine components that have been in service for at least two years receive an FPI, eddy-current and ultrasonic inspection of the high-stress areas at the engine's next shop visit or within two years from the date of this recommendation, whichever occurs first (A-98-20);
- "Require Delta Air Lines to review its operational procedures, with special emphasis on nonmaintenance stations, to ensure that flight crews have adequate guidance about what constitutes a maintenance irregularity or discrepancy (including the presence of fluid drops in unusual locations) before departure, and that following this review Delta should, contingent on FAA approval, amend its flight operations manual to clarify under what circumstances flight crews can, if at all, make independent determinations to depart when maintenance irregularities are noted. Further, the FAA should have its principal operations inspectors review these policies and procedures at their respective operators to clarify, if necessary, these flight-crew responsibilities (A-98-21);
- "Require that all newly manufactured passenger-carrying airplanes operated under [FARs] Part 121 be equipped with independently powered evacuation-alarm systems operable from each crewmember station, and establish procedures and provide training to flight [crews] and cabin crews regarding the use of such systems (A-98-22); [and,]
- "Require that all newly manufactured airplanes be equipped with cockpit indicators showing open exits, including overwing exit hatches, and that these cockpit indicators be connected to emergency-power circuits."♦

Editorial note: This article was based on the U.S. National Transportation Safety Board publication, *Uncontained Engine Failure, Delta Air Lines Flight 1288, McDonnell Douglas MD-88, N927DA, Pensacola, Florida, July 6, 1996*. Report no. NTSB/AAR-98/01, January 1988. The 129-page report contains figures, photographs and appendixes.

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