National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: February 26, 1998

In reply refer to: A-98-9 through -23

Honorable Jane F. Garvey
Administrator
Federal Aviation Administration
Washington, D.C. 20591

On July 6, 1996, at 1424 central daylight time, a McDonnell Douglas MD-88, N927DA, operated by Delta Air Lines Inc., as flight 1288, experienced an engine failure during the initial part of its takeoff roll on runway 17 at Pensacola Regional Airport (PNS) in Pensacola, Florida. Uncontained engine debris from the front compressor front hub (fan hub) of the No. 1 (left) engine penetrated the left aft fuselage. Two passengers were killed, and two others were seriously injured. The takeoff was rejected, and the airplane was stopped on the runway. The airplane, operated by Delta as a scheduled domestic passenger flight under provisions of Title 14 Code of Federal Regulations (CFR) Part 121, with 137 passengers and 5 crew on board, was destined for Hartsfield Atlanta International Airport in Atlanta, Georgia. The JT8D-219 engine was manufactured by Pratt & Whitney. The fan hub was machined, finished, and inspected for Pratt & Whitney by Volvo Aero Corporation in Trollhattan, Sweden, in January 1989. It had accumulated 13,835 cycles at the time of the accident. The service life, or "safe life," of this fan hub was 20,000 cycles.

The National Transportation Safety Board determined that the probable cause of this accident was the fracture of the left engine's front compressor fan hub, which resulted from the failure of Delta Air Lines' fluorescent penetrant inspection (FPI)[1] 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.

[1]FPI is an inspection technique for checking part and component surfaces for cracks or anomalies. The technique involves applying a penetrant fluid (a low viscosity penetrating oil containing fluorescent dyes) to the surface after the part 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.

Contributing to the accident was the lack of sufficient redundancy in the in-service inspection program.[2]

Fan Hub Fracture

The investigation revealed that the left engine fan hub fractured radially in two places within a tierod hole[3] early in the takeoff roll when the airplane was at low speed during normal operation. Metallurgical examination of the microstructure underlying the surface of the tierod hole (closest to the hole wall surface) in the origin areas determined that the material was severely deformed and hard. The appearance of the microstructure suggested high frictional heat. Laboratory analysis indicated that the microstructure contained an oxygen-stabilized layer of recrystallized alpha grains[4] adjacent to the surface of the tierod hole. This indicated that the temperature at the surface of the hole in the damaged area had reached at least 1,200°F, the minimum recrystallization temperature for titanium. Iron was also found in this layer of altered microstructure, both widely dispersed and in a high concentration within small isolated bands.

Although stabilized alpha is often associated with an inclusion in the titanium alloy created during the melting or forging process, it can also be formed during machining operations when tools overheat titanium alloy in the presence of air. The location and appearance of the accident hub's altered microstructure indicated that the deformation was formed by a tool used in creating the tierod hole.

Volvo test drillings conducted after the accident produced altered microstructure in two holes, one of which contained features very similar to the accident hub. Test drilling was conducted using a coolant channel drill,[5] but without coolant and at higher drill revolution and feed speeds to promote tool (drill) breakage and the accumulation of chips in the hole. According to Volvo's report, altered microstructure "can be created during rough [initial] drilling, but not during subsequent boring and honing operations."

According to Volvo, the hole with defect features that most resembled those of the accident hub had a microstructure that was "heavily deformed" and that had a hardness that corresponded "with the values for the failed hub." An analysis determined that the layer of

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[2] National Transportation Safety Board. 1998. *Uncontained Engine Failure, Delta Air Lines Flight 1288, McDonnell Douglas MD-88, N927DA, Pensacola, Florida July 6, 1996.* Aircraft Accident Report NTSB/ AAR-98-01. Washington, D.C.

[3] The aft end of the fan hub attached to the stage 1.5 disk with 24 tierods that passed through tierod holes drilled in the hub rim.

[4] Recrystallization is a formation of a new grain structure from the structure of the deformed metal.

[5] A coolant channel drill has two internal borings that bring coolant/lubricant to the tip of the drill just behind the cutting lips.

deformed microstructure contained ladder type cracking and "a high concentration of iron from the drilling operation."[6]

Because the high temperature (at least 1,200°F) required to form the altered microstructure could not have existed if coolant were flowing freely over the area, the Safety Board 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 Safety Board 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. Based on the number of fatigue striations found in the fatigue fracture region, which was roughly equivalent to the number of the hub's flight cycles, the Safety Board further concludes that the fatigue cracks initiated from the ladder cracking in the tierod hole and began propagating almost immediately after the hub was put into service in 1990.

Analysis of Volvo's Inspection Procedures

A blue etch anodize (BEA)[7] test conducted by the Safety Board on the sectioned accident hub revealed a dark blue indication in the areas of the altered microstructure. However, the accident hub passed BEA and visual inspections at Volvo following the drilling process that created the anomalous microstructure. Although the BEA inspector at Volvo noted on a shop traveler[8] that he observed "manufacturing marks" inside a hole, at a subsequent visual inspection inspectors determined that all the holes conformed to Pratt & Whitney acceptance criteria for surface finish on bolt holes. Postaccident metallurgical analysis confirmed that the surface finish in those areas of the tierod hole was consistent with the surface finish requirements specified by Pratt & Whitney. The Safety Board's examination determined that there was no evidence of excessive machining marks at the surface of the hole. It could not be determined whether the BEA inspector made the notation of "manufacturing marks" because of the different surface finish in the tierod hole (boring marks surrounded by honing marks), because of a different coloration resulting from the BEA inspection process, or for some other reason.

The Volvo manager who testified during the Safety Board's public hearing stated that the notation by the BEA inspector of "manufacturing marks" in the hole did not signify that the

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[6]Drill breakdown, for example, could cause minute parts of the drill to shear off during the drilling process.

[7]The BEA inspection process is unique to titanium and involves a visual inspection of the surface after it is anodized (the part surface is electro-chemically oxidized) for anomalies associated with microstructure changes in the metal.

[8]A shop traveler is a process sheet or record that documents inspections or tasks performed on a component.

inspector had observed a BEA discrepancy based on the BEA defect templates in use at the time, and he stated that this notation was only intended to alert inspectors conducting subsequent visual inspections with different inspection criteria. Thus, the Safety Board concludes that although the altered microstructure in the accident hub tierod hole was detectable by BEA inspection methods, Volvo did not identify it as rejectable because the appearance of the tierod hole did not match any of the existing inspection templates showing rejectable conditions.

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 of and addition of four new templates to assist in identifying microstructural defects similar to the accident hub for use by BEA inspectors. The Safety Board 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 Safety Board 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 Safety Board is concerned that these problems may not be unique to parts manufactured by Pratt & Whitney. Therefore, the Safety Board believes that the FAA should 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. In so doing, it may be appropriate to consider whether any part of these processes can be automated, so as to minimize the possibility of human error.

When Pratt & Whitney approved Volvo's request to use a coolant channel drill, 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 .010 inch to remove material (including defects) created by the drilling phase. The total depth of material removed from the tierod hole after drilling on the accident hub was about .0185 inch. Metallurgical examinations conducted by the Safety Board after the accident indicated that the total depth of the altered microstructure created by the drill was about .024 inch, more than twice the depth anticipated by the .010-inch limit set by Pratt & Whitney. The Safety Board concludes that drilling damage in this accident hub extended much deeper into hole sidewall material than the depth previously anticipated by Pratt & Whitney. Thus, the Safety Board believes that the FAA should 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 reevaluate their manufacturing specifications and procedures with this in mind.

Failure of Delta Maintenance to Detect Cracking in the Accident Hub

On October 27, 1995, Delta's maintenance facility in Atlanta, Georgia, performed an FPI on the accident hub. This inspection, conducted 1,142 cycles before the accident, was part of overhaul work recommended in Pratt & Whitney's engine shop manual for hubs disassembled from engines before reaching their "safe life" limits.

Postaccident metallurgical examinations conducted by the Safety Board indicated that based on the striation count, at the time of the last FPI, the crack on the aft hub surface adjacent to the tierod hole was about 0.46 inch long and that this crack extended about 0.90 inch within the tierod hole, for a total surface length of 1.36 inches. The FAA's review of FPI processes at Delta concluded that based on reliability data collected by the Nondestructive Testing Information Analysis Center (NTIAC), a visible crack of this size should have been detectable with both a probability of detection and confidence level exceeding 95 percent. The crack was well above the minimum detection length of 0.10 inch as calculated by the NTIAC's Nondestructive Evaluation Capabilities Data Book,[9] and the 0.08-inch and 0.10-inch range suggested in the FAA's December 14, 1990, Titanium Rotating Components Review Team (TRCRT) report. Therefore, the Safety Board concludes that the crack was large enough to have been detectable during the accident hub's last FPI at Delta.

The Safety Board considered the possibility that the crack was not visible during the FPI at Delta. The Safety Board's investigation found that there are a number of ways in which the effectiveness of the FPI process could have been compromised by improperly performed or inadequate procedures. The Safety Board also considered the possibility that the crack was visible at the time of the FPI, but that the FPI inspector either overlooked it or discounted it as insignificant.

Part Cleaning, Drying, Processing, and Handling

The FAA's postaccident report of an August 1996 inspection of the FPI process used by Delta indicated that there was no assurance that parts received by FPI operators were "clean enough for an adequate FPI." The FAA report also noted that cleaning personnel were not made aware of the "criticality of the engine components and the end purpose for which these components were being cleaned." The inspector who inspected the accident hub indicated that he frequently had to send parts back for additional cleaning. The Safety Board recognizes that following the FAA's technical review of Delta's FPI process, Delta indicated that it was providing cleaning personnel with training to emphasize different cleaning procedures for critical parts, especially those being prepared for FPI, and that it was working with engine manufacturers to develop cleaning standards for specific parts. However, the Safety Board is concerned that similar shortcomings may exist at other maintenance facilities performing FPIs.

At the conclusion of the cleaning process in preparation for an FPI at Delta, parts were immersed in a "hot water rinse" and flash dried. Because the dye penetrant applied later in the process has an oil base, any water remaining in cracks would block entry of the dye into those areas. For the flash drying process to be effective, the part must be heated to the temperature of the water, which must be kept at a temperature of between 150° and 200°F, according to Pratt & Whitney's Overhaul Standard Practices Manual and Delta's Process Standard. A temperature measuring device was not used to determine whether parts had reached the temperature of the water. Rather, according to a Delta representative, operators determined that parts had reached

[9] See "Nondestructive Evaluation Capabilities Data Book," published by the NTIAC, Texas Research Institute Austin, Inc. DB-95-02, May 1996.

the proper temperature by "feel" and that the water temperature was checked on a weekly basis. After the accident and the FAA inspection, Delta implemented changes requiring more frequent checks of the water temperature.

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...." A representative of a company that produces FPI hardware and chemicals testified that "it's absolutely imperative that the parts come to the process clean and dry." Another 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. 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 Safety Board 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 Safety Board concludes that significant questions exist about the reliability of flash drying in removing water from cracks.

With regard to the processing of parts after drying, specifically, the application of developer powder, the Safety Board 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. The Safety Board 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 hole walls may never be possible. Although in this case that deficiency would not have prevented detection of the crack (because there was also a sizable crack on the aft face of the hub), under other circumstances this incomplete coverage may result in nondetection of an otherwise detectable crack. Therefore, the Safety Board concludes that better techniques are needed to ensure the fullest possible coverage of dry developer powder, particularly along hole walls.

Safety Board observers also found that Delta had no formal logging procedure to identify parts ready for inspection (inspection must occur within 2 hours of the application of the developer powder and indications found after 1 hour are considered questionable). Delta representatives indicated that shop personnel relied on a "group knowledge" of how long a part had been ready for inspection.

The time between application of the developer and inspection must be controlled to maximize the brilliance of indications (which increases over time), 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 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, it could not have been possible for Delta personnel to consistently adhere to the development time requirements using this system or to know exactly how long a part had been ready for inspection. The Safety Board is concerned that Delta had timing requirements in its process standard but failed to provide its personnel with a way to adhere to them. 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 Safety Board 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 Safety Board notes that after the accident, Delta implemented a procedure to record part development times on a status board that formalizes part tracking and adherence to time requirements. However, the Safety Board is concerned that other operators and repair stations may not have adequate methods to positively identify the status of parts processed for FPIs.

During the FPI process at Delta, hubs are placed aft-side down on a plastic disk to keep them from contacting the rollers on the FPI line during inspection. Processors and inspectors used their hands to lift and turn the hub on the plastic disk to gain access to the aft-side and interior. 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, particularly on the aft-face. FPI experts testified at the public hearing that penetrant could be rubbed off during handling. If penetrant was prevented (by dirt or water) from fully entering the crack, then rubbing off the surface penetrant would probably have removed any indication of the crack. But even if penetrant was in the crack, loss or distortion of penetrant at the surface could have resulted in an ill-defined indication, thus making the crack more difficult to detect. Although the extent to which it contributed to the nondetection of the crack could not be determined, the manual handling of the hub at Delta during the processing and inspection of the accident hub increased the opportunity for smearing of an indication on the aft-face. The Safety Board notes that after the accident, Delta advised its FPI personnel to minimize manual handling of hubs and to use support equipment, such as an overhead hoist, in the inspection booth.

The Safety Board previously addressed manual handling and methods to support parts during FPI following a July 19, 1989, accident at Sioux City, Iowa, involving a United Airlines DC-10-10 airplane. That accident was also caused by a crack in a critical rotating engine part.[10] The Safety Board report on that accident stated

> It is possible that the inspector...did not rotate the disk, as it was suspended by a cable, to enable both proper preparation and subsequent viewing of all portions of the disk bore, particularly the area hidden by the suspension cable/hose.

The Safety Board is concerned that deficiencies in the methods for handling critical rotating parts during FPI have been identified in this accident and in the United Airlines accident in Sioux City, Iowa. The Safety Board 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.

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[10] National Transportation Safety Board. 1990. *United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux City Gateway Airport, Sioux City, Iowa, July 19, 1989.* Aircraft Accident Report NTSB/AAR-90/06. Washington, DC.

Further, the Safety Board 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. The Safety Board also concludes that the potential deficiencies identified in the Delta FPI process may exist at other maintenance facilities and be, in part, the reason for the failure to detect cracks in other failed engines identified in this investigation. Therefore, the Safety Board believes that the FAA should 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:

1. Review the efficacy of drying procedures for aqueously cleaned rotating engine parts being prepared for FPIs;
2. Determine whether flash drying alone is a sufficiently reliable method;
3. Address the need to ensure the fullest possible coverage of dry developer powder, particularly along hole walls;
4. Address the need for a formal system to track and control development times; and
5. Address the need for fixtures that minimize manual handling of the part without visually masking large surfaces of the part.

Lack of a Formal Method to Ensure Completeness of Search and Diagnostic Followup

To detect the crack on the aft-face of the hub, the inspector would have had to first detect a bright fluorescent green indication (if there was such an indication) against a dark purple background.[11] To detect the indication, the inspector would have had to systematically direct his gaze across all surfaces of the hub. However, 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.[12] Delta FPI inspectors described inspecting major areas on the -219 hub in the same order each time. Although this technique was variable among inspectors and vulnerable to omission, it would help ensure that major areas of the hub were not missed. However, it is possible that the inspector examined the aft-face of the hub but did not look at the specific area containing the indication near the tierod hole.

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

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[11]The brilliance of an indication is affected by the crack size and amount of penetrant in the defect. Dye penetrant contamination in the work area, processing errors, and methods used to handle and move hubs during the FPI process can also decrease the brilliance of an indication and can affect the inspector's ability to detect a crack.

[12]Department of Transportation. 1996. *Visual Inspection Research Project Report on Benchmark Inspections. Final Report, October 1996.* DOT/FAA/AR-96/95. Washington, DC. This research group advocated development of nondestructive inspection reliability models that acknowledge a background miss rate unrelated to crack length to more accurately model the observed data.

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.[13] In studies of airframe inspectors, some have failed to detect defects because they did not resume their inspection at the appropriate location after stopping to move equipment.

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 followup 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. Such a system would also reduce the opportunity for human error in other procedural inspections, such as eddy current inspections[14] of rivets or holes.

Nondestructive testing (NDT)[15] inspections of critical rotating parts for small flaws are vulnerable to error in visual search and are dependent on the inspector's memory to ensure that an exhaustive search and adequate followup has been conducted. Accordingly, the Safety Board concludes that an inadvertent failure of the inspector to systematically search and complete followup diagnosis when necessary on all surfaces of the hub might have caused the inspector to overlook the crack. Therefore, the Safety Board believes that the FAA should require the development of methods for inspectors to note on the part or otherwise document during an NDT inspection the portions of a critical rotating part that have already been inspected and received diagnostic followup to ensure the complete inspection of the part.

Low Expectation of Finding a Crack and Decreased Vigilance

FPI inspectors are required to diagnose each detected indication to determine if it is a crack because a crack is reason to reject the part. But not every indication is a crack, and most preliminary indications are later found not to be cracks. 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. 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. Therefore, the Safety Board concludes that a low expectation of finding a crack in a -219 series

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[13]It is also possible that the glare associated with the use of white light to diagnose indications contributed to this omission because this process caused his eyes to lose dark adaptation.

[14]Eddy current inspections measure fluctuations in an alternating magnetic field around a part generated by a transducer carrying an alternating current. Eddy current inspections are used to locate surface and near-surface defects.

[15] NDT methods are those that do not damage or significantly alter the component being tested during inspection.

fan hub might have caused the inspector to overlook or minimize the significance of an indication.

A low expectation of finding a crack might also have decreased the inspector's vigilance. Further, research on vigilance suggests that performance decreases with increasing inspection time.[16] However, data to support this conclusion in the aviation inspection domain are inconclusive. In addition, a recent study of eddy current inspection of airframe skin panels found no relationship between inspection duration and probability of defect detection.[17] In any event, 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 inspector who inspected the accident hub characterized the FPI process as tedious and monotonous and stated that he spent about 75 percent of his shift inspecting parts. He also stated that inspection of a -219 hub typically took about 40 minutes to 2 hours, depending on the number of indications detected.

The Safety Board 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. Therefore, the Safety Board believes that the FAA should conduct research to determine the optimum amount of time an inspector can perform NDT inspections before human performance decrements can be expected.

Inadequate Diagnostic Techniques or Controls

It is also possible that the inspector detected an indication at the location of the crack but did not properly complete the followup diagnostic procedure. Diagnostic procedures must be consistently performed and the appropriate time periods must be allowed for redevelopment to ensure that a true defect is not allowed to pass. Delta's Process Standard for conducting FPIs directed inspectors to wait at least 5 minutes to confirm that an indication had not reappeared after developer was applied during the bleedout procedure. As discussed above, there was no formal method for the inspectors to track these indications and to ensure that they were reinspected after the required redevelopment period. Further, no formal method was in place to ensure adherence to the redevelopment time period. The Safety Board anticipates that in establishing the uniform set of standards (recommended above), the FAA will recognize the need for a formal system for measuring and recording development times listed in their process standards for FPI.

Adequacy of Inspector Training and Proficiency

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[16] Drury, C. G. 1992. *Inspection Performance, Handbook of Industrial Engineering*. New York.

[17] Department of Transportation. 1992. *Reliability Assessment at Airline Inspection Facilities, Volume III: Results of an Eddy Current Inspection Reliability Experiment. May 1995. Final Report.* DOT/FAA/CT-92/12, III. Washington, DC.

The Safety Board addressed the issue of NDT inspector training in a previous accident investigation of an uncontained engine failure.[18] In that accident, the Safety Board concluded that a ½-inch crack was present during the last inspection of the disk that would have been detected if proper magnetic particle inspection (MPI) methods had been applied. The Safety Board noted that inspectors at the engine's repair station had trained each other and that the manufacturer had recommended that the repair station develop a formal initial and recurrent training program. In contrast, the Delta FPI inspector had completed a formal training program that included written and practical examinations and his training was consistent with industry standards. However, because this accident revealed that a crack was not detected at a repair facility that followed industry guidance, the Safety Board issued Safety Recommendation A-96-77 on July 29, 1996, asking the FAA to

> Review and revise, 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 tierod and stress redistribution holes.

The Safety Board classified this recommendation "Open—Acceptable Response" in February 1997, pending final FAA action after the FAA stated that it had inspected Delta's FPI facility and concluded that the airline "had the proper guidance for training and qualifying personnel" in NDT and FPI. The Safety Board's decision was also based on FAA plans to have its FPI Review Team visit six FPI facilities, at a rate of two facilities per month. After the inspections, the FAA stated that it would issue a report and determine what course of action, if any, needed to be taken. The FAA stated that it would also evaluate other facilities that perform FPI and other NDT procedures to determine whether systemic problems existed. The FAA has completed these inspections. but the report has not yet been issued.

A human factors expert testified at the public hearing on this accident that methods have been identified to augment training in inspection. These methods include incremental guidance for specific inspection skills and feedback guidance to inspectors during training. As the FAA completes action on A-96-77, the Safety Board anticipates that the FAA will consider these methods to improve inspector performance.

After the FAA's August 1996 review of Delta's FPI facility, the FAA recommended that written and proficiency examinations be required 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. The Safety Board agrees with the FAA that additional and more frequent evaluation of inspectors is needed to ensure that inspectors are qualified to do their job. Written examinations provide information about an inspector's knowledge of the inspection process and

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[18] National Transportation Safety Board. 1996. *Uncontained Engine Failure/Fire, ValuJet Airlines Flight 597, Douglas DC-9-32, N908VJ, Atlanta, Georgia, June 8, 1995.* Aircraft Accident Report NTSB/AAR-96/03. Washington, DC.

procedures. Proficiency examinations like the one administered at Delta determine whether the inspector can apply the inspection procedures and interpret the results using a limited set of test pieces or actual parts. However, 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. It would be beneficial to evaluate the inspector's skills to detect defects on the line, however, because defects that are missed on actual parts can go undetected. Important feedback information required to determine inspector sensitivity is not available.

The Safety Board concludes that 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. Such methods would require an inspector to examine several parts, some containing defects and some without, which 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. A test of this type would provide an indication on the capabilities of the inspector unlike practical tests on only a few samples or that involve training to proficiency. Further, it would facilitate a comparison of how different inspectors perform and if administered on a frequent basis provide a way to track inspector performance and focus recurrent training. Therefore, the Safety Board believes that the FAA should, 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 proficiency examinations incorporate these methods and are administered during initial and recurrent training for inspectors working on critical rotating parts.

Because FPI is dependent on several individuals performing multiple procedures, no single reason for the nondetection of the crack in this accident could be identified. The Safety Board 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.

Adequacy of Inspection Requirements for Critical Rotating Titanium Components

The Safety Board issued comprehensive recommendations following the United Airlines accident in Sioux City, Iowa, in which an in-flight uncontained engine failure led to the loss of the three hydraulic systems that powered the airplane's flight controls. The investigation found that fatigue cracking in the front fan disk originated in a hard alpha inclusion that had formed during the casting of the disk material. Included in the recommendations were Safety Recommendations A-90-89 and -90, which asked the FAA to develop a damage tolerance inspection program for all engine components that, if they failed or separated, posed a significant threat to the structures and systems of airplanes. In response, the FAA formed the TRCRT to assess the quality control procedures used in the manufacture of titanium alloy high-energy rotating components of turbine engines.

The TRCRT final report made several recommendations related to in-service inspections of titanium rotating parts, including using eddy current inspections to supplement FPIs and a requirement to subject such parts to at least two "subsurface inspections" (e.g., ultrasonic)[19] during their cyclic life. However, the implementation schedule for recommendations contained in the TRCRT report was canceled by the FAA following a 1991 industry conference during which industry representatives requested that the schedule be modified. Based on an April 6, 1993, FAA letter to the Safety Board that stated that future action would be taken to "develop implementation schedules commensurate with the needs of the FAA, industry, and the flying public," the Safety Board classified both safety recommendations "Closed—Acceptable Alternate Action" on May 28, 1993. The Safety Board is disappointed that no new schedules were developed and that no further action was taken by the FAA to implement the recommendations in the TRCRT report.

In addition to this accident, several other uncontained engine failures have occurred after the Sioux City accident and the TRCRT report because of fatigue cracking that initiated from various sorts of microstructural conditions created at manufacture.[20] Further, there was also evidence of manufacturing defects in several engines that failed before the Sioux City accident.[21] This accident history demonstrates that a variety of manufacturing anomalies in a variety of locations on engine parts can lead to uncontained failures, and that manufacturing defects are not as rare as might once have been believed. Further, given the loss of life that has resulted from the Sioux City and Pensacola failures, it is also clear that such defects can pose a significant threat to safety.

Most, if not all, of these engine parts were, at the time of manufacture, subjected to one or more nondestructive inspection techniques (such as an etch, ultrasonic inspection, or FPI) designed to detect manufacturing-related flaws and anomalies that may lead to cracking. (Some of the etch and ultrasonic inspections were performed on the rectilinear part [machine forged shape], and not on the final shape,[22] a practice that is no longer being used.) However, none of the flaws and anomalies that existed in those parts were detected, and the parts passed inspection. This demonstrates that the inspection methods used at manufacture can be fallible, and that

[19] Ultrasonic testing is an NDT method in which high-frequency sound waves are introduced to materials to detect surface and subsurface flaws.

[20] A 1993 failure of the HPC stage 3-9 spool in a CF6-80C2 in Los Angeles, California, was attributed to dwell time fatigue initiating an area of aligned alpha colonies in the titanium alloy; a 1995 failure of an Egypt Air CF6-50C2 engine was attributed to a crack originating at a hard alpha inclusion in stage 6 of the HPC 3-9 stage spool; a 1995 failure of a CF6-50C2B engine in Bangkok, Thailand, was attributed to dwell time fatigue resulting from aligned alpha colonies in the disc bore of the 3-9 HPC; and evidence from a 1997 failure of a Canadian Airlines CF6-80C2B6F engine, which is still under investigation, has revealed a microstructural anomaly in the blade slot bottom of the 3rd-stage HPC 3-9 stage spool.

[21] The 1982 failure of a Pan Am JT8D-7 engine was attributed to a crack originating in altered microstructure in a tierod hole, and three CF6 engine failures occurring in 1974, 1979, and 1983 were attributed to cracking originating in hard alpha inclusions.

[22] For example, the parts involved in the Sioux City, Egypt Air, and Canadian Airlines accidents were etched only in their rectilinear shape and were subjected to FPI in their final shape.

newly manufactured engine parts may be placed into service containing potentially dangerous flaws.

Further, many of the flawed engine parts were subjected to in-service FPI or ultrasonic inspections after they developed cracks that had propagated to detectable lengths, yet they were not removed from service.[23] Thus, it is clear that detectable cracks in critical rotating engine parts may escape detection, even though the part has undergone in-service nondestructive testing techniques such as FPI. This point is further demonstrated by the ValuJet uncontained engine failure in Atlanta which, although it did not involve a manufacturing defect, again shows that a critical rotating part with a detectable crack can successfully pass through an NDT process (in that case MPI)[24] and be placed back into service. Probability of detection data confirm that even assuming the FPI procedures are properly executed, some detectable cracks will be missed. However, because FPI procedures may not always be properly carried out, there are several additional reasons why a detectable crack may be missed during the FPI process.

The Safety Board concludes that 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 Safety Board agrees with the TRCRT conclusion that

> [based on the] frequency of occurrence of titanium metallurgical defects, the difficulty of detecting defects in titanium,...the many sources of defects, errors and damage, recent developments in the engineering science of fracture mechanics (crack propagation) analysis...the random approach of inspections of opportunity is not adequate, and can no longer be justified.

In light of the above, the Safety Board is especially concerned that the FAA's initial and recurring inspection program, as outlined in Airworthiness Directive (AD) 97-02-11 and a subsequent final rule addressing the intent of Safety Recommendation A-96-74 (by taking into account the potential for microstructural defects produced by standard drills after a "major event such as tool breakage"), does not include mandatory or fixed-interval repetitive inspections for the remaining population of 2,272 fan hubs urged in Safety Recommendation A-96-75.

The Safety Board is concerned that JT8D-200 series fan hubs with more than 4,000 CSN may not receive FPI and eddy current inspections when these fan hubs are in the shop because there is no requirement to disassemble hubs to the piece-part level. In addition, AD 97-02-11 imposed no inspection requirement before retirement at 20,000 cycles in service (CIS) on fan hubs that have accumulated over 10,000 CIS before March 5, 1997, which constitutes a large

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[23] In addition to the fan hub involved in this accident, the parts involved in the 1989 Sioux City, 1995 Egypt Air, 1982 Pan Am, 1995 Thailand, and 1997 Canadian Air accidents all underwent in-service FPI.

[24] MPI is an NDT testing method that uses part or surface magnetization to locate surface and subsurface effects.

percentage of all JT8D-200 series fan hubs. As such, AD 97-02-11 does not require the population of JT8D-200 series fan hubs with holes produced with standard drills or hubs with no machining or dimensional anomalies to be inspected unless the engine is disassembled to the piece-part level. This approach remains unacceptable.

However, the Safety Board's concern is not limited to JT8D-200 series fan hubs, but extends to all critical rotating titanium engine components. The Safety Board concludes that 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. Therefore, the Safety Board believes that the FAA should require that all heavy rotating titanium engine components (including the JT8D-200 series fan hubs) receive appropriate NDT 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. In developing the inspection intervals, the Safety Board urges the FAA to assume that a crack may begin to propagate immediately after being put into service, as occurred in this accident and the United Airlines accident at Sioux City.

The Safety Board recognizes that all necessary probability of detection data and crack propagation rates may not be immediately available, and may have to be developed for some components. Therefore, the Safety Board believes that the FAA should require, as an interim measure, pending implementation of Safety Recommendation A-98-15, that critical rotating titanium engine components that have been in service for at least 2 years receive an FPI, eddy current, and ultrasonic inspection of the high-stress areas at the engine's next shop visit or within 2 years from the date of this recommendation, whichever occurs first.

These recommendations supersede Safety Recommendations A-96-74 and A-96-75, which the Safety Board now classifies "Closed—Unacceptable Action/Superseded."

Maintenance Deficiencies

During the preflight inspection the first officer found a small amount of oil on the bullet nose of the left engine and two rivets missing from the left wing. 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. Therefore, the Safety Board concludes that these were not factors in the subsequent engine failure.

However, the Safety Board is concerned that the flightcrew did not request maintenance action before departure from Pensacola and that flightcrews 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 Flight Operations Manual (FOM), which required flightcrews to notify Delta maintenance personnel of maintenance irregularities, or fluid leaks, at the gate. However, the flightcrew'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.

Thus, the Safety Board concludes that there is a lack of clarity in written guidance in the FOM to Delta flightcrews on what constitutes maintenance "discrepancies" and "irregularities" and when to contact maintenance personnel and to log anomalies. Therefore, the Safety Board believes that the FAA should require Delta Air Lines to review its operational procedures, with special emphasis on nonmaintenance stations, to ensure that flightcrews 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 FOM to clarify under what circumstances flightcrews can, if at all, make independent determinations to depart when maintenance irregularities are noted. Further, the Safety Board is concerned that similar situations may be encountered by flightcrews at other airlines. Therefore, the Safety Board believes that the FAA should have its principal operations inspectors review these policies and procedures at their respective operators to clarify, if necessary, these flightcrew responsibilities.

Crew Actions and Survival Factors

Immediately following the engine failure, the circumstances in the aft cabin were markedly different than those in the forward cabin. The aft flight attendants were presented with structural damage, serious injuries, and an engine fire, any one of which was sufficient to initiate an evacuation pursuant to Delta's policy and procedures. In contrast, the cockpit crew and forward flight attendant were unaware of these circumstances and, based on the absence of any indications of fire, the captain determined that an evacuation was not warranted. Unaware that passengers were evacuating, the captain did not shut down the engines until the first officer alerted him to do so after having walked through the cabin to assess the situation.

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. 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. By the time emergency electrical power was restored to the interphone and the first officer again attempted to contact the aft flight attendants, the flight attendants were no longer in a position to, and would not have been expected to, respond to calls over the interphone because they were carrying out the evacuation and attending to injured passengers.

The Safety Board concludes that 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. However, the Safety Board is troubled by the lack of communication among crewmembers in the front and back of the airplane. Specifically, the Safety Board is concerned that crewmembers in the cockpit were unaware that emergency conditions existed and an evacuation was ongoing in the rear of the airplane. Even if this information would not have affected the captain's determination not to evacuate the entire airplane, at the very least it likely would have prompted him to immediately shut down the engines to minimize the hazards to those passengers who were evacuating.

The Safety Board has long been concerned about the difficulties that can arise when normal means of communication (interphone and/or public address systems) become unavailable during an emergency situation, when they generally are most needed. Evacuation decisions, which must often be made very quickly, should be based on the most complete information possible about the condition of the airplane and possible hazards. As noted in an accident report on the December 20, 1995, accident involving Tower Air flight 41 at JFK International Airport,[25] "positive communications are essential to coordinate the crew's response, even if the decision is not to evacuate."

In 1972 and 1981 the Safety Board recommended that the FAA require independently powered evacuation alarm systems. However, at that time, the FAA determined that the cost of installing such alarm systems "would far outweigh any identifiable safety benefits." Thus, in most airplanes today, if there is a loss of airplane electrical power, crewmembers and passengers in one part of the airplane may not be aware of an evacuation that is occurring in another part of the airplane. Because a decision to evacuate generally indicates that there may be a hazard to passengers if they remain on board, the Safety Board remains concerned that the lack of an independently powered evacuation alarm system on most airplanes is a significant safety deficiency that should be corrected.

The Safety Board concludes that every passenger-carrying airplane operating under 14 CFR 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. Therefore, the Safety Board believes that the FAA should require that all newly manufactured passenger-carrying airplanes operated under 14 CFR Part 121 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 issue of retrofitting existing airplanes with such systems will be addressed in the Safety Board's upcoming evacuation study.

As illustrated in this accident, emergency exits are sometimes opened by passengers before any evacuation order has been given or any decision has been reached. 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 potential hazards to passengers who may be departing the airplane through those exits. The Safety Board is aware that some airplanes, including the MD-

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[25] National Transportation Safety Board. 1996. *Runway Departure During Attempted Takeoff, Tower Air Flight 41, Boeing 747-136, JFK International Airport, New York, December 20, 1995.* Aircraft Accident Report NTSB/AAR-96/04. Washington, DC.

88, are equipped with cockpit indicators showing open exits, but the Safety Board concludes that safety could be enhanced if all cockpit crews were immediately made aware of when exits are opened during an emergency. Therefore, the Safety Board believes that 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 issue of retrofitting existing airplanes will be addressed in the Safety Board's upcoming evacuation study.

Finally, the Safety Board is concerned that the overwing exits were opened while the airplane was still moving. The passenger who opened that exit told Safety Board investigators that he was uncertain whether he should open the exit and wished that he had received some guidance as to when it should be opened. The "Passenger Safety Information" card made available to each passenger on the Delta MD-88 illustrates how to open the exits, and states that persons seated in emergency exit seats must be able to "[a]ssess 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 Safety Board concludes that the 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 Safety Board is also concerned that guidance provided by other airlines on other airplanes might be similarly vague. The Board will address this issue further in its upcoming evacuation study.

As a result of the investigation of this accident, the National Transportation Safety Board recommends the following to the Federal Aviation Administration:

> Form a task force to evaluate the limitations of the blue etch anodize and other postmanufacturing etch processes and develop ways to improve the likelihood that abnormal microstructure will be detected. (A-98-9)
>
> 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 reevaluate 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 fluorescent penetrant inspection 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 fluorescent penetrant inspections;
>>
>> Determine whether flash drying alone is a sufficiently reliable method;

Address the need to ensure the fullest possible coverage of dry developer powder, particularly along hole walls;

Address the need for a formal system to track and control development times; and

Address the need for fixtures that minimize manual handling of the part without visually masking large surfaces of the part. (A-98-11)

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-98-12)

Conduct research to determine the optimum amount of time an inspector can perform nondestructive testing inspections before human performance decrements can be expected. (A-98-13)

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 proficiency examinations incorporate these methods and are administered during initial and recurrent training for inspectors working on critical rotating parts. (A-98-14)

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. (A-98-15)

Require, as an interim measure, pending implementation of Safety Recommendation A-98-15, that critical rotating titanium engine components that have been in service for at least 2 years receive a fluorescent penetrant inspection, eddy current, and ultrasonic inspection of the high-stress areas at the engine's next shop visit or within 2 years from the date of this recommendation, whichever occurs first. (A-98-16)

Require Delta Air Lines to review its operational procedures, with special emphasis on nonmaintenance stations, to ensure that flightcrews 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 flightcrews 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 flightcrew responsibilities. (A-98-17)

Require that all newly manufactured passenger-carrying airplanes operated under 14 Code of Federal Regulations Part 121 be equipped with independently powered evacuation alarm systems operable from each crewmember station, and establish procedures and provide training to flight and cabin crews regarding the use of such systems. (A-98-18)

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. (A-98-19)

Chairman HALL, Vice Chairman FRANCIS, and Members HAMMERSCHMIDT, GOGLIA, and BLACK concurred in these recommendations.

By: Jim Hall
Chairman