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National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: December 14, 1990

In reply refer to: A-90-167 through 175

Honorable James B. Busey
Administrator
Federal Aviation Administration
Washington, D.C. 20591

On July 19, 1989, at 1516, a DC-10-10, N1819U, operated by United Airlines (UAL) as flight 232, experienced a catastrophic failure of the No. 2 tail-mounted engine during cruise flight. The separation, fragmentation and forceful discharge of stage 1 fan rotor assembly parts from the No. 2 engine led to the loss of the three hydraulic systems that powered the airplane's flight controls. The flightcrew experienced severe difficulties controlling the airplane, which subsequently crashed during an attempted landing at Sioux Gateway Airport, Iowa. There were 285 passengers and 11 crewmembers onboard. One flight attendant and 110 passengers were fatally injured.[1]

The National Transportation Safety Board determines that the probable cause of this accident was the inadequate consideration given to human factors limitations in the inspection and quality control procedures used by United Airlines' engine overhaul facility which resulted in the failure to detect a fatigue crack originating from a previously undetected metallurgical defect located in a critical area of the stage 1 fan disk that was manufactured by General Electric Aircraft Engines. The subsequent catastrophic disintegration of the disk resulted in the liberation of debris in a pattern of distribution and with energy levels that exceeded the level of protection provided by design features of the hydraulic systems that operate the DC-10's flight controls.

Commercial air carriers certificated under Title 14 Code of Federal Regulations Part 121, operate per the basic maintenance regulations contained in Subpart L - Maintenance, Preventive Maintenance and Alterations. Key elements are trained personnel, proper instructions, and the required tooling and facilities.

There were six maintenance inspections of the accident fan disk, including an inspection 760 cycles before the accident, which was performed in accordance with UAL procedures.

[1] For more detailed information, read Aircraft Accident Report "United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux City, Iowa, July 19, 1989" (NTSB/AAR-90-06)

Fracture mechanics evaluations showed that at the time of the disk separation, a fatigue crack existed that was large enough to cause fracture and resulting separation of the fan disk under normal loads. The number of major striations on the fatigue region was nearly equal to the total number of takeoff/landing cycles on the disk (15,503), indicating that the fatigue crack initiated very early in the life of the disk.

The Safety Board attempted to determine the size of the fatigue crack at the time of UAL's fluorescent penetrant inspection (FPI) of the disk 760 cycles prior to the accident. One possibility was that the discolored portion of the fatigue crack was created during the alkaline cleaning of the disk in preparation for the inspection. The fractographic examination of the fatigue region disclosed no topographic explanation for the discoloration. In addition, the Safety Board is not aware of any operational environment or conditions that would cause such discoloration. For these reasons, the Safety Board concludes that the discoloration on the surface of the fatigue crack was created during some step in the FPI process performed by UAL 760 cycles prior to the accident, and that the discolored area marks the size of the crack at the time of this inspection. The actual surface length of the discolored area is 0.476 inch. The fracture mechanics analysis was also used to estimate the size of the fatigue crack at the time of the inspection. The analysis estimated that the surface length of the crack was 0.498 inch long at the last inspection.

Analytical procedures were developed to examine the smaller piece of the disk to determine if chemical residues from the UAL inspection were present on the fatigue fracture surface. Secondary Ion Mass Spectroscopy measurements of the fatigue fracture surface showed an ion fragmentation pattern that was consistent with chemical compounds used in the FPI fluid.

The UAL procedure warned inspectors that titanium parts resist the capillary action of the penetrant and that "complete penetrant coverage is required for these materials." Also, the procedure cautioned not to overwash the parts or the penetrant might be flushed out of true indications. The disk bore is mentioned as one of the critical areas for inspection.

A review of the inspection process suggests several explanations for the inspector's failure to detect the crack. It is possible that the inspector did not adequately prepare the part for inspection or that he did not rotate the disk, while 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. It is also possible that loose developer powder, which could have dropped from the suspension cable, obscured the crack sufficiently to prevent its recognition as a flaw. Finally, inspection experience indicates that certain areas of CF-6 disks, because of their geometry, frequently show large FPI indications and that other areas rarely do so. One such area of frequent indications is around the perimeter of the disk near the dovetail posts. By contrast, the central bore area has apparently rarely produced FPI indications. Thus, it is possible that the inspector did not consider the bore area a critical area for inspection, as stated in UAL's inspection directives, and that he gave the bore area only cursory attention, thereby reducing the likelihood that a crack would be detected. Any of these possibilities, or some combination of them, could have contributed to nondetection of the crack.

The UAL maintenance program is comprehensive and based on industry standards. The company's inspection requirements for the CF6-6 stage 1 fan disk are generally consistent with other airline practices and comply with Federal regulations. Further, UAL's procedures for selecting, training, and qualifying nondestructive inspection (NDI) personnel are also consistent with industry practices. However, it is clear that the adequacy of the inspections is dependent upon the performance of the inspector. That is, there are human factors associated with NDI processes that can significantly degrade inspector performance. Specifically, NDI inspectors generally work independently and receive very little supervision. Moreover, there is minimum redundancy built into the aviation industry's FPI process to prevent human error or other task or workplace factors that can adversely affect inspector performance. Because of these and other similar factors, the Safety Board is concerned that NDI inspections in general, and FPI in particular, may not be given the detailed attention that such a critical process warrants.

The Safety Board addressed the issue of human factors in NDI inspector reliability following the Aloha Airlines B-737 accident near Maui, Hawaii, in April 1988. As a result of its investigation of the Aloha accident, the Safety Board issued two recommendations to the FAA that are relevant to the maintenance and inspection issues identified in this case.

A-89-56

Require formal certification and recurrent training of aviation maintenance inspectors performing nondestructive inspection functions. Formal training should include apprenticeship and periodic skill demonstration.

A-89-57

Require operators to provide specific training programs for maintenance and inspection personnel about the conditions under which visual inspections must be conducted. Require operators to periodically test personnel on their ability to detect the defined defects.

In its response to these recommendations, the FAA acknowledged that its Aging Fleet Evaluation Program has highlighted some of the same deficiencies outlined by the Safety Board and that it is addressing these issues as part of regulatory reviews of 14 CFR Parts 65 and 147. The FAA also indicated that the utilization of inspector personnel, and the human factors aspects of such utilization, are also being examined. Based on the FAA's response, these recommendations have been classified as "Open--Acceptable Action."

The Safety Board also believes that the manual inspection systems used to inspect most aircraft structural and engine components are inherently susceptible to human factors problems that can significantly reduce the probability of detecting defects. Automation of NDI is already available with current technology. Automated eddy current, ultrasonic, and FPI equipment can be employed by airline maintenance centers. The Safety Board believes that the FAA should intensify research to identify emerging technologies for NDI that simplify or automate the inspection processes, provide funding to initiate demonstration programs, and encourage operators and other parties that perform inspections to adopt superior techniques and equipment. The FAA should also encourage the development and implementation of redundant ("second set of eyes") inspection oversight for critical part inspections, such as for rotating engine parts.

The three independent continuously operating hydraulic systems are intended to provide power for full operation and control of the DC-10 in the event that one or two of the hydraulic systems are rendered inoperative. System integrity of at least one hydraulic system is required--the presence of fluid and the ability to hold pressure--for continued flight and landing; there are no provisions for reverting to manual flight control inputs.

During the investigation of this accident, the Safety Board reviewed alternative flight control system design concepts for wide-body airplanes. The concept of three independent hydraulic systems is not unique. Boeing and Airbus have three such systems on some of their most recently certified models. Lockheed and Boeing have also provided four independent systems on some of their wide-body airplanes. The Safety Board can find no inherent safety advantage to the installation of additional independent hydraulic systems for flight controls to supplement those currently operating in today's fleet. However, the Safety Board believes that backup systems to the primary hydraulic systems should be developed and included in the initial design for certification. Such backup systems are particularly important for the coming generation of wide-body airplanes since manual reversion flight control systems are quite likely impractical due to the power requirements to deflect large control surfaces. Therefore, the Safety Board recommends that the FAA encourage continued research and development into backup flight control systems that employ an alternative source of motive power.

Hydraulic system enhancements provided by Douglas and mandated by FAA AD-90-13-07 appear to protect the airplane in the unlikely event of a similar No. 2 engine catastrophic failure. In other failures involving the hydraulic systems and the No. 1 and No. 3 engines, the enhancements do not provide any additional margin of safety. The vulnerability of the DC-10 or other wide-bodied airplanes in the event of such failures is not known. Therefore, the Safety Board has a vital interest in the work of the Systems Review Task Force (SRTF) industry group. As evident from the UA 232 accident, inadequate predictions of secondary damage in the area of flight control redundancy have resulted in both this accident and the crash of a B-747 in Japan. There are many other wide-body-type airplanes in the world transport fleet that may benefit from a systems safety review, such as that desired by the FAA Administrator in the charter to the SRTF group. The Safety Board therefore recommends to the FAA that the SRTF activities receive maximum encouragement and support to attain the stated objectives.

The Safety Board considers in retrospect that the potential for hydraulic system damage as a result of the effect of random engine debris should have been given more consideration in the original design and certification requirements of the DC-10 and that Douglas should have better protected the critical hydraulic system(s) from such potential effects. As a result of lessons learned from this accident, the hydraulic system enhancement mandated by AD-90-13-07 should serve to preclude loss of flight control as a result of a No. 2 engine failure. Nonetheless, the Safety Board is concerned that other aircraft may have been given similar insufficient consideration in the design for redundancy of the motive power source for flight control systems or for protecting the electronic flight and engine controls of new generation aircraft. Therefore, the Safety Board recommends that the FAA conduct system safety reviews of currently certificated aircraft in light of the lessons learned in this accident to give all possible consideration to the redundancy and protection of power sources for flight and engine controls.

AC 20-128 provides the airframe manufacturer with a method for compliance with 14 CFR 25.903. It implies that the manufacturer should consider fragment energy levels that only the engine manufacturer can provide, and that compressor and turbine disk segment noncontainment should be considered. The Safety Board believes that the engine manufacturer should provide accurate data for future designs that would allow for a total safety assessment of the airplane as a whole. It is possible that in the interest of marketing a new engine to an airframe manufacturer, the engine manufacturer may underestimate the potential for failure and resultant damage. Similarly, the airframe manufacturer may not possess the data necessary to estimate the total interactive effect of the powerplant installation on the airframe.

The AC does not specifically address large fan disk segments. Further, the AC is predicated on a three-piece disk rupture with only 1/3 of the disk penetrating the airplane. The Safety Board believes that in future aircraft certifications, the FAA, when assessing compliance by the airframe manufacturer with 14 CFR 25.903, should require that the engine manufacturer provide, and the airframe manufacturer consider, fragment sizes and energies such as those encountered in this accident.

In addition, in the case of large fragments, such as the fan disk segments, the spread angle or dispersion area as defined in AC 20-128 may be inadequate. This accident demonstrated inconsistencies between the predictions of AC 20-128 and the realities of the actual damage to an airframe. Also, the fact that there was titanium alloy transferred to a No. 4 banjo frame piece may mean that the banjo piece moved into the dispersion path. However, it may also mean that the frame was struck by the uncontained fragment of the rotor disk assembly when the fragment was oriented out of its plane of rotation by unbalanced forces during the separation sequence. If the uncontained fragment is displaced out of plane, the spread angle is then a function of the disk fragment dimensions and should be considered when showing compliance with FAR 25.903. Therefore, the Safety Board recommends that the FAA analyze the dispersion pattern, fragment size, and energy level of released engine rotating parts in this accident and include the results of this analysis, and any other peripheral data available, in a revision of AC 20-128 for future aircraft certification.

Following this accident, the Safety Board attempted to obtain historical data and recent operating experience regarding engine rotating part failures and noncontainment events. The most recent information readily available were two Society of Automotive Engineers (SAE) reports that provided data only through 1983. The Safety Board is concerned that there may not be a central repository for a current and complete data base for engine rotating part noncontainment events. The Safety Board believes that the FAA should review the current reporting requirements for manufacturers and operators to establish a centrally available data base of these events based on operator and engine manufacturer knowledge and inservice experience.

The Safety Board recommends that the FAA establish a system to monitor the engine rotary parts failure history of turbine engines and to support a data base sufficient for design assessment, comparative safety analysis among manufacturers, and more importantly, to establish a verifiable background for the FAA to research during certification review. This system should collect worldwide data by means of the malfunction and defect reporting requirements for manufacturers contained in 14 CFR Part 21.

GEAE has undertaken a replacement program for all fan disks identified by CF6-6 SB 72-947 and AD 89-20-01 as Category I, II, and III. The program is administered by the GEAE Manager of Customer Service. Replacement disks were immediately made available for the Category I disks that were recalled. Category II and III disks were more numerous and were more difficult to replace. As newly manufactured spares become available in the GEAE inventory, the spares are being exchanged for disks that were removed from engines that were disassembled for either AD compliance inspections or other maintenance activity. GEAE has stated that it intends to remove from service all Category II and III disks prior to accumulation of 1,500 cycles after the immersion-ultrasonic inspection. The Safety Board recommends that the FAA issue an AD to mandate further service limits or methods of inspection to extend residual life on disks inspected per AD-89-20-01.

GEAE also released SB 72-962, dated July 2, 1990, which directed contact and immersion inspections of all disks forged by ALCOA. The inspections are to be conducted in a manner similar to those mandated by CF6-6 Service Bulletin 72-947 for Category I, II, and III disks--contact ultrasonic interval, not to exceed 500 cycles until a once-through-the-fleet immersion-ultrasonic inspection can be accomplished. GEAE informally stated that this inspection was initiated to verify the quality of any ALCOA disks that may have been affected by recordkeeping anomalies during manufacture.

The Safety Board has been informed that the FAA intends to issue an AD to mandate compliance with the intent of GEAE Service Bulletin 72-962. Until such time as an AD is issued, the Safety Board remains on record as recommending that the FAA mandate compliance with the Service Bulletin.

Not all records associated with the manufacture of fan rotor disks relevant to this accident were available from GEAE. The TIMET and ALCOA records indicate that the billet and forgings were manufactured and certified in accordance with the then current GEAE specification for titanium used in rotating parts. However, several anomalies appear in the GEAE records, which call into question the reliability or accuracy of all the disk records from the same period.

A primary purpose for lengthy retention of manufacturing and maintenance records, in addition to the certification of materials and procedures, is traceability in the event of in-service difficulties or failures. However, the records are only as useful as the thoroughness and accuracy of the persons initiating them and the system used for auditing, handling, and storing them. It appears that in the early 1970's, much of the data entry and transferral was accomplished by hand and that GEAE did not adequately audit critical parts records for accuracy. Consequently, the Safety Board concludes that the recordkeeping portion of GEAE's quality assurance program on the manufacture of CF6-6 fan disks in the early 1970's was deficient.

The Safety Board is concerned that adequate manufacturers' recordkeeping provisions may not currently be in effect. Consequently, the Safety Board recommends that the FAA conduct a comprehensive evaluation of manufacturing recordkeeping and audit procedures to ensure that adequate quality assurance and traceability of critical airplane parts can be accomplished at all manufacturing facilities.

There were two types of cabin preparation contained in UAL's Land Evacuation Checklist: Full Cabin Preparation (over 10 minutes) and Short Notice Emergency Landing Preparation (under 10 minutes). Both types of preparation required the senior flight attendant to determine how much time was available prior to landing. The senior flight attendant elected to keep things "normal" in the cabin and delayed the emegency cabin preparations. Although the delay did not affect the eventual safety of passengers, the Safety Board believes that the senior flight attendant's primary goals should have been to ensure that there was adequate time to complete a full cabin preparation in the face of an obviously severe emergency. The Safety Board recommends that time management of emergency cabin preparations be reiterated in flight attendant emergency training.

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

> Intensify research in the nondestructive inspection field to identify emerging technologies that can serve to simplify automate, or otherwise improve the reliability of the inspection process. Such research should encourage the development and implementation of redundant ("second set of eyes") inspection oversight for critical part inspections, such as for engine rotating components. (Class II, Priority Action) (A-90-167)

Encourage research and development of backup flight control systems for newly certificated wide-body airplanes that utilize an alternative source of motive power separate from that source used for the conventional control system. (Class II, Priority Action) (A-90-168)

Conduct system safety reviews of currently certificated aircraft as a result of the lessons learned from the July 19, 1989, Sioux City, Iowa, DC-10 accident to give all possible consideration to the redundancy of, and protection for, power sources for flight and engine controls. (Class II, Priority Action) (A-90-169)

Analyze the dispersion pattern, fragment size and energy level of released engine rotating parts from the July 19, 1989, Sioux City, Iowa, DC-10 accident and include the results of this analysis, and any other peripheral data available, in a revision of AC 20-128 for future aircraft certification. (Class II, Priority Action) (A-90-170)

Conduct a comprehensive evaluation of aircraft and engine manufacturers' recordkeeping and internal audit procedures to evaluate the need to keep long-term records and to ensure that quality assurance verification and traceability of critical airplane parts can be accomplished when necessary at all manufacturing facilities. (Class II, Priority Action) (A-90-171)

Create the mechanism to support a historical data base of worldwide engine rotary part failures to facilitate design assessments and comparative safety analysis during certification reviews and other FAA research. (Class II, Priority Action) (A-90-172)

Issue an Air Carrier Operations Bulletin for all air carrier flightcrew training departments to review this accident scenario and reiterate the importance of time management in the preparation of the cabin for an impending emergency landing. (Class II, Priority Action) (A-90-173)

Issue an Airworthiness Directive to mandate service life limits or recurrent inspection requirements on GEAE CF6-6 engine stage 1 fan disks inspected in accordance with AD-89-20-01. (Class II, Priority Action) (A-90-174)

Issue an Airworthiness Directive based on the GEAE CF6-6 Engine Service Bulletin 72-962, pertaining to 119 stage 1 fan disks made from ALCOA forgings, to mandate compliance with the intent of the service bulletin by all operators. (Class II, Priority Action) (A-90-175)

Also, the Safety Board issued Safety Recommendations A-90-176 to the Air Transport Association; A-90-177 to the Aerospace Industries Association of America; and A-90-147 through A-90-150 to the U.S Department of the Air Force.

KOLSTAD, Chairman, COUGHLIN, Vice Chairman, LAUBER, BURNETT, and HART, Members, concurred in these recommendations.

By: James L. Kolstad
Chairman