National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

CORRECTED COPY

Date: March 6, 1998

In reply refer to: A-98-27 through -33

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

On September 7, 1997, Canadian Airlines International flight CP30, a Boeing 767-300ER airplane, equipped with General Electric Aircraft Engines (GEAE) CF6-80C2B6F engines, experienced an uncontained failure[1] of the high-pressure compressor (HPC) stage 3-9 spool (figure 1) in the No. 1 (left) engine during takeoff at Beijing, China. The airplane was on a regularly scheduled passenger flight from Beijing to Vancouver, Canada. The flightcrew reported that during the initial part of the takeoff as the throttles were advanced, the No. 1 engine surged. This was followed by a fire warning in the cockpit and significant vibration in the airplane. The crew rejected the takeoff at a speed of about 20 knots and discharged both fire bottles for the No. 1 engine. The engines were shut down, and the airplane was towed to the terminal without further incident. The 199 passengers and 10 crewmembers on board sustained no injuries.

The examination of the engine revealed substantial damage in the area of the HPC. The HPC case was ruptured aft of the stage 2 variable stator vanes. The stage 3 disk portion of the HPC stage 3-9 spool had separated from the remainder of the spool, exited the engine, and broken into three pieces, all of which were recovered. The No. 1 engine's right-hand thrust reverser cowl had a 2-inch by 1-inch cut in the skin. The reported fire was caused by fuel that had leaked from a line that supplies pressure to the active clearance control[2] valve, which was severed by one of the liberated pieces of the 3rd-stage disk.

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[1] An uncontained engine failure occurs when an internal part of the engine fails and is ejected through the cowling.

[2] The active clearance control system provides air to externally cool the turbine cases to minimize the thermal growth of the cases that reduces the gaspath leakage between the turbine blade tips and turbine case air seals to improve an engine's fuel efficiency.

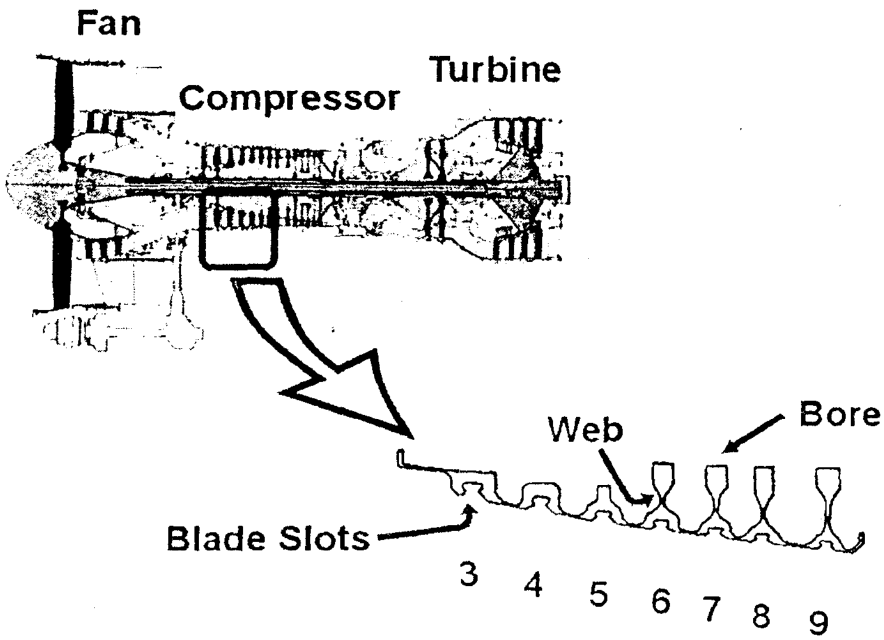

Figure 1.—Typical 3-9 spool in cross section.

The investigation of this incident is under the direction of the Transportation Safety Board of Canada (TSB). The National Transportation Safety Board, under the provisions of Annex 13 to the International Convention on Civil Aviation, is assisting the TSB with its investigation. Information gathered in the investigation thus far raises serious concerns that warrant action by the Federal Aviation Administration (FAA).

The HPC stage 3-9 spool is a rotor component that is composed of disks joined together with integral spacer segments and end flanges and is made from Ti-6242 titanium alloy.[3] The incident spool, part number 1333M66G01, was a two-piece assembly made by GEAE in 1989.[4] According to maintenance records, the spool had accumulated a total of 25,653 hours and 4,744 cycles since new (CSN). The front portion of the spool was forged by Schlosser Forge Company

[3]Titanium-based alloy containing 6 percent aluminum, 2 percent tin, 4 percent zirconium, and 2 percent molybdenum.

[4]The stage 3-9 spool was first manufactured by GEAE in 1971 for the CF6-50 engine as a one-piece spool that was forged from a 16-inch diameter billet. (A billet is a semifinished round product from which a part is forged. The required diameter of a billet is achieved by hot-working [forging] of an ingot in several stages.) In 1980, the billet diameter was reduced to 13 inches to improve the inspectability and provide for more working of the material during forging. Also around 1980, GEAE began to produce two-piece spools from 12-inch and 13-inch diameter billets. In the two-piece configuration, the front (stages 3 through 5) and rear (stages 6 through 9) portions of the spool are forged separately. The forgings are then machined to a rectilinear shape (which has straight sides and perpendicular corners), welded together, heat treated, and machined to the final shape. Between 1988 and July 1995, GEAE produced two-piece spools that had the front and rear portions of the spool forged from 9-inch and 10-inch diameter billets, respectively. Until 1995, all two-piece spools received a postweld solution heat treatment followed by a slow cool down. In 1995, that process was replaced by a postweld stress-relief process. Also, in July 1995, GEAE started to produce two-piece spools forged from 8-inch diameter billets.

from a 9-inch diameter billet produced by Reactive Metals Incorporated (RMI), and the aft portion was forged by Wyman-Gordon Company from a 10-inch diameter billet produced by Titanium Metals Corporation of America. Both pieces were welded by GEAE, and machined to the final shape by Volvo Aero Corporation, Trollhattan, Sweden.

Metallurgical examination of the 3rd-stage disk of flight CP30's HPC spool was conducted at the TSB's engineering and the Safety Board's materials laboratories. The examination revealed a fatigue fracture that was about 1 ¾-inches long and about ½-inch deep, emanating from an area (not a clear, specific origin) at or near the bottom of a dovetail blade slot. Metallographic examination of numerous sections from the area of the fracture revealed a band of abnormal microstructure that contained predominantly alpha phase (the Ti-6242 alloy outside of the area of abnormal microstructure contained a mixture of approximately equal amounts of alpha and beta phases[5]) and elevated oxygen levels. This band of abnormal microstructure extended from the front to the rear face of the 3rd-stage disk and intersected the bottom of the dovetail slot.

Microprobe and wavelength dispersive analysis of several locations along the band of abnormal microstructure revealed oxygen levels of 0.4 to 0.6 percent. The applicable GEAE specification for Ti-6242 titanium alloy, C50TF39-S4, restricts oxygen content to a maximum of 0.15 percent. A spectrographic chemical analysis of the 3rd-stage disk material away from the fracture area and well outside the band of abnormal microstructure showed that it conformed to the GEAE specification requirements for Ti-6242 alloy. Hardness tests showed that the maximum hardness in the oxygen-rich area was 43 on the Hardness Rockwell C scale (HRC). In comparison, the hardness in other areas of the spool ranged from 29 HRC to 40 HRC (averaging 35 HRC), which, according to GEAE, is typical for premium quality Ti-6242 alloy.[6]

Further, the examination of the fracture surface with a scanning electron microscope revealed that about 80 percent of the fatigue region contained brittle cleavage-like,[7] faceted features with no identifiable fatigue striations, and about 20 percent contained classical fatigue striations. Metallurgists were able to count about 800 classical fatigue striations along a radial line extending through the fatigue region from the dovetail slot bottom to the stage 3 disk bore.

Adequacy of Current In-Service Inspection Techniques for Detecting Cracks

The records for the incident engine show that in October 1994, the engine, including the HPC stage 3-9 spool, was overhauled because of the ingestion of recapped tire fragments into the engine during the takeoff roll. The overhaul was performed by Caledonian Airmotive,[8] Prestwick, Scotland, at 2,758 CSN (1,986 cycles before the incident) and included a fluorescent penetrant

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[5]When titanium takes the crystallographic form known as "alpha phase" (also referred to as a low-temperature titanium phase) it has a hexagonal close-packed crystal structure. When it takes the crystallographic form known as "beta phase" (also referred to as a high-temperature titanium phase) it has a body-centered cubic crystal structure.

[6]Applicable GEAE material specification C50TF39-S4 does not specify a required minimum or maximum hardness level for Ti-6242.

[7]Cleavage refers to the splitting of a crystallized substance along definite crystal planes.

[8]Caledonian Airmotive was subsequently acquired by Greenwich Aviall, and then by GE Caledonian.

inspection (FPI)[9] and an ultrasonic[10] inspection. The maintenance records show that neither the FPI nor the ultrasonic inspection revealed any rejectable indications in the spool.[11]

The investigation revealed that the FPI and ultrasonic inspection techniques performed on the spool in 1994, even when combined with the eddy current inspections,[12] which were subsequently included in the GEAE engine maintenance manual for the inspections of HPC stage 3-9 spools, do not provide 100 percent inspection coverage of the spool. According to GEAE, the currently prescribed manner in which the ultrasonic inspection probe is directed at the spool's disk bore results in several internal "blind spots" that are beyond the coverage capabilities of the ultrasonic inspection technique. The crack that resulted in the uncontained failure of flight CP30's HPC stage 3-9 spool originated from an area located in one of these blind spots. The investigation determined that by repositioning the ultrasonic probe to the dovetail slot, this area could be fully inspected. However, it is uncertain whether, even if the probe had been repositioned, a detectable crack existed in the incident spool at the time of the 1994 inspections.

The Safety Board concludes that because the currently prescribed in-service inspection techniques do not provide 100 percent inspection coverage of the HPC stage 3-9 spool, these inspections do not ensure the detection of all cracks. Although improved inspection coverage might not have affected the outcome of this incident, the Safety Board is nonetheless concerned that the inspection techniques currently in use permit blind spots in the area of the dovetail blade slots, which are high-stress areas of the spool. Therefore, the Safety Board believes that the FAA should require GEAE to develop and implement improved inspection techniques that will provide 100 percent inspection coverage of high-stress areas of the CF6-50 and -80 series HPC stage 3-9 spool and that will provide the maximum coverage possible of other areas. The Safety Board is also concerned that the incomplete inspection coverage of multistage compressor spools may not be limited only to GEAE CF6-50 and -80 series HPC stage 3-9 spools, but may exist for other multistage compressor spools. Therefore, the Safety Board believes that the FAA should review the prescribed nondestructive inspection techniques for all turbine engine multistage titanium compressor spools to ensure 100 percent inspection coverage of high-stress areas and maximum coverage possible for all other areas and, if necessary, require engine manufacturers to develop and implement improved inspection techniques.

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[9]During FPI, a dye is applied to the surface of the part. The dye penetrates cracks and leaves a surface indication detectable with fluorescent light.

[10]Ultrasonic inspection is a nondestructive method in which beams of high-frequency sound waves are introduced into materials to detect subsurface flaws in the material.

[11]GEAE, Air Accident Investigation Branch of the United Kingdom, and Safety Board personnel reviewed the strip charts from the ultrasonic inspection and confirmed that there were no indications requiring any action. (A strip chart is a continuous length of graph paper that is used to record data in relation to time or distance.)

[12]Eddy current inspections measure fluctuations in an alternating magnetic field around a part generated by a transducer carrying an alternating current. The inspection is used to locate surface and near-surface defects. Eddy current inspections of the HPC stage 3-9 spool were not performed in 1994, when the incident engine and spool were last overhauled.

Possible Role of Melt Deviations in Creating Abnormal Microstructure

The investigation has not formally determined the cause of the abnormal microstructure in the incident spool. However, investigators are examining the possibility that it was related to deviations in the melt process that allowed the introduction of oxygen into the melt. The manufacturing records of the ruptured HPC stage 3-9 spool from flight CP30 indicate that the forward section of the spool (stages 3 through 5) was produced by RMI from Heat[13] No. 981897. RMI's manufacturing records for that heat indicate that the titanium electrode[14] shifted position within the crucible[15] during the second melt. The manufacturing records also indicate that about the same time as the electrode's shift in position, the pressure inside the crucible increased from the normal vacuum of about 100 microns of atmospheric pressure to 900 microns of atmospheric pressure.[16] This increase occurred over the space of 1 minute. Approximately 30 minutes later, the pressure had returned to the normal vacuum of about 100 microns of atmospheric pressure. According to RMI, it is likely that the increase in pressure resulted from the electrode's shift in position, which could have allowed the cooling water from the jacket that surrounds the crucible to leak into the melt. Although the extent of the pressure change (known as a "vacuum excursion") was within RMI and GEAE specifications, which permitted pressure deviations of up to 1,000 microns during the second melt, RMI notified GEAE of the vacuum excursion.[17] GEAE accepted the melt. Subsequently, in October 1991, RMI reduced the specifications for permissible vacuum excursions during secondary and final melts to 750 microns.

A review of GEAE manufacturing records showed that 21 HPC stage 3-9 spools, in addition to the flight CP30 spool, were manufactured from RMI Heat No. 981897.[18] On October 31, 1997, the FAA issued Airworthiness Directive (AD) 97-22-14, which required the removal from service of all 21 spools within 30 days. The FAA and GEAE have advised the Safety Board that all of the other HPC stage 3-9 spools that had been manufactured from RMI Heat No. 981897 have been removed from service. According to GEAE, one of those spools has

[13]A heat, or ingot, is a mass of metal melted into a convenient shape for handling that is later finished by rolling, forging, or other means.

[14]Titanium electrodes for the first (primary) melt consist of cold-pressed compacts containing a mixture of titanium sponge and elemental alloying materials that are welded together into an approximately 15-foot long, 18-inch diameter cylinder. The electrode in the second (intermediate) melt is produced by welding together two or three primary melt ingots end to end. The electrode in the third melt is the melted together mass from the second melt.

[15]The crucible is a water-cooled copper vessel in which the titanium electrode is melted.

[16]An absolute vacuum is zero microns. A standard day pressure of 29.92 inches of mercury is equivalent to 9,875,118 microns.

[17]According to RMI, it notified GEAE of the vacuum excursion because it was close to the maximum excursion allowable (within 100 microns) and its time span was unusually long (approximately 30 minutes).

[18]Of these, only one spool was installed in a U.S.-registered airplane, a Continental Airlines DC-10, N87071. This spool had accumulated 1,075 CSN, far less than the 4,744 cycles that had been accumulated on the spool from flight CP30.

received an ultrasonic, eddy current, and blue-etch anodize (BEA) inspection,[19] and there were no indications of defects or cracks.[20]

According to GEAE, there have been 10 uncontained HPC stage 3-9 spool failures in CF6-50 and -80 series engines.[21] GEAE further indicated that two of these failures, occurring in 1974 and 1979, were caused by fatigue fractures originating from oxygen-rich inclusions in the spools. These spools, which were produced from 16-inch diameter billets melted by RMI, had reportedly accumulated 483 and 2,854 CSN, respectively, at the time of the failures. In a December 5, 1997, letter to the TSB, RMI stated that the furnace records for the two heats from which these spools had been produced showed that minor vacuum excursions had occurred during the initial melt but that those excursions were typical for the production process that was in use and well within RMI and GEAE specification limits. Records also show that one of the heats had an excursion of 600 microns in the second melt (which was within the then-current limits and is within the revised limits for secondary melts).

The Safety Board is concerned that additional HPC stage 3-9 spools or other critical components manufactured from ingots that contain melt variations that can result in abnormal microstructure may be currently in service. Therefore, the Safety Board believes that the FAA should review GEAE's Ti-6242 titanium alloy suppliers' melting records and identify any vacuum excursions or other process deviations that exceed current specifications or that may otherwise cause an inclusion or abnormal microstructure. The Safety Board also believes that based on the results of this review, the FAA should issue an AD to require removal from service and/or inspections of the components manufactured from these melts.

Rapid Propagation of the Crack and the Possible Role of Dwell Time Fatigue

As mentioned above, the fracture morphology of the incident spool was atypical in that most of the fracture region contained brittle cleavage-like, faceted features, rather than classical fatigue striations. Further, the areas of classical fatigue striations included evidence of only 800 flight cycles, indicating a very rapid crack propagation. This fracture morphology is similar to that

[19] In 1991, GEAE began performing BEA inspections on the surface of newly manufactured spools as a further measure to prevent spools with microstructural anomalies from being put into service. However, within areas of generally abnormal microstructure, the arrangement of alpha and beta grains may be such that a given cross-section of the material may not indicate an abnormality that would be apparent from a different view. Therefore, although it is possible that a BEA inspection could detect an area of abnormal microstructure such as that in the incident spool, it is also possible that the microstructure at the surface might not exhibit an abnormal appearance and thus would not be detected by a BEA inspection.

[20] The AD did not require that the spools be subjected to testing after being removed from service.

[21] The Safety Board has previously expressed concern about the continued airworthiness of GEAE CF6-50 and -80 series engine HPC stage 3-9 spools. In 1995, the Safety Board assisted the Egyptian Civil Aviation Authority with the investigation of an uncontained failure of a GEAE CF6-50 HPC stage 3-9 spool that occurred on an Egypt Air Airbus A300B4 during takeoff at Cairo, Egypt, on April 10, 1995. The failure of that spool was caused by a fatigue crack that initiated from a nitrogen-stabilized hard-alpha inclusion in the web portion of the stage 6 disk.

exhibited in several earlier fractures of CF6-50 and -80 series 3-9 spools[22] that were attributed to a cracking phenomenon that became known as dwell time fatigue (DTF). (The Safety Board first became aware of DTF in 1995 during the investigation of the uncontained failure of the CF6-50 stage 3-9 spool that occurred on the Egypt Air Airbus A300.)

DTF refers to a fracture mechanism in which progressive crack growth occurs during cyclic loading (rise and fall of stress) and also over time during sustained peak-stress loading (during the dwell time at the peak stress level), both at low temperature. The fracture morphology is characterized by subsurface initiation and brittle, faceted-cleavage fracture features. According to GEAE, the DTF phenomenon is related to increased plastic strain and slip along crystallographically aligned alpha colonies[23] in the material microstructure. According to metallurgical research literature, the faceted fracture features that occur during DTF in alpha-beta titanium alloys are associated with large primary alpha colonies possessing a similar crystallographic orientation.[24] Other literature indicates that DTF develops at high stresses (approaching the yield stress of the material) and is associated with hydrogen embrittlement developed during time-dependent plastic deformation at the dwell stress.[25]

GEAE conducted a test program[26] that indicated that a significant reduction in a material's fatigue life occurs when it is subject to DTF as compared to conventional fatigue cycling. However, GEAE has been unable to determine the time it takes from manufacture until a crack initiates or the propagation rate of a crack once it initiates in DTF. Absent a predictable crack initiation time and propagation rate (which can be used to establish required inspection intervals designed to detect cracks before they propagate to failure), the prior failure history of the component provides the only data on which to base inspection intervals.

On August 25, 1995, as a result of a review of the spool failures associated with the DTF phenomenon, the Safety Board issued Safety Recommendation A-95-85 urging the FAA to revise AD 95-03-01 (applicable to GEAE CF6-50, -80A, and -80C2 model engines) to require repeated inspection of all HPC stage 3-9 spools that had been solution heat treated after welding.[27] The

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[22]Of the 10 aforementioned uncontained HPC stage 3-9 spool failures, GEAE attributed 4 of the failures to the DTF fracture mechanism. [(a) the 1985 failure in Dakar, Senegal, of a CF6-50, stage 9 disk with 4,075 CSN, which was part of a one-piece spool; (b) the 1991 failure in Seoul, Korea, of a CF6-50, stage 9 disk with 10,564 CSN, which was part of a one-piece spool; (c) the 1993 failure in Los Angeles, California, of a CF6-80C2 stage 6 disk with 4,403 CSN, which was part of a one-piece spool; and (d) the 1995 failure in Bangkok, Thailand, of a CF6-50 stage 8 disk with 8,438 CSN, which was part of a one-piece spool.]

[23]Crystallographically aligned alpha colonies are areas of the microstructure in which a group of alpha grains in proximity to one another have their crystallographic planes similarly oriented.

[24]Woodfield, A.P. et. al. 1995. "Effect of Microstructure on Dwell Fatigue Behavior of Ti-6242." *Titanium '95: Science and Technology*. p. 1116-1123.

[25]Hack, J. E.; Leverant, G. R. 1982. "The Influence of Microstructure on the Susceptibility of Titanium Alloys to Internal Hydrogen Embrittlement." *Metallurgical Transactions*, Volume 13A. p. 1729–1738.

[26] The results of this test program are documented in "Effect of Microstructure on Dwell Fatigue Behavior of Ti-6242," published in *Titanium '95: Science and Technology*. (See complete citation in footnote 24, above).

[27]Until 1995, all two-piece spools received a postweld solution heat treatment followed by a slow cool down. In 1995, according to GEAE, it replaced the solution heat treatment process with a postweld stress-relief process to

Safety Board urged that the maximum interval between inspections should be appropriately less than the 4,000 cycles specified in that AD.[28]

The FAA responded that it agreed with the safety recommendation to require inspections of most GEAE CF6-50, -80A, and -80C2 HPC stage 3-9 spools but did not agree that there should be a maximum interval between all inspections. On November 13, 1995, the FAA issued AD 95-23-03, superseding AD 95-03-01, which reduced the repetitive inspection interval requirements for one-piece HPC stage 3-9 spools made from 16-inch diameter billets used in GEAE CF6-50, -80A and -80C2 engines from a maximum of 4,000 cycles to a maximum of 3,500 cycles. A 3,500-cycle inspection interval was also established for spools made from 13-inch diameter billets that are used on GEAE CF6-80C2 engines. However, the FAA did not make any requirements for mandatory repetitive inspections for one-piece HPC spools made from 13-inch diameter billets installed in CF6-80A engines or on any spools made from two-piece forgings.

In its April 16, 1996, response to the FAA, the Safety Board expressed its concern that further failures of stage 3-9 spools could occur at the 3,500-cycle inspection interval and stated that it believes the 3,500-cycle inspection interval was based primarily on economic considerations, not on fracture propagation or low-cycle failure events. The Safety Board response further stated that the earliest DTF separation of a compressor spool had occurred after 4,075 CSN in a spool made from a 16-inch diameter billet. The Safety Board also investigated the separation of an HPC spool made from a 13-inch diameter billet that occurred in a CF6-80C2 engine after 4,403 CSN. The pieces of the separated spool containing the fracture origin area were not recovered, so the exact fracture mechanism was not determined. However, the investigation concluded that the aligned alpha colonies in the microstructure of the spool made it susceptible to DTF. These spool separations indicate that complete failure resulting from DTF can occur after a relatively low number of cycles.

In a December 3, 1996, letter, the Safety Board indicated that AD 95-23-03 did not satisfy the intent of Safety Recommendation A-95-85, and the recommendation was classified "Closed—Unacceptable Action."

The Safety Board notes that in addition to having a fracture morphology similar to that of the spools that failed from DTF, the fracture of the stage 3 disk on flight CP30 initiated at a subsurface location in an area of high stress, and the material microstructure contained an aberrant alpha structure. Although the fracture initiation area of the flight CP30 spool did not exhibit crystallographically aligned alpha grains, such as has been associated with previous DTF fractures, it did contain an area of predominately alpha phase. In contrast, the fracture mechanism on the spool of the Egypt Air Airbus A-300 that failed in 1995, which was also made from Ti-6242,

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eliminate what GEAE had determined to be a propensity for grain growth and crystallographically aligned alpha colonies that occurred during the slow cool down from high temperature.

[28]AD 95-03-01, issued on February 16, 1995, required repetitive (at intervals not to exceed 4,000 cycles) ultrasonic and eddy current inspections of spools made from 16-inch diameter billets. (AD 91-20-01, issued October 25, 1991, had earlier required one-time [within 3,500 cycles] ultrasonic and eddy current inspections of spools made from 16-inch diameter billets.)

showed classical fatigue striations that correlated by striation count to the total engine cycles for the spool (indicating much slower propagation rates than those produced by DTF). Further, the fracture features on the Egypt Air spool did not contain cleavage-like, faceted fractures like those associated with DTF, nor did the microstructure contain any aberrant alpha phase. This shows that not all fatigue failures of the Ti-6242 alloy exhibit this unusual fracture morphology and those that do have aberrant alpha phase in the microstructure.

This suggests that although stage 3-9 spools made from Ti-6242 that have a normal, homogeneous alpha/beta microstructure can operate in service free of any cracking, if the spool has an abnormal alignment or distribution of alpha grains in a high-stress area, it can fracture unpredictably and rapidly. Although the Safety Board recognizes that failures associated with DTF and the failure of the 3-9 spool from flight CP30 might also have been affected by other as-yet-unknown factors, the Safety Board concludes that CF6-50 and -80 series HPC stage 3-9 spools may be uniquely susceptible to unpredictable crack-initiation times and rapid-crack growth rates. Therefore, the Safety Board believes that the FAA should conduct a critical design review of CF6-50 and -80 series HPC stage 3-9 spools to assess the overall safety and soundness of the part. The review should, at a minimum, evaluate the following: the adequacy of current and past manufacturing processes, including the ability of current and previous melt specifications and postweld procedures to protect against the creation of microstructural abnormalities; the propriety of using Ti-6242 titanium alloy, including the possible susceptibility of this alloy to the development of aberrant or undesirable crystallographic arrangements of alpha phase and a resulting vulnerability to rapid cracking; and the adequacy of the stress margins for the spool in the presence of an aberrant or undesirable microstructure.

Further, the Board remains concerned that not all CF6-50 and -80 series HPC stage 3-9 spools are required to be subjected to repeated inspections at intervals appropriately less than 4,000 cycles. Further, because it is not yet known (because the change is too recent) whether the cessation in 1995 of the postweld solution heat treatment has eliminated the susceptibility of those parts to DTF, it is possible that even those spools that were not subjected to this process are vulnerable. Therefore, the Safety Board believes that the FAA should revise AD 95-23-03, applicable to GEAE CF6-50, -80A, and -80C2 model engines, to include the -80E model engines, and to require repeated inspections of all HPC rotor stage 3-9 spools at maximum intervals appropriately less than 4,000 cycles.

Therefore, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Require General Electric Aircraft Engines to develop and implement improved inspection techniques that will provide 100 percent inspection coverage of high-stress areas of the CF6-50 and -80 series high-pressure compressor stage 3-9 spool and that will provide the maximum coverage possible of other areas. (A-98-27)
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> Review the prescribed nondestructive inspection techniques for all turbine engine multistage titanium compressor spools to ensure 100 percent inspection coverage of high-stress areas and maximum coverage possible for all other areas and, if

necessary, require engine manufacturers to develop and implement improved inspection techniques. (A-98-28)

Review General Electric Aircraft Engines' Ti-6242 titanium alloy suppliers' melting records and identify any vacuum excursions or other process deviations that exceed current specifications or that may otherwise cause an inclusion or abnormal microstructure. Based on the results of this review, issue an airworthiness directive to require removal from service and/or inspections of the components manufactured from these melts. (A-98-29)

Conduct a critical design review of CF6-50 and -80 series high-pressure compressor stage 3-9 spools to assess the overall safety and soundness of the part. The review should, at a minimum, evaluate the following:

- the adequacy of current and past manufacturing processes, including the ability of current and previous melt specifications and postweld procedures to protect against the creation of microstructural abnormalities; (A-98-30)

- the propriety of using Ti-6242 titanium alloy, including the possible susceptibility of this alloy to the development of aberrant or undesirable crystallographic arrangements of alpha phase and a resulting vulnerability to rapid cracking; (A-98-31) and

- the adequacy of the stress margins for the spool in the presence of an aberrant or undesirable microstructure. (A-98-32)

Revise Airworthiness Directive 95-23-03, applicable to General Electric Aircraft Engines CF6-50, -80A, and -80C2 model engines, to include the -80E model engines, and to require repeated inspections of all high-pressure compressor rotor stage 3-9 spools at maximum intervals appropriately less than 4,000 cycles. (A-98-33)

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

By: Jim Hall
Chairman