National Transportation Safety Board
Washington, D.C. 20594

Safety Recommendation

Date: December 12, 2000

In reply refer to: A-00-121 through -124

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

In this letter, the National Transportation Safety Board recommends that the Federal Aviation Administration (FAA) take action to address safety issues that were identified during its investigation of an uncontained engine failure[1] that occurred at Philadelphia, Pennsylvania, on September 22, 2000, as a result of cracking and rupture of a high pressure turbine (HPT) stage 1 disk[2] in a General Electric (GE) CF6-80C2B2 engine (see figure 1).

Background

On September 22, 2000, a US Airways Boeing 767-2B7(ER) airplane, N654US, equipped with GE CF6-80C2B2 engines, experienced an uncontained failure of the HPT stage 1 disk in the No. 1 engine during a high-power ground run for maintenance at Philadelphia International Airport, Philadelphia, Pennsylvania. Because of a report of an in-flight loss of oil, US Airways mechanics had replaced a seal on the No. 1 engine's integral drive generator and were performing the high-power engine run to check for any oil leakage. For the maintenance check, the mechanics had taxied the airplane to a remote taxiway on the airport and had performed three runups for which no anomalies were noted. During the fourth excursion to high power, at around 93 percent N1 rpm,[3] there was a loud explosion followed by a fire under the left wing of the airplane. The mechanics shut down the engines, discharged both fire bottles into the No. 1 engine nacelle, and evacuated the airplane. Although both fire bottles were discharged, the fire continued until it was

[1] An uncontained engine failure occurs when an integral part of the engine fails and is ejected through the cowling.
[2] The HPT stage 1 disk/shaft consists of separate forgings for the disk and the shaft section in front of the disk, which are welded together.
[3] N1 rpm is the low pressure rotor speed.

extinguished by airport fire department personnel. The No. 1 engine and the airplane sustained substantial damage.[4] The three mechanics were not injured.

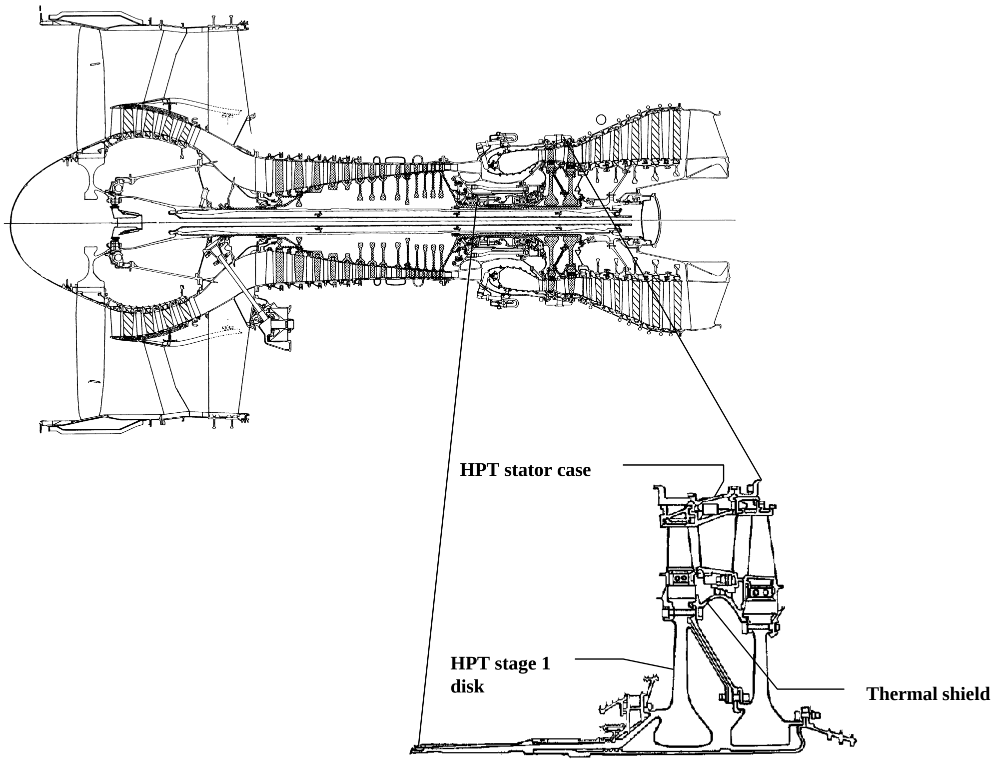

Figure 1. Cross-section of a GE CF6-802 engine and enlarged view of the HPT module

This incident raises serious safety concerns because, if it had occurred during flight rather than on the ground during maintenance, the airplane might not have been able to maintain safe flight. Examination of the airplane revealed that a portion of the HPT stage 1 disk penetrated the left wing just inboard of the No. 1 engine pylon. Investigators determined that this portion of the disk, which is approximately 140 square inches and 45 pounds, penetrated a dry bay, made a 1-inch-wide vertical cut through the lower half of the forward wing spar, and penetrated a fuel tank before exiting through the top of the wing and passing over the fuselage. Examination of the engine revealed that the disk rupture split the engine in half, leaving the rear of the engine joined to the front only by the fan midshaft. The disk had separated from the shaft and was completely missing from the engine. Two pieces of the disk, which amounted to about two-thirds of it, and three blade slot posts were recovered.[5] Although an extensive search was conducted, the remaining one-third of the ruptured disk (the piece that passed through the wing) was not recovered. Trajectory analysis performed by the Safety Board indicates that it may have landed in the Delaware River, which is adjacent to the airport.

[4] Although the airplane was substantially damaged, the Safety Board has categorized this event as an incident rather than an accident because there was no intention for flight, as defined by 49 *Code of Federal Regulations* (CFR) 830.2, when the engine rupture occurred.

[5] One piece of the disk and the blade slot posts were recovered from under the airplane and engine. The other piece of the disk was recovered approximately 1,200 feet away from the airplane.

The ruptured HPT stage 1 disk was machined from an Inconel 718 nickel alloy forging. According to US Airways' maintenance records, the ruptured disk, part number 9392M23G12, serial number MPOS9912, had accumulated 7,547 cycles since new (CSN). US Airways' maintenance records further reveal that, in December 1989 at 2,439 CSN, some of the disk's blade slot bottom aft corners were blend repaired[6] during overhaul at Caledonian Airmotive in Prestwick, Scotland.[7] The records also show that in April 1994 at 5,873 CSN (1,675 cycles before the rupture occurred) additional blend repairs were made to several blade slot bottoms by Caledonian Airmotive. The records indicate that at that time, the disk underwent fluorescent penetrant inspection (FPI)[8] and no defects were noted. Following these repairs, before the disk was put back in service, the disk was shipped to GE's Aviation Component Service Center (ACSC), in Cincinnati, Ohio, so that the disk's armpit[9] could be machined. Maintenance records indicate that, while at this facility, the part also underwent FPI and all blended areas were shotpeened.[10] The part was then returned to Caledonian Airmotive.[11] US Airways' records show that in November 1999, GE Engine Services in Ontario, California, installed the incident disk, at 6,942 CSN, into the incident engine.

Examination of the recovered pieces of the disk at the Safety Board's materials laboratory revealed that it had separated from a rim-to-bore radial fracture that intersected a blade slot bottom. Examination of the fracture with a binocular microscope and at higher magnifications with a scanning electron microscope revealed that most of the fracture was overstress stemming from a preexisting intergranular fatigue region adjacent to the blade slot bottom. Although the periphery of the fatigue region contained secondary damage, the presence of randomly located areas of fatigue striations indicated that fatigue initiation was from the corner between the blade slot bottom and the aft face of the disk. Metallurgical examination also showed that the material composition, grain size, microstructure, and hardness conformed to material specifications. The examination did not reveal any evidence of melt-related inclusions or disk overheating at the

[6] The CF6-80C2 Engine Manual provides repair instructions for blending damage in the blade slot bottoms and corners in Tasks 72-53-02-300-002 - Repair of Scratches in Dovetail Slot Bottom, Repair 002 and 72-53-02-300-009 - Blend Repair of the Critical Areas of the HPT Stage 1 Disk, Repair 009. Repair 002 requires that any scratches in the dovetail slot bottoms be blended out using abrasive paper or crocus cloth so the finish and contour on the blended surface is as close to the original as possible. The blended surface is then to be etched, fluorescent penetrant inspected, and shotpeened. Repair 009 is performed in areas that have been identified as critical, such as the blade slot bottom corner radius, and requires the repair station to substantiate that it can perform the repair. Repair 009 requires that the corner radius be blended using an abrasive paper then polished with a rubberized abrasive wheel to a surface finish of 32 microinches (the height between the bottom and peak of the blending marks), or less. The blended surface is then to be etched, fluorescent penetrant inspected, and shotpeened.

[7] US Airways, which at the time of the repair was known as US Air, used Caledonian Airmotive, a 14 CFR Part 145 repair station, to repair its CF6-80C2 engines until mid-1996. Caledonian Airmotive was subsequently purchased by GE Engine Services and renamed GE Caledonian.

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

[9] The disk's armpit is the inner diameter radius between the front face of the disk and the conical section of the shaft.

[10] Shotpeening is a metallurgical surface treatment to improve resistance to cracking wherein the surface to be treated is bombarded with air-propelled steel shot.

[11] The records also show that during the FPI at GE, the disk was dropped. The part was visually inspected, nicks on the aft bore face and post tips resulting from the drop were blended, and the part underwent FPI with no defects noted.

fracture location. The aft face of the disk and the blade slot bottom surface contained dimpled features indicative of shotpeening.[12]

During the investigation of the US Airways incident, the Safety Board learned of two other CF6-80C2 HPT stage 1 disks that had cracks emanating from blade slot bottoms that were similar to the cracks observed on the US Airways HPT stage 1 disk.[13] The disks had been forwarded to GE's ACSC facility for overhaul where the cracks were detected during FPI. GE provided the Safety Board with metallurgical investigation reports for both of these disks, one of which had been installed on an airplane operated by Thai Airways International and the other on a Gulf Air airplane.

The Thai Airways disk, which was examined by GE in 1996 at 5,144 CSN and 1,453 cycles since overhaul (CSO),[14] was found to have three blade slot bottoms with intergranular fatigue cracks. The cracks originated from areas of blending marks (referred to in the GE report as "grinding") at the corner between the slot bottom and the aft face of the disk. From each origin area, cracking progressed radially inward and forward. GE's visual examination of the cracked blade slot bottoms revealed evidence of blending marks at the origin areas but no evidence that shotpeening had been reapplied over the blending.[15] A cross-section through the cracked blade slot bottoms showed the aft corner of the slot bottom had been cut back 0.008 inches from the original contour. The GE report concluded that a metal rod was improperly used to remove the thermal shield[16] that attaches to the rear face of the disk and that this caused damage to the blade slot bottoms that had to be blend repaired.

The Gulf Air disk, which was examined by GE in 1999 at 9,532 CSN,[17] was found to have one blade slot bottom with an intergranular fatigue crack. This crack also initiated at the corner between the slot bottom and the aft face of the disk and progressed radially inward and forward. GE's visual examination of the disk showed the crack origin was in an elliptical-shaped area of displaced material, such as would be made by a rod. Examination of the disk's surface showed no evidence of any surface blending or shotpeening on the displaced material.

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[12] The Safety Board is unable to determine whether this operation occurred at manufacture or following a blend repair.

[13] The three HPT stage 1 disks were each produced from different batches of metal.

[14] The Thai Airways disk was overhauled at KLM Royal Dutch Airlines' maintenance facility.

[15] As previously mentioned, according to Repair 002, the blade slot bottoms should have been shotpeened after being blended.

[16] The thermal shield front rabbet (a diametric feature on a part that engages to a diametric feature on an adjacent part) has an interference fit to the rear face of the disk, which makes it difficult to remove. The diameters of the two features are machined to slightly different dimensions, typically between 0.005 to 0.010 inches, to create an interference fit in order to align and lock the parts together. Subtask 72-53-00-040-053 - Removal of Stage 1 Disk/Shaft, Disassembly in GE's CF6-80C2 Engine Manual specifies placing dry ice about the thermal shield forward face to reduce the interference rabbet fit and then using a heat gun to increase the temperature of the stage 1 disk, starting at the bore and moving toward the outer diameter. The disk is to be turned slowly for approximately 3 minutes while the heat is applied.

[17] The Gulf Air HPT stage 1 disk was overhauled by Gulf Air. GE's metallurgical report for this disk did not contain CSO data.

Surface Damage to HPT Stage 1 Disks

Photographs of the Gulf Air disk clearly show that the crack originated from an area of surface damage on the aft face directly adjacent to the blade slot bottom corner. The blending repair that had been accomplished to the blade slot bottom corners on the Thai disk and GE's assessment of the disk and possible reason for the repair suggest that the cracks in this disk also originated from areas that had been damaged on the surface. The US Airways disk fracture origin was obliterated by secondary damage that prevented identifying any surface damage or blending marks (which would indicate an attempt to repair surface damage). However, as was mentioned previously, US Airways maintenance records show that the ruptured disk's blade slot bottoms had been blended on two occasions, the last of which occurred during the 1994 repair by Caledonian Airmotive 1,675 cycles before the rupture occurred. Therefore, although it is not known whether any of those blend repairs were to the same blade slot bottom that subsequently fractured, it is possible that they were. If so, this would suggest that the origin of the fatigue crack in the US Airways disk was also located in an area that had been damaged. The possibility that the US Airways disk's blade slot bottom may have sustained surface damage similar to that sustained by the Thai Airways and Gulf Air disks is further supported by the nearly identical location and fracture mode exhibited by all three disks.

The Thai Airways disk indicates that even if a blend repair to the damaged area is accomplished, underlying damage may remain that can cause cracking. The cracks in the Thai Airways and Gulf Air disks very likely would have propagated to catastrophic failure if they had not been detected during maintenance that was unrelated to the HPT stage 1 disk. The US Airways event indicates that a crack can initiate and propagate to failure in as little as 1,675 cycles. It should be noted that the HPT stage 1 disk is not required to be inspected at regular intervals; it is inspected only "on condition." Consequently, the Board is concerned that there may be other CF6-80C2 engines with HPT stage 1 disks in which damage to blade slot bottoms could exist which, even if blend repaired, could allow cracking to initiate and propagate to failure. Although there is no clear method for identifying all disks that have sustained surface damage that might lead to cracking, the accomplishment of a blend repair would likely identify many, if not most, disks that have sustained such damage. (Although there was no evidence of a blend repair to the Gulf Air disk, the damage was significant enough to warrant a blend repair and the Safety Board expects that on most disks such damage would have been blend repaired.) Therefore, the Safety Board believes that the FAA should require operators of GE CF6-80C2 engines to review their engine maintenance records for any HPT stage 1 disks with blade slot bottoms that have been blend repaired. Any CF6-80C2 engines that are found to have an HPT stage 1 disk with a record of having had a blade slot bottom blend repaired should be removed from service and inspected at appropriately less than 1,675 cycles since the blend repair was accomplished and at appropriate intervals thereafter.

The possibility that surface damage might have been caused by the use of a metal rod to remove the thermal shield from an HPT stage 1 disk is of particular concern to the Safety Board because it is contrary to the maintenance procedures specified in GE's CF6-80C2 Engine Manual. Further, it appears that this practice may induce damage that can lead to cracking and possible failure of the HPT stage 1 disk. Although the Board has no way of determining the prevalence of this unacceptable maintenance practice, its possible role in causing the cracked disks discussed in this safety recommendation letter is sufficiently alarming to warrant FAA action. Therefore, the Safety Board believes that the FAA should issue a flight standards information bulletin that informs principal maintenance inspectors and GE CF6-80C2 engine overhaul facilities of the circumstances of the cracking detected in the US Airways, Thai Airways, and Gulf Air HPT stage 1 disks and that emphasizes the potentially catastrophic consequences of damage caused by not adhering to prescribed maintenance procedures when removing the thermal shield, or any other components, from GE CF6-80C2 HPT stage 1 disks.

The Safety Board notes that Task 70-32-02-230-001, Class G in the CF6-80C2 Engine Manual currently specifies that HPT stage 1 disks undergo FPI with an ultra-high sensitivity penetrant solution. The Safety Board is concerned that although the specified FPI process detected the cracks in the Thai Airways and Gulf Air HPT stage 1 disks, the process may not always be able to detect such cracks (GE has expressed a similar concern). The Safety Board is also concerned that the blending process used to repair surface damage on the blade slot bottoms can smear the metal and possibly mask cracks that would otherwise be detectable by FPI.[18] GE has indicated that because FPI may not always detect cracks like those in the Thai Airways and Gulf Air disks, it is developing an eddy current inspection[19] procedure, which has a higher probability of detection than FPI, for use on CF6-80C2 HPT stage 1 disk blade slot bottoms. Therefore, the Safety Board believes that the FAA should require implementation of the eddy current inspection procedure being developed by GE for CF6-80C2 HPT stage 1 disk blade slot bottoms.

Adequacy of HPT Stage 1 Disk Design and Continuing Airworthiness Program

As previously discussed, it is possible that the cracks in each of the three HPT stage 1 disks discussed in this letter were the result of surface damage. However, the Safety Board recognizes that there is no clear evidence of surface damage on the area of the US Airways disk from which the crack originated and, therefore, it is also possible that the crack in that disk initiated from an undamaged blade slot bottom. Further, metallurgical examination revealed that in the area immediately adjacent to the fracture origination point, the radius between the slot bottom and the forward and aft faces of the disk conformed to the engineering drawing requirements for that radius, suggesting that the area from which the crack initiated also conformed. This possibility raises concerns that the design of the slot bottom of the GE CF6-80C2 HPT stage 1 disk may not provide an adequate margin of safety even when the disk is manufactured to specifications. Further, during the Safety Board's examination of the separated disk from the US Airways airplane, it was found that many of the radii between the slot bottoms and the forward and aft faces of the disk either exceeded or were less than the engineering drawing requirements for this radius. The number of corners with a nonconforming radius far exceeded the quantity that records indicate had been blend repaired, which suggests that this

[18] It should be noted that the Gulf Air disk was not blend repaired, and all steps in the blend repair process were not accomplished on the Thai Airways disk.

[19] 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.

condition may have occurred at manufacture.[20] The Safety Board is concerned that out-of-tolerance radii may negatively affect the fatigue life of the CF6-80C2 HPT stage 1 disk and that this factor was not taken into account in establishing the operating stress levels.

Therefore, the Board believes that the FAA should conduct a design review of the GE CF6-80C2 engine's HPT stage 1 disk (including a stress analysis) to evaluate the adequacy of the current design. On the basis of the results of this review and the results of the inspection of blend-repaired disks, require appropriate changes to the disk's design and/or to its continuing airworthiness program; in addition to requiring eddy current inspections as previously specified, the FAA should consider establishing hard time inspection intervals, or modifying the blend repair procedures and/or the circumstances under which such repairs are allowable.

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

> Require operators of General Electric (GE) CF6-80C2 engines to review their engine maintenance records for any high pressure turbine (HPT) stage 1 disks with blade slot bottoms that have been blend repaired. Any CF6-80C2 engines that are found to have an HPT stage 1 disk with a record of having had a blade slot bottom blend repaired should be removed from service and inspected at appropriately less than 1,675 cycles since the blend repair was accomplished and at appropriate intervals thereafter. (Urgent) (A-00-121)
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> Issue a flight standards information bulletin that informs principal maintenance inspectors and General Electric (GE) CF6-80C2 engine overhaul facilities of the circumstances of the cracking detected in the US Airways, Thai Airways, and Gulf Air high pressure turbine (HPT) stage 1 disks and that emphasizes the potentially catastrophic consequences of damage caused by not adhering to prescribed maintenance procedures when removing the thermal shield, or any other components, from GE CF6-80C2 HPT stage 1 disks. (Urgent) (A-00-122)
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> Require implementation of the eddy current inspection procedure being developed by General Electric for CF6-80C2 HPT stage 1 disk blade slot bottoms. (A-00-123)
>
> Conduct a design review of the General Electric CF6-80C2 engine's high pressure turbine stage 1 disk (including a stress analysis) to evaluate the adequacy of the current design. On the basis of the results of this review and the results of the inspections of blend-repaired disks specified in Safety Recommendation A-00-121, require appropriate changes to the disk's design and/or to its continuing airworthiness program; in addition to the requiring eddy current inspections as specified in Safety Recommendation A-00-123, the FAA should consider establishing hard time inspection intervals, or modifying the blend repair

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[20] According to GE, the blade slot bottom corner radius is produced by a hand-finishing operation during the manufacturing process.

procedures and/or the circumstances under which such repairs are allowable. (A-00-124)

Acting Chairman HALL and Members HAMMERSCHMIDT, GOGLIA, BLACK, and CARMODY concurred in these recommendations.

Original signed

By: Jim Hall
Acting Chairman