National Transportation Safety Board
Washington, D.C. 20594

Safety Recommendation

Date: August 9, 2000

In reply to refer to: A-00-104

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 a safety issue concerning uncontained engine failures[1] as a result of cracking and rupture of high pressure compressor (HPC) stage 3-9 spools in General Electric (GE) CF6-50 and -80 series engines. The Safety Board identified this safety issue during its participation in the Brazilian Centro de Investigaçáo e Prevençáo de Accidentes Aeronauticos' (CENIPA) investigation[2] of an uncontained engine failure that occurred at São Paulo, Brazil, on June 7, 2000. Although the investigation is continuing, information gathered thus far has raised serious concerns that warrant immediate action by the FAA.

On June 7, 2000, Varig Brasil Airlines flight 886, a Boeing 767-241ER airplane, equipped with GE CF6-80C2B2 engines, experienced an uncontained failure of the HPC stage 3-9 spool in the No. 2 (right) engine during takeoff at São Paulo, Brazil. The airplane was departing São Paulo on a regularly scheduled passenger flight to Lima, Peru. The flight crew reported that at a speed of about 60 knots, they heard a loud bang. They rejected the takeoff and stopped the airplane on the runway. The copilot opened the right-side cockpit window to look out and advised the pilot that there was a fire around the right main landing gear. The flight crew reported that they then attempted to taxi clear of the fire but stopped the airplane on the runway again when they realized it was the engine that was on fire and ordered an evacuation. Although the flight crew discharged both fire bottles into the No. 2 engine nacelle, the fire continued until it was extinguished by airport fire department personnel.[3] Of the 2 pilots, 11 flight attendants, and 178 passengers on board, 4 passengers were injured during the evacuation.

[1] An uncontained engine failure occurs when an integral part of the engine fails and is ejected through the cowling.
[2] The Safety Board is assisting CENIPA with its investigation under the provisions of Annex 13 to the International Convention on Civil Aviation.
[3] The fire warning did not activate until some time after the event occurred. The failure of the fire warning system to activate is under investigation.

Examination of the airplane revealed that the fuselage forward of the right main landing gear was penetrated, but the passenger compartment was not. There was no damage to any aircraft systems. The underside of the right wing adjacent to the No. 2 engine strut was damaged by heat from the fire. The fire was caused by fuel leaking from the fuel inlet line, which was pulled out of the fuel pump by the outward movement of the HPC case when the spool ruptured. Although the wing had numerous impact marks, it was not penetrated by any debris.

Examination of the engine revealed that the HPC case had an almost 360° rupture between the stage 5 variable stator vanes and the stage 8 compressor bleed air ports. The stage 6, 7, and 8 disks and a portion of the rim and web of the stage 9 disk had separated from the rest of the HPC stage 3-9 spool and were ejected radially outward from the engine. Approximately 95 percent of the ejected pieces of the HPC stage 3-9 spool were recovered.

The ruptured HPC stage 3-9 spool is a rotor one-piece component machined from a single forging[4] of Ti-6-2-4-2 titanium alloy and composed of disks joined together with integral spacer segments and end flanges (see figure 1). According to Varig Airlines' maintenance records, the ruptured HPC stage 3-9 spool, part number 9380M28P05 and serial number VOL02558, had accumulated 37,755 hours and 9,948 cycles since new (CSN). Varig's maintenance records also show that, on September 22, 1997, at 8,907 hours and 2,375 cycles before the rupture, the entire spool underwent a fluorescent penetrant inspection (FPI)[5] and the disk bores underwent an ultrasonic inspection[6] at Varig Brasil Airlines' engine shop.[7] No defects were noted during those inspections.

In addition, the record sheet for the FPI inspection was annotated to indicate that the inspection was accomplished in accordance with GE's best practices[8] for FPI of deep disk spools. A review of the HPC stage 3-9 spool FPI process at GE Varig revealed that it conformed with GE's best practices for FPI of deep disk spools. According to the FPI shop personnel, the process had not changed from what was accomplished when Varig Brasil Airlines operated the engine overhaul facility.

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[4] The ruptured HPC stage 3-9 spool was made from a one-piece 13-inch diameter billet. (A billet is a semifinished round product from which a part is forged.) In the past, GE has also made HPC stage 3-9 spools from one-piece 16-inch diameter billets, two-piece 9- and 10-inch diameter billets, and two-piece 8-inch diameter billets. In 1999, GE began producing five-piece HPC stage 3-9 spools, made of four pieces (stages 3 through 5, 6, 7, and 8) of Ti 6-4 titanium alloy (containing 6 percent aluminum and 4 percent vanadium) and one piece of Ti 6-2-4-2 titanium alloy (containing 6 percent aluminum, 2 percent tin, 4 percent zirconium, and 2 percent molybdenum).

[5] 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.

[6] Ultrasonic inspection is a nondestructive testing (NDT) method in which high-frequency sound waves are projected into a solid object to detect and locate subsurface flaws.

[7] On October 7, 1998, GE Engines Services formed a joint venture with Varig Brasil Airlines, and the engine overhaul facility was renamed GE Varig.

[8] In 1995, GE sent an all operators wire to operators of CF6-6, -50, -80A, -80C, and -80E engines that recommended using support equipment to hold the stage 3-9 spools horizontally when dipping them into the penetrant solution and to rotate the spool in the solution to ensure 100 percent coverage.

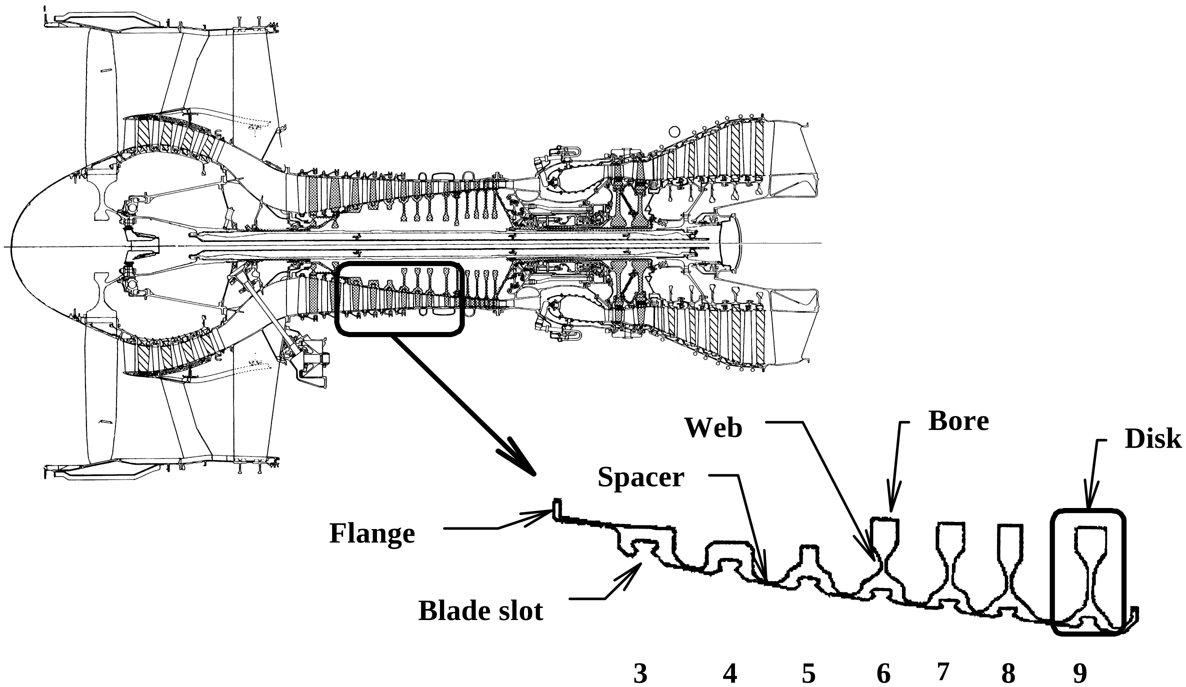

Figure 1. CF6-80C2 Engine and HPC Stage 3-9 Spool in Cross Section

Metallurgical examination[9] of the Varig 3-9 spool revealed a fracture that originated in the stage 7 web from a 0.12 by 0.04-inch subsurface area of quasi-cleavage (rather than a specific point of origin).[10] From the origin area, the fracture propagated in a combination of low cycle fatigue and quasi-cleavage radially inward toward the bore and outward toward the rim and dovetail blade slots, reaching an overall length of about 2.6 inches, before the spool separated. Metallographic examination of the web near the area of the fracture's origin and the bore revealed that the microstructure was comprised of about 75 percent primary alpha with 25 percent transformed beta grains.[11] The microstructure of the rim (under the blade slots) was a 50/50 mix of primary alpha and transformed beta grains.

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[9] Portions of the metallurgical examination were conducted at Centro Tecnológico da Aeronáutica, San José dos Campos, Brazil; the Safety Board's materials laboratory, Washington, D.C.; and, with Safety Board participation, at GE's materials laboratory, Cincinnati, Ohio.

[10] Quasi-cleavage is a brittle fracture mode in which separation occurs largely along crystallographic planes.

[11] Primary alpha and transformed beta grains are types of crystallographic structure. Ti-6-2-4-2 should have a homogeneous 50/50 mix of primary alpha and transformed beta grains, with a random crystallographic orientation.

Electron backscatter diffraction[12] of the origin region revealed colonies of primary alpha grains aligned such that their basal planes[13] were nearly perpendicular to the hoop stress.[14] The scanning electron microscope (SEM) examination of the fracture surface further revealed that the morphology of the fracture away from the origin was predominately quasi-cleavage with random patches of classical fatigue striations. The quasi-cleavage fracture features observed on the fracture surface during metallurgical examination and the highly aligned primary alpha crystal structure are indicative of dwell-time fatigue (DTF).[15]

The examination of the fracture surface with the SEM revealed approximately 18,000 striations from the origin area to the end of the progressive growth region.[16] On the basis of the metallurgical examination, it was determined that the crack had broken through the surface and was estimated to be about 0.3 to 0.6 inch long on the stage 7 web surface at the time of the last FPI but had not been detected.

According to nondestructive test (NDT) literature, the probability of detection of a 0.3 to 0.6 inch-long surface defect when looking directly at the surface is about 83 to 89 percent, respectively.[17] Although GE reported during the investigation of a previous 3-9 spool rupture[18] that inspections had detected DTF in at least 21 spools, GE fracture mechanics personnel recently stated that, to their knowledge, FPI has never detected a DTF crack on the interior surfaces of an HPC stage 3-9 spool.[19] This statement and the circumstances of the Varig Airlines HPC stage 3-9 spool failure suggest that FPI of the interior surfaces of an HPC stage 3-9 spool may be inadequate to detect cracks that are not in the inspector's direct line of sight.

The Safety Board has assisted with the investigations of other uncontained HPC stage 3-9 spool failures in which then-current inspection methods were found deficient. In 1995, the Safety Board assisted the Egyptian Civil Aviation Authority in its investigation of an uncontained failure

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[12] Electron backscatter diffraction, or orientation imaging, is a technique that can use the electron backscatter patterns generated by a scanning electron microscope to determine crystallographic orientation of a material.

[13] The basal plane is one of the planes in the unit cell of the primary alpha grains of the titanium material.

[14] Hoop stress is the circumferential stress within ring-shaped parts.

[15] DTF is a fracture mechanism in which progressive crack growth occurs during cyclic loading and also over time during sustained peak-stress loading. DTF occurs when there is large concentration, or colony, of primary alpha grains that are crystallographically aligned so the primary alpha grain's basal plane is perpendicular to the primary stress field.

[16] GE stated that a DTF crack actually advances 2 or 3 striations per flight cycle because of the high thrust settings required for reverse, takeoff power, and certain types of approaches. (GE reported that because of the high air traffic density at airports in the United States and Europe, airplanes approaching to land at airports in these locations have to maintain high power settings when they level off at intermediate altitudes. GE further reported that airplanes operating into South American airports, where the air traffic density is not as high, typically do not have to level off at intermediate altitudes.)

[17] Rummel, Ward D.; Matzkanin, George A. 1996. *Nondestructive Evaluation (NDE) Capabilities Data Book.* Appendix C, Data Set PTAA01L-A. Nondestructive Testing Information Analysis Center, Texas Research Institute Austin, Inc., Austin, Texas.

[18] In 1998, the Safety Board assisted the Canadian Transportation Safety Board in its investigation of an uncontained HPC stage 3-9 spool failure at Beijing, China, in a CF6-80C2B6F engine that was installed on a Canadian Airlines International Boeing 767-300ER.

[19] Much of the interior surface of an HPC stage 3-9 spool cannot be seen directly; therefore, the inspection of the spool's disk webs requires the use of a mirror in addition to an ultraviolet light source.

at Cairo, Egypt, of a CF6-50C2 engine that was installed on an EgyptAir A300B4 airplane. The failure in the EgyptAir engine was attributed to a nitrogen-stabilized hard alpha inclusion[20] in the stage 6 disk web. The investigation revealed that engine overhaul shops were dipping HPC stage 3-9 spools into the fluorescent penetrant solution vertically and that this procedure permitted a bubble of air to become trapped under the disk web, thus preventing the fluorescent penetrant solution from contacting the entire interior surface of an HPC stage 3-9 spool. As a result of the EgyptAir investigation, GE issued the all operators wire that detailed FPI best practices for deep disk spools.

In 1998, the HPC stage 3-9 spool failure in the Canadian Airlines engine was attributed to a DTF fracture that occurred in the stage 3 rim below the dovetail blade slot. The investigation revealed that the FPI and ultrasonic inspection techniques performed on the spool 4 years before it failed did not provide 100 percent inspection coverage of the spool. The Safety Board is aware of 10 other CF6-50 and -80 series engines that have experienced ruptured HPC stage 3-9 spools from either hard alpha inclusions or DTF.[21]

As a result of the findings in the Canadian Airlines International investigation, the Safety Board issued Safety Recommendation A-98-27 requesting the FAA to require GE to develop and implement improved inspection techniques that will provide 100 percent coverage of high-stress areas of the CF6-50 and -80 series HPC stage 3-9 spool and maximum coverage possible for all other areas. In response, the FAA issued Airworthiness Directive (AD) 99-24-15 on October 18, 1999, which requires an ultrasonic inspection of the disk bores and webs and an eddy current inspection[22] of the dovetail slots for the CF6-50 and -80 series HPC stage 3-9 spool.[23]

GE's recommended best practices for FPI notwithstanding, the Safety Board remains concerned that the FPI process is inadequate to inspect the interior surfaces of the HPC stage 3-9 spool. The Board is also concerned that the in-service HPC stage 3-9 spools that have not yet been inspected in accordance with AD 99-24-15 may have undetected cracks that could propagate to critical length and rupture. Such ruptures, if uncontained, could result in a catastrophic accident.

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[20] Hard alpha inclusions are anomalies in titanium alloys that usually form during the initial melting of the raw materials and are caused by localized excess amounts of either oxygen or nitrogen that have been introduced through atmospheric reaction with titanium in the molten state.

[21] Of these 10, all were uncontained engine failures, six occurred because of hard alpha inclusions, and four occurred because of DTF. The Safety Board does not have any information about whether FPI failed to detect the cracks that led to these failures.

[22] Eddy current inspection is an NDT method for detecting surface cracks in which an electromagnetic field is induced into a metal part by an external coil carrying an alternating current. If the coil passes over a crack, the magnetic field is altered and induces a voltage in a second coil. The induced voltage is displayed on an instrument to indicate the presence of a crack.

[23] AD 99-24-15 provides a complex schedule for the ultrasonic and eddy current initial and recurring inspections that is based on the engine model that the spool operated in, the spool's CSN and last inspection, and the billet size from which the spool was made.

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

> Immediately issue an airworthiness directive (AD) to require the expeditious removal from service of CF6-50 and -80 series engines with high pressure compressor stage 3-9 spools that are most at risk of rupturing and inspect those spools in accordance with AD 99-24-15 and engine manual instructions. (Class 1, Urgent Action) (A-00-104)

Chairman HALL and Members HAMMERSCHMIDT, GOGLIA, BLACK and CARMODY concurred in this recommendation.

Original Signed

By: Jim Hall
Chairman