Core Lock

Investigators consider possibility of a condition that could prevent an in-flight restart.

BY MARK LACAGNINA

A rare condition that could freeze an engine core after an in-flight flameout and prevent a windmill restart has come to light as a result of the continuing investigation of a 2004 regional jet accident. "Core lock," as it is known by engineers, can occur when the more rapidly cooling engine components increase turning resistance to the rotating components to the point of preventing a windmill restart of an engine.

Investigators for the U.S. National Transportation Safety Board (NTSB) are seeking to determine whether core lock might have prevented the flight crew of a Bombardier CRJ200 from restarting the engines after they flamed out during an upset at Flight Level (FL) 410, approximately 41,000 ft, on Oct. 14, 2004. The pilots were unable to restart the GE CF34-3B engines, and they were killed when the airplane struck terrain in a residential area while gliding toward the Jefferson City (Missouri, U.S.) Memorial Airport. No one on the ground was injured.

The nearly 3,300 pages of information that have accumulated as of May 2006 in the public docket on the accident investigation include assertions by engineers at Bombardier and GE Transportation that core lock cannot occur in the CF34-3B turbofan unless N_2 — high-pressure rotor speed, or core speed — decreases to zero after an in-flight engine shutdown or flameout. A GE representative said that core lock can occur only if recommended operating procedures are not followed. The only known events before the accident have involved engine tests, not engines in service.

The underlying issue is differences in the expansion and contraction rates of engine components as their temperatures change. Simply stated, if an engine is shut down or flames out at altitude, the static components cool and contract more quickly than the rotating components because of their lower mass and more direct exposure to internal airflow.

In engineering terms, the static components have a faster thermal time constant than the rotating components. If the high-pressure rotor — the engine core — stops rotating, contact between the static seals and the shafts can contribute substantially to overall drag, or turning resistance, in the engine and prevent the core from being turned by the relatively low-torque rotational force available from ram air during an attempted windmill restart.

Engine Screening

Bombardier's first encounter with core lock occurred about 30 years ago during a flight test of a CL604 Challenger, which has the same CF34-3B engines as the CRJ200. After an engine was shut down, N_2 dropped to zero percent while the airplane was flown to its restart altitude/airspeed envelope, and the core could not be rotated by ram air for a restart.

GE isolated the problem to contact between components of the high-pressure-turbine interstage seal — a static, pressurized honeycomb component — and the rotating seal teeth on the outer torque coupling. The company initially established a more rigorous break-in procedure in the factory test cell. When this proved inadequate, the company developed an in-flight screening procedure to check CF34-3A1 and -3B/3B1 engines.

Bombardier adopted the screening procedure for production aircraft flight tests. The procedure for the CRJ200 involves flying the airplane to FL 310, throttling an engine to idle for five minutes, then shutting down the engine. The five-minute operation at idle is intended to stabilize engine temperatures before shutdown and prevent thermal damage during restart and acceleration. A drift-down is conducted at 190 kt, or a lower airspeed if necessary to achieve zero percent N_2. About 8.5 minutes after shutdown, the airplane's nose-down pitch attitude is increased to achieve an airspeed of 320 kt, which typically provides enough ram-air torque for a windmill restart. The windmill restart typically is attempted at FL 210. The screening procedure is designed to verify that the engine core will resume turning during the windmill-restart attempt.

Bombardier initially found that the cores in 20 percent of the engines failed to break free during the windmill-restart attempts. The rate was reduced to 11 percent in the early 1990s by design changes incorporated by GE that increased the clearances on the interstage seals. Information gathered during the accident investigation to date indicates that the failure rate currently is 1.5 percent to 4.0 percent.

Grind-in Procedure

Bombardier developed a follow-up procedure for engines that do not pass the screening. The "break-in" or "grind-in" procedure involves restarting the engine using bleed air from the operating engine, which provides more torque than the ram air used during a windmill restart attempt. The airplane is flown back to FL 310, and the engine is shut down again. This time, the drift-down is conducted at a higher airspeed, about 240 kt, to maintain 4 percent N_2 for eight minutes to 10 minutes. This is when the break-in occurs. The engine is restarted again with bleed air from the operating engine, and the screening procedure is repeated.

According to GE, no engine has failed to restart using bleed air from the operating engine after the grind-in procedure. Bombardier said that only one engine has failed the repeated

Bombardier CRJ200

The Canadair Group of Bombardier began design studies of the Canadair Regional Jet (CRJ) in 1987. The first model, the CRJ100, entered service in 1992 with General Electric CF34-3A1 engines. The CRJ200, introduced in 1995, has the same airframe and upgraded CF34-3B1 engines.

The high-bypass CF34 turbofan engine is flat-rated at 9,200 lb (41 kilonewtons) takeoff thrust on the CRJ200 and also is used on the Bombardier Challenger business jets. The engine is a derivative of the TF34, which powers the U.S. Air Force Fairchild Republic A-10 and the U.S. Navy Lockheed S-3A. CF34 engines have accumulated more than 25 million flight hours.

Two versions of the 50-passenger CRJ200 currently are in production. The extended-range model has a maximum takeoff weight (MTOW) of 51,000 lb (23,134 kg) and a range of 1,345 nm (2,491 km). The long-range model has an MTOW of 53,000 lb (24,041 kg) and a range of 1,700 nm (3,148 km).

Both models have a maximum payload of 13,100 lbs (5,942 kg). Normal cruise speed is 0.74 Mach/424 kt; high-cruise speed is 0.81 M/474 kt. Maximum operating altitude is 41,000 ft.

Standard flight deck equipment includes a six-display electronic flight instrument system, a two-display engine indicating and crew alerting system, dual attitude heading reference systems, a traffic-alert and collision avoidance system and digital weather radar.

Bombardier also produces the larger CRJ700, CRJ705 and CRJ900 models, which have CF34-8 series engines. More than 1,300 CRJs are in operation worldwide.

Sources: Bombardier, GE Transportation and *Jane's All the World's Aircraft*

screening procedure. The engine was returned to GE, which found that a machining process had not been performed on one of the seals when the engine was manufactured.

Bombardier told NTSB that there have been no reports of core lock in service. The company said that in-flight engine shutdowns overall are rare, occurring at a rate of 0.016 per 1,000 flight hours. During a public hearing, a Bombardier engineer said that he was aware of about 350 in-flight engine shutdowns in CRJs, most of which were performed by the flight crews following malfunction indications.

Positioning Flight

Not all CF34-3 engines undergo the GE/Bombardier screening procedure. Some are shipped directly from the GE factory to CRJ200 and Challenger operators. The accident airplane had been operated by Pinnacle Airlines since it was manufactured in 2000. Preliminary information indicates that the left engine had undergone the screening procedure but does not specify whether the right engine also had undergone the procedure.

The left engine had been installed on the airplane in April 2004 and had accumulated 8,856 hours and 8,480 cycles at the time of the accident. The right engine had been installed new in October 2003 and had accumulated 2,304 hours and 1,971 cycles.

At the time of the accident, Pinnacle Airlines, a subsidiary of Northwest Airlines, employed more than 800 pilots and operated 110 CRJs. Another flight crew had been scheduled to fly the accident airplane from Little Rock, Arkansas, to the airline's base in Minneapolis, Minnesota, but the flight was delayed because of a problem with the bleed air sensing loop in the right engine. Maintenance personnel replaced the loop and released the airplane for service later that day.

The accident flight crew were on standby duty at the airline's base in Detroit, Michigan, at 1700 local time when they were assigned to conduct the positioning flight. They dead-headed on a company flight from Detroit and arrived in Little Rock at 2040. The accident flight departed about 2141.

The captain, 31, had 6,900 flight hours, including 973 flight hours in type and 150 flight hours as pilot-in-command in type. The first officer, 23, had 761 flight hours, including 22 flight hours in type.

Pitch Excursions

Flight data recorder (FDR) data indicate that soon after takeoff, the airplane's nose-up pitch attitude was increased abruptly to 22 degrees, resulting in a vertical acceleration (load) of 1.8 g — that is, 1.8 times standard gravitational acceleration — and activation of the stall-protection system's stick shaker.

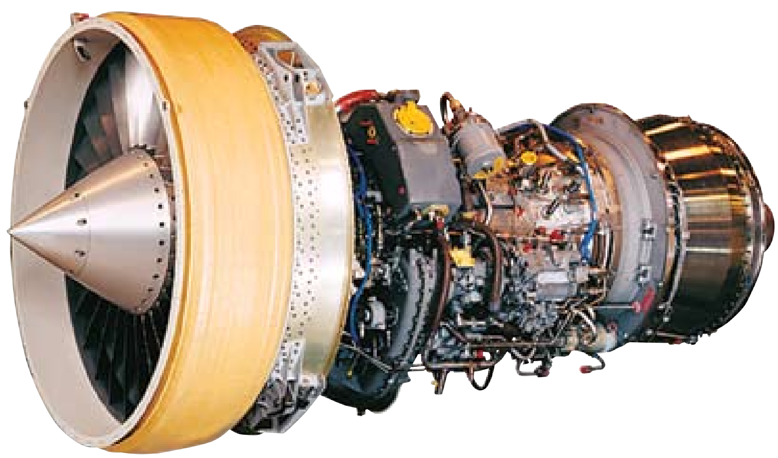
The CRJ200's stall-protection system includes angle-of-attack (AOA) sensors mounted on both sides of the forward fuselage. The system has three "trip points": When AOA increases to the first trip point, the engine autoignition systems are activated to help prevent the engines from flaming out. At the second trip point, the stick-shaker motors are activated, causing the control columns to vibrate — warning the crew of an impending stall. At the third trip point, a warning horn, or warbler, is activated, red "STALL" warning lights are illuminated and the stick-pusher motor is activated, generating 80 lb (36 kg) of forward force on the control columns. The stick-pusher trip point is set to prevent AOA from increasing to stall AOA and to prevent airflow disturbed by the wings at high AOA from entering the engines and causing them to flame out.

While climbing to their assigned altitude, 15,000 ft, the captain and first officer exchanged seats, and the first officer assumed control of the airplane. The airplane was being hand-flown in level flight at 15,000 ft when control-column inputs caused the nose to pitch up about 17 degrees, resulting in a 2.3-g load, then to pitch down, resulting in a 0.3-g load. The control-column inputs were repeated soon thereafter, resulting in similar loads. Substantial rudder-control inputs then were applied.

Allure of FL 410

The airline had dispatched the flight to FL 330, but the crew requested and received clearance from air traffic control to climb to FL 410. "Investigators formed the impression that there was a sense of allure to some pilots to cruise at FL 410 just to say they had 'been there and done that,'" said a report on a human factors analysis conducted by NTSB for the investigation.

The FDR recorded two more pitch excursions as the airplane climbed through FL 250. The first occurred when the control column was moved aft, with the autopilot engaged. Pitch attitude increased to more than 10 degrees, resulting in a 1.9-g load and a climb rate of more than 5,000 fpm for several seconds. The second excursion, which occurred after the autopilot disconnected, resulted in a nearly 15-degree nose-up pitch attitude.



The autopilot then was re-engaged, and a climb rate of 3,000 fpm initially was selected. The selected climb rate was reduced to 1,400 fpm and then to 1,000 fpm.

Recommended cruise-climb airspeeds for the CRJ200 vary from 0.70 Mach for a long-range climb to 0.77 Mach for a high-speed climb. The crew maintained about 0.60 Mach until the airplane reached FL 350. The selected climb rate then was reduced incrementally from 1,000 fpm to zero fpm, and the airplane was flown level at 36,500 ft for about a minute. Airspeed increased to 0.65 Mach, and the crew selected a climb rate of 500 fpm and maintained that climb rate until the airplane reached FL 410. During this time, airspeed decreased to 0.57 Mach.

The airplane's climb-performance charts indicate that under the existing conditions, which included an airplane weight of about 38,000 lb (17,237 kg) and outside temperatures of about minus 46 degrees Celsius (minus 51 degrees Fahrenheit) — about 10 degrees above standard — a climb rate of 500 fpm at the recommended 0.7 Mach climb speed could be maintained only to FL 380.

'We're Losing Here'

The airplane was at FL 410 for about 3.5 minutes. The controller commented on the unusually high altitude, and the captain said, "We don't have any passengers on board, so we decided to have a little fun and come on up here."

With the autopilot holding altitude, airspeed decreased to 0.53 Mach, about 150 kt, and AOA increased to nearly 7 degrees. The captain told the first officer, "We're losing here. … This thing ain't going to hold altitude, is it." He then asked the controller for clearance to descend to FL 390 or FL 370 and was told to stand by.

The airplane stalled, rolled 82 degrees left and pitched 32 degrees nose-down.

At 2154, the stick shaker activated and the autopilot disconnected. The control column was moved aft, increasing pitch attitude to nearly 8.5 degrees. The stick pusher activated, reducing pitch attitude to minus 3.5 degrees and AOA to zero degrees. The control column again was moved aft, increasing pitch attitude to eight degrees and AOA to 11 degrees, which prompted another stick pusher activation.

During the next 20 seconds, this cycle was repeated three times, with the amplitude of the pitch changes increasing each time. The airplane then stalled, rolled 82 degrees left and pitched 32 degrees nose-down.

'Declaring Emergency'

During the upset, both engines flamed out, apparently because of inlet airflow disruption, and the air-driven electrical generator automatically deployed. Substantial movements of the control column and rudder pedals were recorded for the next 14 seconds. The crew recovered control of the airplane at about FL 380.

The captain declared an emergency, and the controller cleared the crew to descend to FL 240. The captain later requested, and received, clearance to descend to 13,000 ft.

A performance study by NTSB found that from 30,000 ft, the airplane was in gliding range of six airports suitable for a landing. From 20,000 ft, the airplane could have reached five of the airports. From 10,000 ft, only one suitable airport was within gliding range; that airport was in Kaiser Lake Ozark, Missouri.

The captain began to brief the first officer on the "Double Engine Failure" checklist procedure, noting that airspeed should not be less than 300 kt. "Push it up there," he said. "Three hundred knots." FDR data indicated, however, that the maximum airspeed attained during the descent was 236 kt.

The "Double Engine Failure" checklist says that a windmill restart should be attempted below FL 210 and that a target airspeed of 240 kt should be maintained until ready to begin the procedure. The minimum airspeed for a windmill restart is 300 kt, and the checklist cautions that an altitude loss of 5,000 ft can be expected while accelerating from 240 kt to 300 kt.

The checklist says that below 13,000 ft, a restart using bleed air from the auxiliary power unit (APU) should be attempted with airspeed between 170 kt and 190 kt.

During the briefing, the captain noted that N_2 must be at least 12 percent for a windmill restart. He then said, "We're not getting any N two at all, so we're going to have to go to thirteen thousand feet. … We're going to use the APU bleed air procedures."

The controller inquired about the nature of the emergency, and the captain said that the airplane had stalled and that one engine had failed at FL 410. "So, we're going to descend down now to start our other engine."

The controller replied, "Understand controlled flight on a single engine right now," and said that he would relay that information when he handed off the flight to the next controller.

APU Restarts Fail

The airplane was descending through about 18,000 ft when the captain established radio communication with the next controller. The crew then donned their oxygen masks. The cabin altitude had increased from about 8,000 ft to about 16,500 ft.

The captain briefed the first officer on the APU-assisted restart procedure and then requested clearance from the controller to descend to 11,000 ft. When asked his intentions, the captain said, "We're going to start this other engine and … make sure everything's OK."

The airplane was descending through 13,000 ft when the crew attempted unsuccessfully to start the left engine. An attempt to restart the right engine also failed. The airplane was descending through 10,000 ft when the pilots exchanged seats again and the captain assumed control of the airplane. He told the first officer to advise the controller that neither engine was operating and to request vectors to an airport.

The first officer told the controller that they needed vectors to the closest airport. "We're descending fifteen hundred feet per minute. We have nine thousand five hundred feet left."

The controller cleared the crew to the Jefferson City airport, which was almost directly ahead. She also provided information on the surface winds — 290 degrees at six kt — and the radio frequency for the instrument landing system (ILS) approach to Runway 30. The airport had 10 miles (six km) visibility and a 4,400-foot overcast.

The crew again attempted to restart the engines. "Why isn't the [expletive] engine going anywhere?" the first officer asked.

"I don't know," the captain said. "We're not getting any N two."

The controller told the crew that the airport was at their 11 o'clock position and eight nm (15 km). "From you, it is a three sixty heading." The first officer said that they did not have the airport in sight. The controller said, "Keep turning left. It's now about a three fifty heading."

The first officer told the captain that he had the approach end of the runway in sight and that he should turn slightly right. A few seconds later he said, "We're not going to make it."

The crew apparently were maneuvering to land on a road when the airplane struck trees in a residential area 2.5 nm (4.6 km) south of the airport at about 2215. It then traveled 1,234 ft (376 m) through the backyards of several residences and across a street before striking a concrete retaining wall. The airplane was destroyed by the impact and a post-accident fire.

Breaking Free

According to NTSB, FDR data indicate that the engine cores were beginning to break free just before the impact. A GE engineer who participated in the tear-down inspections of the engines told investigators that although the right engine had significant over-temperature damage that would have prevented it from producing power, there was no indication that the core in either engine was not free to rotate.

FDR data indicate that the engine cores were beginning to break free just before the impact.

"As long as core rotation is maintained, you will not have core lock," the engineer said. GE has no data indicating that core lock has occurred in 25 million hours of CF34 engine operation in service, he said. When asked whether he considered core lock to have been involved in the accident, the engineer said, "We don't know."

Bombardier has revised the "Double Engine Failure" checklist for the CRJ200. Among the changes is a cautionary note that says that "failure to maintain positive N_2 may preclude a successful relight." The checklist also says that airspeed should be increased if necessary to maintain a positive N_2 indication.

Among actions taken by the airline after the accident were the establishment of a minimum climb speed of 250 kt/0.7 Mach above 10,000 ft and a prohibition against flying above FL 370.

Information gathered by NTSB during public hearings on the CRJ200 accident indicates that core lock has occurred in engines other than the CF34; however, the engine types were not specified in the public docket. ●

The information in this article is based on the NTSB public docket as of May 1, 2006, and is subject to change as the accident investigation proceeds.