National Transportation Safety Board
Washington, D.C. 20594

Safety Recommendation

Date: November 20, 2006

In reply refer to: A-06-70 through -76

Honorable Marion C. Blakey
Administrator
Federal Aviation Administration
Washington, DC 20591

On October 14, 2004, Pinnacle Airlines flight 3701 (doing business as Northwest Airlink), N8396A, a Bombardier CL-600-2B19[1] equipped with General Electric (GE) CF34-3 turbofan engines, crashed into a residential area about 2.5 miles south of Jefferson City Memorial Airport (JEF), Jefferson City, Missouri. The airplane was on a repositioning flight[2] from Little Rock National Airport, Little Rock, Arkansas, to Minneapolis-St. Paul International Airport, Minneapolis, Minnesota. The captain and the first officer were killed, and the airplane was destroyed. No one on the ground was injured. The flight was operating under the provisions of 14 *Code of Federal Regulations* (CFR) Part 91 on an instrument flight rules flight plan. Visual meteorological conditions prevailed at the time of the accident.

The accident flight crew decided to climb to the airplane's maximum operating altitude of 41,000 feet.[3] The airplane arrived at 41,000 feet at less than its best rate of climb speed and slowed to its stall speed. An aerodynamic stall followed, which resulted in a loss of control of the airplane. The flight data recorder (FDR) and the cockpit voice recorder (CVR) indicated that the engines were operating normally before the upset. The flight crew recovered the airplane from the upset at an altitude of 34,000 feet. However, during the upset, the airflow to the engine inlets was disrupted, and both engines flamed out.[4] The rotation speed of both engines' cores (N_2) continued to decrease.[5] Before the airplane descended to an altitude of 28,000 feet, the core

[1] The accident airplane was a Canadair regional jet (CRJ) -200 model, which is one of three models in the CL-600-2B19 series. (The other two models are the CRJ-100 and CRJ-440.) Bombardier acquired Canadair in December 1986.

[2] A repositioning flight relocates an airplane to the airport where the airplane's next flight is scheduled. Repositioning flights do not carry passengers or cargo.

[3] A maximum operating altitude is the maximum density altitude at which the best rate of climb airspeed will produce a 100-feet-per-minute (fpm) climb at maximum weight, while in a clean configuration, and with maximum continuous power. For the CRJ-200, the maximum operating altitude represents the maximum capability of the airplane; the actual climb capability will primarily depend on airspeed, weight, and ambient temperature. The accident airplane was not at maximum weight and was capable of climbing at a rate greater than 100 fpm while at an altitude of 41,000 feet if the airspeed had been maintained at Mach 0.7 during the climb and at altitude.

[4] A flameout is an interruption of a turbine engine's combustion process that results in an uncommanded engine shutdown.

[5] A turbine engine gas generator section is commonly referred to as the core.

rotation speed of both engines had reached 0 indicated rpm. The flight crew attempted to restart the engines several times but was unable to do so. The flight crew then attempted to make an emergency landing at JEF, but the airplane crashed before reaching the airport.[6]

This accident is still under investigation, and the National Transportation Safety Board has not yet determined the probable cause of the accident. Nonetheless, the investigation has revealed a safety issue regarding a condition that can preclude pilots from restarting an engine after a double engine failure.

Restart Attempts for Accident Engines

Pinnacle Airlines' double engine failure checklist at the time of the accident indicated that pilots were to maintain a target airspeed of 240 knots.[7] The purpose of maintaining this airspeed was to keep the engine cores rotating at an appropriate speed for either a windmill restart[8] or an auxiliary power unit (APU)-assisted restart.[9] FDR data and the CVR recording showed that the flight crew did not accelerate the airplane after the upset and that the engine core rotation slowed to 0 indicated rpm. FDR data also showed that the crew did not achieve the 240-knot airspeed before or after attempting to restart the engines.

The flight crew first attempted to restart the engines using the windmill restart procedure. A windmill restart requires accelerating the airplane to an airspeed of at least 300 knots to increase the core rotation speed before the attempted restart. FDR data showed that the crew did not achieve the 300-knot airspeed (the maximum airspeed recorded by the FDR was 236 knots) and that the engine cores remained at 0 indicated rpm during the restart attempt. The CVR recording indicated that the flight crewmembers then elected to descend to an altitude of 13,000 feet so that they could attempt to restart the engines using the APU-assisted restart procedure, which requires slowing the airplane to 170 or 190 knots (depending on the airplane's weight) before initiating the restart. Once the airplane descended to an altitude of 13,000 feet, the flight crew attempted four APU-assisted engine restarts (two attempts per engine), but FDR data showed that the engine cores still remained at 0 indicated rpm.

The accident airplane's APU and start system components were found mostly intact at the accident scene. Examination and testing of these components found nothing that would have prevented adequate torque from being delivered to the engines for the restart attempts. Engine disassembly inspections found no mechanical failures or evidence of any condition that would have prevented engine core rotation. Although the inspections disclosed thermal damage in the No. 2 engine that would have impeded the engine's ability to produce thrust, this damage would not have prevented core rotation during an attempted restart.[10]

---

[6] For more information about this accident, see DCA05MA003 at the Safety Board's Web site at <http://www.ntsb.gov>.

[7] All airspeeds cited in this letter are knots indicated airspeed.

[8] A windmill restart is an emergency in-flight procedure in which the effect of ram airflow passing through the engine as the airplane moves through the air provides rotational energy to turn the core.

[9] Pinnacle Airlines' double engine failure checklist indicated that the windmill restart procedure was to be used at altitudes from 21,000 to 13,000 feet and that the APU-assisted restart procedure was to be used at altitudes of 13,000 feet and below.

[10] The inspections found no preimpact damage to the No. 1 engine.

Manufacturer's Core Lock Screening Procedure

During the accident investigation, the Safety Board learned that GE CF34-1 and CF34-3 engines[11] had a history of failing to rotate during in-flight restart attempts on airplanes undergoing production acceptance flight testing at Bombardier. The manufacturers referred to this condition as "core lock." Bombardier first identified this problem in 1983 during Challenger certification tests, and GE attributed the problem to interference contact at a high pressure turbine (HPT) air seal.

The CF34 HPT air seals are designed to control cooling and balance airflow. The seals include teeth on the rotating components that grind operating grooves into abradable surfaces on the stationary components. The efficiency of these seals significantly affects engine performance, so the seals are designed to operate with minimal clearances.

Bombardier added a procedure to the production acceptance flight tests for its CF34-1- and CF34-3-powered airplanes to screen engines for the potential to experience core lock. At the time of the accident, this screening procedure was as follows:

1. Climb to flight level 310.
2. Retard the test engine throttle to idle and stabilize for 5 minutes.
3. Shut down the test engine.
4. Descend at 190 knots.
5. Slow the aircraft until N_2 is reduced to 0 percent.
6. At 8 1/2 minutes from shutdown, push over to 320 knots.
7. If N_2 is 0 rpm at flight level 210, the engine is declared to be core locked.

Engines that are found to be core locked are reworked using an in-flight "grind-in" procedure that was designed to remove seal material at the interference location.[12] Engines that undergo grind-in rework are then rescreened for core lock. The grind-in procedure, which includes a cross-bleed start for the core locked engine, is as follows:

1. Air turbine starter cross-bleed start.
2. Ascend to flight level 310.
3. Repeat core lock screening procedure but descend at an airspeed of about 240 knots to establish 4 percent N_2.
4. Maintain 4 percent N_2 for at least 8 1/2 minutes.
5. Confirm that no core lock exists by repeating screening procedure.

As testimony during the Safety Board's June 2005 public hearing on the Pinnacle Airlines accident indicated, neither Bombardier nor GE considered core lock to be a safety-of-flight issue. The manufacturers claimed that engines that passed the screening procedure, with or without grind-in rework, would not core lock as long as the 240-knot airspeed was maintained.

[11] Bombardier airplanes that are powered by either GE CF34-1 or CF34-3 engine models are the Challenger 601, Challenger 604, CRJ-100, CRJ-200, and CRJ-440.

[12] Newly manufactured engines undergo a test cell seal grind-in before delivery.

Turbine Engine Shutdowns

The operating temperatures in parts of the HPT reach more than 2,000° Fahrenheit. After a turbine engine has been operating, its rotating and stationary components have expanded to their normal operating dimensions and clearances. When an engine is shut down, its rotating and stationary components do not contract at the same rates because of differences in their material properties and their exposure to cooling air. Temporary losses of clearance between the rotating and stationary components and misalignment between the rotating teeth and stationary grooves of the air seal occur until the temperatures of the components reach equilibrium. Because of this characteristic, turbine engine shutdown procedures include operation for several minutes at a lower power setting to permit internal temperatures and clearances to stabilize. Engines that flame out suddenly in flight experience more severe thermal changes that may result in losses of clearance so that the rotating and stationary components rub or bind.

More importantly, flameouts at high power and high altitude conditions produce even greater thermal distress because internal temperatures are the hottest at high power settings and the air is colder at high altitudes. The increased thermal shock exacerbates the loss of component clearance and alignment. Because the accident engines flamed out under these conditions, axial misalignment caused the seal teeth, which were positioned aft of their normal grooves, to contact stationary abradable material when radial seal clearances closed down. Once core rotation stopped, binding prevented core rotation from resuming during the windmill or APU-assisted restart attempts. Thus, the lack of core rotation on the accident airplane engines could be explained by the core lock phenomenon.

Potential for Core Lock in CF34-1 and CF34-3 Engines

Bombardier's core lock screening procedure requires a cool-down period before engine shutdown to stabilize internal temperatures and clearances.[13] However, as previously discussed, this procedure does not produce the more severe thermal distress associated with the high power, high altitude flameouts that occurred during the accident flight. Thus, the successful demonstration of Bombardier's production flight test procedure may not ensure that an engine will not experience core lock if the core is allowed to stop rotating after a high power, high altitude flameout. In fact, the Safety Board notes that the No. 1 accident engine had successfully passed the screening procedure during initial production acceptance testing.[14] Also, the successful demonstration of Bombardier's production flight test procedure may not ensure that slowing the airplane to an airspeed of 170 to 190 knots is sufficient to maintain core rotation during an attempted APU-assisted restart.

During the public hearing for the Pinnacle Airlines accident, a GE manager testified, "As long as core rotation is maintained, you will not have core lock … we have a body of data

[13] After the accident, Transport Canada mandated that Bombardier change the engine stabilization time from 5 to 2 minutes.

[14] The No. 2 accident engine was installed new as a spare engine and was not subject to the the core lock screening procedure because it applies only to engines that are installed in Bombardier's production airplanes.

that shows that 240 knots maintains core rotation."[15] This testimony suggests that the most effective way to mitigate the safety risk of core lock during in-flight restarts is to use an operational procedure to keep an engine's core rotating until a restart can be attempted. The Safety Board is unaware of flight test data that demonstrate that 240 knots is sufficient to keep the core rotating after the more severe thermal distress associated with a high power, high altitude flameout. Thus, the Board is concerned that sufficient testing and engineering analysis have not been performed to demonstrate whether the 240-knot airspeed is effective in maintaining core rotation and preventing core lock after high power, high altitude flameouts.

The Safety Board concludes that it is critical to identify the airspeed needed to maintain core rotation in CF34-1 and CF34-3 engines after high power, high altitude flameouts and to ensure that restart procedures can be accomplished under such conditions. Therefore, the Safety Board believes that, for airplanes equipped with CF34-1 or CF34-3 engines, the Federal Aviation Administration (FAA) should require manufacturers to perform high power, high altitude sudden engine shutdowns; determine the minimum airspeed required to maintain sufficient core rotation; and demonstrate that all methods of in-flight restart can be accomplished when this airspeed is maintained.[16]

The importance of maintaining a minimum airspeed to keep the engine cores rotating was not communicated to pilots in airplane flight manuals (AFM). For example, at the time of the accident, Bombardier's and Pinnacle Airlines' double engine failure checklists stated that 240 knots was the "target" airspeed for the procedure but did not indicate that this airspeed was essential to the success of the restart procedure. As a result of the accident, Bombardier and Pinnacle Airlines revised their double engine failure checklists to indicate that 240 knots was the "minimum" airspeed and that the failure to maintain positive core rotation might prevent a successful restart.

The Safety Board concludes that it is important for pilots to be aware of the possibility of core lock and the specific actions that are needed to preclude this condition. Therefore, the Safety Board believes that the FAA should ensure that AFMs of airplanes equipped with CF34-1 or CF34-3 engines clearly state the minimum airspeed required for engine core rotation and that, if this airspeed is not maintained after a high power, high altitude sudden engine shutdown, a loss of in-flight restart capability as a result of core lock may occur.

Performance Penalties for CRJ-100, -200 and -440 Airplanes

The 240-knot airspeed included in Bombardier's and Pinnacle Airlines' double engine failure checklists is 70 knots greater than the airplane's best glide speed[17] (at an airplane weight of 36,000 pounds) of 170 knots. To maintain the 240-knot airspeed with no engine power and

[15] The GE manager further testified that the 240-knot airspeed also served to maintain a minimal hydraulic pressure.

[16] The Safety Board notes that Bombardier Aerospace and Transport Canada have performed high altitude, high power engine shutdowns to verify the 240-knot target airspeed included in Bombardier's double engine failure checklist. The APU-assisted in-flight restart process has not yet been verified.

[17] An airplane's best glide speed provides the airplane with the most distance forward for a given loss of altitude.

transition to a 300-knot airspeed for a windmill restart, a flight crew must significantly increase the airplane's descent rate, thereby reducing the range of available landing locations if a forced (emergency) landing were to become necessary as a result of a failure to restart at least one engine. Because of the effect that this loss of glide range could have on a flight crew's ability to find a viable emergency landing site, the Safety Board concludes that CRJ-100, -200, and -440 pilots must be fully aware of the performance penalties that can be incurred while maintaining core rotation and attempting a windmill restart. Therefore, the Safety Board believes that the FAA should require that operators of CRJ-100, -200, and -440 airplanes include in AFMs the significant performance penalties, such as loss of glide distance and increased descent rate, that can be incurred from maintaining the minimum airspeed required for core rotation and windmill restart attempts.

Potential for Core Lock in Other Engine Models

Turbine-powered airplanes other than the Challenger 601 and 604 and the CRJ-100, -200, and -440 have turbine engine components with a similar physical design as those for the CF34-1 and CF34-3 engines. As a result, the Safety Board concludes that other turbine engines may also be susceptible to core lock after high power, high altitude flameouts. Therefore, the Safety Board believes that the FAA should review the design of turbine-powered engines (other than the CF34-1 and CF34-3, which are addressed in Safety Recommendation A-06-70) to determine whether they are susceptible to core lock and, for those engines so identified, require manufacturers of airplanes equipped with these engines to perform high power, high altitude sudden engine shutdowns and determine the minimum airspeed to maintain sufficient core rotation so that all methods of in-flight restart can be accomplished. Further, the Safety Board believes that, for those airplanes with engines that are found to be susceptible to core lock (other than the CF34-1 and CF34-3, which are addressed in Safety Recommendation A-06-71), the FAA should require airplane manufacturers to incorporate information into AFMs that clearly states the potential for core lock; the procedures, including the minimum airspeed required, to prevent this condition from occurring after a sudden engine shutdown; and the resulting loss of in-flight restart capability if this condition were to occur. In addition, the Safety Board believes that the FAA should require manufacturers to determine, as part of 14 CFR Part 25 certification tests, if restart capability exists from a core rotation speed of 0 indicated rpm after high power, high altitude sudden engine shutdowns. For those airplanes determined to be susceptible to core lock, the FAA should mitigate the hazard by providing design or operational means to ensure restart capability.

Windmill Restart Requirements

Airplane manufacturers rely on the windmill method as the primary means of restart after an all-engine flameout event. Consequently, the portion of the flight envelope in which a windmill restart is effective is critical to flight safety. However, increases in the bypass ratios of turbofan engines over the years have significantly reduced the windmill restart portion of the in-flight restart envelope. Specifically, the engines powering many current transport-category airplanes bypass between 80 and 90 percent of the airflow entering the inlet around the engine core, so as little as 10 percent of the inlet air enters the core during normal operation. Thus, the cores of high bypass ratio engines, such as the CF34,[18] require significantly higher airspeeds to achieve windmill restart than the cores of low bypass engines installed on older generation airplanes.

After an all-engine high power flameout, pilots need to sacrifice a substantial amount of altitude to achieve the higher airspeeds that are necessary for a windmill restart with high bypass engines. However, depending on the altitude where the shutdown occurred, a pilot may not have enough altitude available to use this restart option.

Certification requirements currently address the minimum airspeed needed to ensure windmill restart capability. However, there is no upper limit on the value of the minimum airspeed required for a windmill restart and no limit on the amount of altitude loss that can occur during a windmill restart. If the minimum airspeed value is too high, an excessive amount of altitude loss may be needed to accomplish a windmill restart. In September 1999, the FAA issued a notice of availability and request for comments on a proposed Propulsion Mega Advisory Circular,[19] which addressed this and other engine certification-related issues, but the FAA has taken no subsequent action.

The Safety Board concludes that, during design, airplane manufacturers must consider that a pilot's ability to restart high bypass turbine engines after an all-engine flameout might be compromised if an excessive airspeed or an excessive amount of altitude loss were needed for the restart. Therefore, the Safety Board believes that the FAA should establish certification requirements that would place upper limits on the value of the minimum airspeed required and the amount of altitude loss permitted for windmill restarts.

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

> For airplanes equipped with CF34-1 or CF34-3 engines, require manufacturers to perform high power, high altitude sudden engine shutdowns; determine the minimum airspeed required to maintain sufficient core rotation; and demonstrate that all methods of in-flight restart can be accomplished when this airspeed is maintained. (A-06-70)
>
> Ensure that airplane flight manuals of airplanes equipped with CF34-1 or CF34-3 engines clearly state the minimum airspeed required for engine core rotation and that, if this airspeed is not maintained after a high power, high altitude sudden engine shutdown, a loss of in-flight restart capability as a result of core lock may occur. (A-06-71)
>
> Require that operators of CRJ-100, -200, and -440 airplanes include in airplane flight manuals the significant performance penalties, such as loss of glide distance and increased descent rate, that can be incurred from maintaining the minimum airspeed required for core rotation and windmill restart attempts. (A-06-72)

---

[18] The CF34 engine bypasses about 85 percent of inlet air past the core.

[19] For more information, see 64 *Federal Register* 52819, September 30, 1999.

Review the design of turbine-powered engines (other than the CF34-1 and CF34-3, which are addressed in Safety Recommendation A-06-70) to determine whether they are susceptible to core lock and, for those engines so identified, require manufacturers of airplanes equipped with these engines to perform high power, high altitude sudden engine shutdowns and determine the minimum airspeed to maintain sufficient core rotation so that all methods of in-flight restart can be accomplished. (A-06-73)

For those airplanes with engines that are found to be susceptible to core lock (other than the CF34-1 and CF34-3, which are addressed in Safety Recommendation A-06-71), require airplane manufacturers to incorporate information into airplane flight manuals that clearly states the potential for core lock; the procedures, including the minimum airspeed required, to prevent this condition from occurring after a sudden engine shutdown; and the resulting loss of in-flight restart capability if this condition were to occur. (A-06-74)

Require manufacturers to determine, as part of 14 *Code of Federal Regulations* Part 25 certification tests, if restart capability exists from a core rotation speed of 0 indicated rpm after high power, high altitude sudden engine shutdowns. For those airplanes determined to be susceptible to core lock, mitigate the hazard by providing design or operational means to ensure restart capability. (A-06-75)

Establish certification requirements that would place upper limits on the value of the minimum airspeed required and the amount of altitude loss permitted for windmill restarts. (A-06-76)

Chairman ROSENKER, Vice Chairman SUMWALT, and Members HERSMAN and HIGGINS concurred with these recommendations.

[*Original Signed*]

By: Mark V. Rosenker
Chairman