National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Got Any Ideas?

When the 155 passengers and crew members aboard U.S. Airways Flight 1549 left New York City on a cold day in January 2009, no one anticipated the drama that was about to unfold. Takeoff proceeded normally, but when the aircraft climbed to 3,200 feet, a flock of migratory geese crossed its flight path. Each of the Airbus A320's turbofan engines ingested a goose and subsequently suffered damage that disabled its thrust-producing capability. Unable to return to the airport and left without other landing options, the flight crew valiantly ditched the plane in the Hudson River. Seconds after the aircraft skidded onto the frigid water, passengers evacuated onto the wings and waited for rescue (Figure 1). Within minutes, commuter ferries and Coast Guard vessels arrived at the scene where they rescued the airplane occupants: shivering, shaken, but alive.

Figure 1: Passengers and crew members of U.S. Airways Flight 1549 stand on the aircraft wings and slide/rafts as they wait to be rescued.

Background

Engine Structure and Testing

The FAA National Wildlife Strike Database shows that bird strikes have caused 229 deaths in civil and military aviation between 1998 and 2009. Because bird strikes can result in catastrophic engine damage, the FAA requires aircraft engines to undergo bird ingestion tests before becoming certificated. To receive certification, the Airbus A320's two turbofan engines were required to have a 2½ pound bird volleyed into the engine core followed by four 1½ pound birds volleyed toward other areas of the fan disk. To pass the tests, the engines were required to remain operational at 75% power for more than five minutes after the bird ingestion. In 1996, the engines that would later be used on U.S. Airways Flight 1549 were certificated for bird ingestion according to these standards. In 2007, the FAA adopted new regulations regarding bird strikes, and the new rules increased the size of the birds used in the core tests to 5½ pounds. However, engines certificated prior to 2007 were not obliged to meet the new requirements.

Aircraft Controls

The Airbus A320 is not equipped with a conventional control yoke. Instead, pilots use a sidestick to fly the aircraft. Sidestick inputs are analyzed by an electronic interface called a fly-by-wire system designed to prevent the aircraft from executing maneuvers outside of its performance limits. It does this by attenuating pilot commands and activating hydraulic flight control surfaces through electrical signals. As long as the system is set to "Normal Law," the flight computer keeps the aircraft within a safe flight envelope with respect to roll, pitch, yaw, and speed. Normal Law includes "alpha-protection" (α-prot), which prevents the aircraft from stalling.

The airspeed display in the A320 cockpit is depicted in Figure 2. Green Dot speed represents the speed at which the aircraft must travel to obtain the best lift over drag ratio, allowing the maximum range for a glided flight. V_{LS} is the lowest selectable

Pilots Ditch Passenger Jet in Hudson River; All Occupants Survive.

Proximate Causes:

- **Bird strikes critically damage core in both engines**
- **Pilot approaches landing below optimum gliding airspeed**
- **Low airspeed increases descent rate, damages fuselage**
- **Water-rated aircraft remains afloat long enough for rescue**

Underlying Issues:

- **In-Flight Engine Diagnostics**
- **Emergency Event Checklist Design**
- **Simulation Training**

speed at which the aircraft can travel while still generating lift. α-prot activates when the airspeed drops below V_{LS}.

Extended Over Water Operations

Of the U.S. Airways fleet of 75 A320's, 20 are certificated for extended over water (EOW) operations. EOW aircraft contain water safety features not found on conventional planes. Significant aspects include emergency slide/rafts at the forward and aft exits, passenger life vests, and ditching certification. The National Transportation Safety Board (NTSB) defines a ditching as a planned maneuver where the flight crew attempts a water landing with the aircraft under control. Airplanes certificated for ditching must comply with many FAA airworthiness regulations, one of which requires the aircraft to remain afloat long enough for the occupants to evacuate into the slide/rafts.

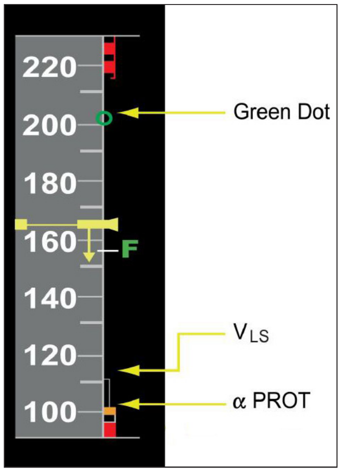

Figure 2: Airbus A320 Airspeed scale, showing important characteristics and protection speeds.

What Happened

Loss of Engine Thrust and Ditching

On January 15, 2009, U.S. Airways Flight 1549 was cleared for takeoff from LaGuardia airport at 3:24 p.m. EST with the first officer in control of the plane. As it climbed to cruising altitude, the aircraft encountered a flock of migratory Canada Geese. At 3,200 feet, both aircraft engines, operating at 80% fan speed, sucked several geese through their inlets (Figure 3). At least one goose impacted and destroyed each engine's core, abruptly terminating engine capability to generate usable thrust. The captain, realizing that the aircraft's low altitude and lack of power narrowed viable landing options, assumed control of the aircraft and activated the auxiliary power unit (APU). He reported the situation to air traffic control and began turning back toward LaGuardia. Meanwhile, the first officer began conducting the first part of the Quick Reference Handbook (QRH) Dual Engine Failure Checklist, which began with an attempt to relight the engines.

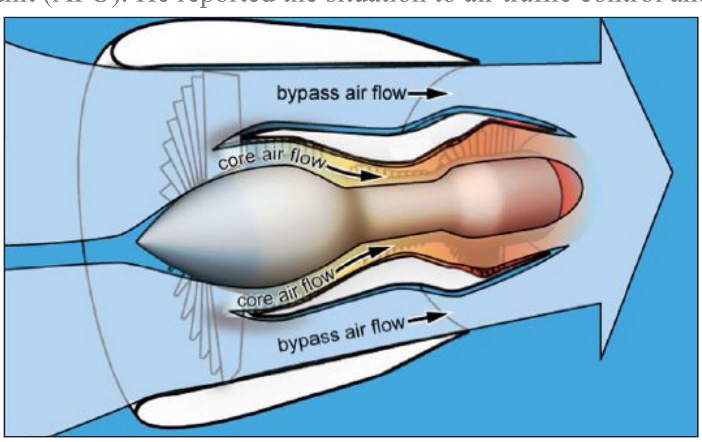

Figure 3: Airflow paths in the Airbus A320 engines. Centrifugal force from the fan blades slings small foreign objects through the bypass duct, but large objects could damage the engine core.

During the next two minutes, air traffic control relayed instructions for landing at New York's LaGuardia airport and then at New Jersey's Teterboro airport, but the captain had already analyzed both options. "We can't do it," he responded. "We're gonna be in the Hudson." During the next 60 seconds, the captain and first officer prepared the plane for a water landing and instructed the passengers to brace for impact. Amid the flurry of ditching preparations, neither the captain nor the first officer observed that the plane's airspeed had fallen well below the Green Dot indicator.

As the aircraft descended, its speed hovered near V_{LS}, and at 150 feet, it entered alpha-protection mode. Three minutes after the bird strike, the airplane skidded onto the water at a descent rate of 12.5 feet per second (Figure 4). External pressure from the impact collapsed the aft fuselage frame, cracking the aft fuselage skin. Water poured through the breach and into the cabin, rendering the rear exits and slide/rafts useless. The flood forced passengers to evacuate onto the wings and into the forward slide/rafts. The first ferry arrived within five minutes of the ditching, and the last passengers were rescued approximately 20 minutes later. Some individuals had been submerged to the chin when water flooded the cabin, and a few were later hospitalized for hypothermia. The aircraft endured significant damage, five people suffered critical injuries, but all of the passengers and crew members survived.

Proximate Cause

Each engine of the accident aircraft ingested at least one 8-pound Canada Goose. Each bird's impact with the engine core caused critical damage that resulted in an almost complete loss of thrust. NTSB commended the captain, first officer, and flight attendants for excellent crew resource management during the emergency: their professionalism and coordination allowed them to maintain control of the aircraft and increase the survivability of the impact. The captain's swift and thoughtful action in immediately activating the APU also contributed to the successful ditching because the APU allowed the fly-by-wire system to remain in Normal Law. Without the APU, the aircraft would not have descended with the flight envelope and stall protections that Normal Law afforded. These protections proved especially crucial because the aircraft entered alpha-protection during the final approach, and the system may have kept the plane above the stall speed during the last 150 feet of the descent.

The accident investigation report further noted the aircraft operated that day had been certificated for EOW operations even though the FAA did not mandate the use of a water-rated plane for the flight from New York to Charlotte. Without the forward slide/rafts, many passengers would likely have been submerged in the freezing water. Such conditions could easily have led to "cold-shock," a phenomenon that can lead to drowning in as little as five minutes. As per NTSB, these slide/rafts, in conjunction with the proximity and swift response of passenger ferries, likely saved dozens of lives (Figure 5).

NTSB identified inadequate ditching certification standards, poor industry training on ditching techniques, and task saturation as contributors to the captain's difficulty in maintaining his intended airspeed (Green Dot speed) during the final approach. Therefore, the descent rate was higher than anticipated, resulting in the extensive aft fuselage damage and unavailability of the aft slide/rafts. The captain had the ditching maneuver under such control that he had time to ask his copilot if any task had been missed, at twenty seconds before water impact: "Got any ideas?" There were none: the aircraft was as ready as possible.

Underlying Issues

In-Flight Engine Diagnostics

Information from the Flight Data Recorder (FDR) and Cockpit Voice Recorder (CVR) showed that the first officer spent the first 30-40 seconds after the bird strike attempting to relight the engines as per instructions on the emergency checklist. According to NTSB, the flight crew had no way of knowing the engines had been damaged to an extent such that relighting would be impossible. Only three minutes elapsed from the time of the bird strike to the time of the ditching, so the first officer's attempts to relight the engines only wasted precious time. If the flight crew had been aware of the extent and type of damage the engine had sustained, it could have bypassed the relight portion of the checklist and skipped to the steps more applicable to the situation. NTSB concludes in-flight diagnostics that provide more detailed information on engine problems could be instrumental in saving seconds that could mean the difference between life and death in an emergency.

Emergency Checklist Design

Emergency event checklists are important because task saturation often afflicts flight crews when they are confronted with critical situations. The checklists are meant to aid the crew by prioritizing important tasks and facilitating the work-

Figure 4: Flight path of U.S. Airways Flight 1549

Figure 5: Commuter Ferries and Coast Guard vessels surround U.S. Airways Flight 1549 as it sinks into the Hudson River minutes after the last passenger was rescued.

load. Airbus' 3-page QRH Dual Engine Failure checklist began with engine diagnostics and ended with ditching procedures. The checklist had been designed for use at altitudes over 20,000 feet, but at the time of the bird strike, Flight 1549 had only reached 3,200 feet. Therefore, time did not allow the flight crew to reach items critical to the ditching. For example, the flight computer had been programmed to issue a warning when it detected low descent speed, but the Ground Proximity Warning System (GPWS) stifled it. Airbus ditching procedures instructed the flight crew to turn off the GPWS in order to allow the low airspeed warning to activate.

If there had been a checklist tailored for low altitudes, the crew would likely have reached the ditching instructions in time. The procedures would have directed them to increase the airspeed and effectively lower the descent rate, making it possible to prevent damage to the aft fuselage and subsequent cabin flood. Then, escape through the aft exit and slide/rafts could have minimized passengers' risk of cold-shock or hypothermia by limiting their exposure to the frigid waters. In its official report, NTSB criticized Airbus for failing to develop a procedure for dual engine failure at low altitudes and recommended that the FAA require aircraft manufacturers to develop a procedure for such an event. NTSB commended the captain for activating the APU despite the fact that this instruction was not listed until the last page of the procedure. Since time did not allow the crew to reach several important items on the emergency checklist, NTSB recommended that the FAA review the ways in which steps on the checklists are prioritized.

Simulation Training

After the accident, NTSB investigated industry curricula on dual engine failure training and ditching training. It discovered that dual engine failure scenarios only occurred during initial training, always took place at 25,000 feet, and never forced a pilot to conduct a ditching or forced landing. Scenarios for ditching training always had power available from at least one engine and did not emphasize the visual illusions and height misperceptions that often accompany water landings. Based on these findings, NTSB concluded that such training programs are incomprehensive; the flight crew would have been more prepared if they had encountered situations similar to the low altitude dual engine failure in their training. NTSB suggested injecting such scenarios into initial training courses and recurrent training programs.

Aftermath

The crew of U.S. Airways Flight 1549 was awarded the Master's Medal of the Guild of Air Pilots and Air Navigators, and the ditching event became popularly known as the "Miracle on the Hudson." Salvage teams worked long into the night to hoist the fuselage from the river, and the aircraft was deemed damaged beyond repair. After a 15-month investigation, NTSB made 35 recommendations regarding airplane safety, including improving in-flight engine diagnostics, improving pre-flight safety briefings, and expanding simulator training to include low altitude engine failure scenarios.

For Future NASA Missions

The story of U.S. Airways Flight 1549 tells of a disaster averted. Yet without the confluence of specific events, environmental factors, and crew actions, the landing that has been hailed a miracle might instead have been considered a tragedy. The flight crew displayed excellent resource management and coordination during the crisis, but even its admirable efforts might not have saved the passengers if the plane had not been EOW-equipped, if the incident had occurred without daylight, or if commuter ferries and Coast Guard vessels had not been on hand for immediate rescue. Unfortunately, coincidences such as these are not the norm.

NASA must never underestimate the importance of mishap preparedness and contingency planning. History has shown that circumstances are much more likely to conspire against, rather than work toward, a goal to save missions or spacecraft in crisis. Installing procedures for severe scenarios often provides structure to environments that, in an emergency, can become harried and chaotic. High workloads and stress levels can lead to task saturation, which could increase the chances of making errors and mental mistakes. Therefore, ensuring the presence of efficient emergency procedures can help operators perform situational analyses and make sound decisions in the face of a crisis.

Effectively executing such plans also requires a leader that can prevent a haphazard response and a team that can manage tasks and resources successfully. Flight 1549's crew repeatedly pointed to their training in crew resource management (CRM) as an integral part of their success that day. The captain told NTSB investigators that CRM training gave the flight crew its capability to establish a team, share common goals, work together, and communicate effectively. Similarly, NASA's operator training should emphasize effective team communication, situational analysis, and workload management. CRM training must teach crews how to create conditions that increase survivability in a worst-case scenario.

Many links went right in a chain of events that terminated with a safe rescue and a happy ending. Some of those links were a direct result of the flight crew's actions or decisions, but if factors outside the cockpit had been different, this story's ending might have changed. NASA must prepare for different situations based on factors outside its control. By continuing to advance a culture of preparedness, teamwork, and communication, NASA leaves little to chance in saving its missions, spacecraft, or crew members when disaster strikes.

Questions for Discussion

- **Does your project have contingency plans? What kinds of situations do your contingency plans cover?**
- **Have you considered low-probability but high-risk scenarios that could affect your project? Have you formulated procedures to prepare for such events?**
- **What assumptions did you make when formulating your emergency procedures? How do you know those assumptions are valid?**
- **Have your teams been trained in dealing with task saturation and workload management?**
- **Have your teams been trained in executing emergency procedures? Have your teams been exposed to CRM Training?**

References

Batty, David. "Pilot Tells of Crash-Landing as Plane Pulled from River." Guardian News and Media Limited. 18 January 2009. < http://www.guardian.co.uk/world/2009/jan/18/new-york-plane-crash-salvage>

Briere, Dominique & Pascal Traverse. "AIRBUS A320/A330/A340 Electrical Flight Controls." IEEE, 1993.

Eisen, Lewis & Richard Savel. "What Went Right: Lessons for the Intensivist from the the Crew of US Airways Flight 1549." Chest 2009; 136:910-917.

Helmreich, Robert, et al. The Evolution of Crew Resource Management Training in Commercial Aviation. The University of Texas at Austin, Department of Psychology.

Lowe, Paul. "Miracle on the Hudson Prompts Safety Review." Aviation News. 1 June 2010.

National Transportation Safety Board. Aircraft Accident Report: Loss of Thrust in Both Engines After Encountering a Flock of Birds and Subsequent Ditching on the Hudson River. Washington D.C., May 2010.

U.S. Department of Agriculture. Factsheet: Safer Skies for Birds and People. USDA Wildlife Services, 2009.

"U.S. Airways Airbus Crashes in the Hudson River." Online Image. Airline World. 16 January 2009. < http://airlineworld.wordpress.com/2009/01/16/us-airways-airbus-crashes-in-the-hudson-river/>

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