Uncontained Engine Failure and Subsequent Fire
American Airlines Flight 383
Boeing 767-323, N345AN
Chicago, Illinois
October 28, 2016

Accident Report

NTSB/AAR-18/01
PB2018-100344

National
Transportation
Safety Board

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490 L'Enfant Plaza, SW
Washington, DC 20594

National Transportation Safety Board. 2018. ***Uncontained Engine Failure and Subsequent Fire, American Airlines Flight 383, Boeing 767-323, N345AN, Chicago, Illinois, October 28, 2016*****. NTSB/AAR-18/01. Washington, DC.**

Abstract: This report discusses the October 28, 2016, accident involving American Airlines flight 383, a Boeing 767-323, which experienced an uncontained failure of the right engine and subsequent fire during its takeoff ground roll at Chicago O'Hare International Airport, Chicago, Illinois. Of the 2 flight crewmembers, 7 flight attendants, and 161 passengers on board, 1 passenger received a serious injury and 1 flight attendant and 19 passengers received minor injuries during the emergency evacuation. The airplane was substantially damaged from the fire. Safety issues identified in this report include the lack of recent guidance comparing production inspection processes for nickel alloy engine components, the need for improved in-service inspection techniques for critical rotating parts of all engines, the lack of recent guidance about design precautions to minimize hazards resulting from uncontained engine failures, the need for separate engine fire checklist procedures for ground operations and in-flight operations, the need for improved flight attendant training regarding assessing exits for evacuations and using interphone systems during emergencies, the need for research on the effects of evacuating with carry-on baggage, and the need for improved communication between flight and cabin crews during emergency situations, including evacuations. As a result of this investigation, the National Transportation Safety Board makes seven safety recommendations to the Federal Aviation Administration and one recommendation each to Boeing and American Airlines.

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Abbreviations

AAIB	Air Accidents Investigation Branch
AC	advisory circular
AD	airworthiness directive
AIA	Aerospace Industries Association
APU	auxiliary power unit
ARAC	aviation rulemaking advisory committee
ARFF	aircraft rescue and firefighting
ATC	air traffic control
ATI SM	ATI Specialty Materials
ATSB	Australian Transportation Safety Board
BOS	General Edward Lawrence Logan International Airport
CFR	*Code of Federal Regulations*
CLT	Charlotte/Douglas International Airport
CRM	crew resource management
CVR	cockpit voice recorder
ECI	eddy current inspection
EDT	eastern daylight time
EICAS	engine indicating and crew alerting system
ESN	engine serial number
FAA	Federal Aviation Administration
FDR	flight data recorder
FPI	fluorescent penetrant inspection
GE	General Electric
HPT	high-pressure turbine
JFK	John F. Kennedy International Airport
MIA	Miami International Airport
MTU	Motoren- und Turbinen-Union GmbH
NPRM	notice of proposed rulemaking
NTSB	National Transportation Safety Board
ORD	Chicago O’Hare International Airport

PA	public address [system]
POI	principal operations inspector
QRH	quick reference handbook
RTO	rejected takeoff
SAFO	safety alert for operators
SB	service bulletin
SEM	scanning electron microscope
TWA	Trans World Airlines
UPS	United Parcel Service
V_1	takeoff decision speed

Executive Summary

On October 28, 2016, about 1432 central daylight time, American Airlines flight 383, a Boeing 767-323, N345AN, had started its takeoff ground roll at Chicago O'Hare International Airport, Chicago, Illinois, when an uncontained engine failure in the right engine and subsequent fire occurred. The flight crew aborted the takeoff and stopped the airplane on the runway, and the flight attendants initiated an emergency evacuation. Of the 2 flight crewmembers, 7 flight attendants, and 161 passengers on board, 1 passenger received a serious injury and 1 flight attendant and 19 passengers received minor injuries during the evacuation. The airplane was substantially damaged from the fire. The airplane was operating under the provisions of 14 *Code of Federal Regulations* Part 121. Visual meteorological conditions prevailed at the time of the accident.

The uncontained engine failure resulted from a high-pressure turbine (HPT) stage 2 disk rupture. The HPT stage 2 disk initially separated into two fragments. One fragment penetrated through the inboard section of the right wing, severed the main engine fuel feed line, breached the fuel tank, traveled up and over the fuselage, and landed about 2,935 ft away. The other fragment exited outboard of the right engine, impacting the runway and fracturing into three pieces.

Examination of the fracture surfaces in the forward bore region of the HPT stage 2 disk revealed the presence of dark gray subsurface material discontinuities with multiple cracks initiating along the edges of the discontinuities. The multiple cracks exhibited characteristics that were consistent with low-cycle fatigue. (In airplane engines, low-cycle fatigue cracks grow in single distinct increments during each flight.) Examination of the material also revealed a discrete region underneath the largest discontinuity that appeared white compared with the surrounding material. Interspersed within this region were stringers (microscopic-sized oxide particles) referred to collectively as a "discrete dirty white spot." The National Transportation Safety Board's (NTSB) investigation found that the discrete dirty white spot was most likely not detectable during production inspections and subsequent in-service inspections using the procedures in place.

The NTSB's investigation also found that the evacuation of the airplane occurred initially with one engine still operating. In accordance with company procedures and training, the flight crew performed memory items on the engine fire checklist, one of which instructed the crew to shut down the engine on the affected side (in this case, the right side). The captain did not perform the remaining steps of the engine fire checklist (which applied only to airplanes that were in flight) and instead called for the evacuation checklist. The left engine was shut down as part of that checklist. However, the flight attendants had already initiated the evacuation, in accordance with their authority to do so in a life-threatening situation, due to the severity of the fire on the right side of the airplane.

The NTSB identified the following safety issues as a result of this accident investigation:

- **Lack of recent guidance comparing production inspection processes for nickel alloy engine components.** The HPT stage 2 disk was made of a nickel-based alloy. Ultrasonic inspections are typically performed during the manufacture of nickel alloy engine components to detect internal defects (such as cracks and voids) in the material. However, the discrete dirty white spot, which is consistent with the description of a "stealth" anomaly in a 2008 Federal Aviation Administration (FAA) report on turbine rotor material design, was most likely not detectable by the ultrasonic inspection methods used during production of the HPT stage 2 disk. A 2005 FAA report that presented the results of industry's research about nickel billet inspections found that enhanced ultrasonic inspection techniques, such as multizone and phased array inspections, could better detect internal defects than conventional ultrasonic inspection techniques. The report also stated that multizone inspection techniques were being used for titanium engine parts but that conventional ultrasonic inspection techniques were still being used for nickel engine parts during manufacturing. Additional FAA and industry efforts are needed to evaluate the appropriateness of current and enhanced inspection technologies for nickel engine parts. Updated FAA guidance describing the results of such evaluations would benefit those involved with the inspection process for nickel alloy rotating engine components.

- **Need for improved in-service inspection techniques for critical rotating parts of all engines.** In January 2011, American Airlines performed maintenance—an eddy current inspection (ECI) and a fluorescent penetrant inspection (FPI)—of the forward bore region of the HPT stage 2 disk with no anomalies found. (American Airlines did not have another opportunity to inspect the disk before the accident because no engine maintenance between January 2011 and the time of the accident involved disassembling the HPT stage 2 disk.) These inspection techniques were not capable of detecting the cracks that emanated from the discrete dirty white spot (a subsurface anomaly) because they could only detect cracks and other anomalies at the surface (FPI) and near the surface (ECI) of a material.

  Although ultrasonic inspections might be limited in their capability to detect anomalies during the production stage, such a subsurface inspection technique would be appropriate for in-service maintenance because of the propensity for cracks to propagate over time. If a subsurface ultrasonic inspection had been required at the time of the disk's last inspection, the cracks that developed from the discrete dirty white spot would most likely have been detectable because of the size of the cracks at that time and the sensitivity of ultrasonic inspection techniques.

  In September 2017, the FAA issued a notice of proposed rulemaking to mandate the ultrasonic inspection of HPT stage 1 and 2 disks of General Electric CF6-80-series turbofan engines (the model engine on the accident airplane). The proposed airworthiness directive would be an appropriate step for ensuring the continued airworthiness of airplanes with those engines, but the FAA has not addressed ultrasonic inspections on other engine models during in-service maintenance to ensure their continued airworthiness.

- **Lack of recent guidance about design precautions to minimize hazards resulting from uncontained engine failures.** In March 1997, the FAA issued Advisory Circular (AC) 20-128A, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure." The AC provided rotor burst and blade release fragment trajectory data so that airframe manufacturers could integrate appropriate design precautions to minimize hazards to an airplane and its occupants. The AC also contained specific information about accepted design precautions to reduce the overall risk of an uncontrolled fire for airplanes with fuel tanks located in impact areas.

Since the time that the AC was issued, numerous uncontained disk rupture events have occurred, and lessons learned from these events could be incorporated into more robust guidance, including updated trajectory analyses, for airframe manufacturers to use when considering design mitigations for minimizing hazards resulting from uncontained engine failures. Also, even though the flight 383 accident airplane had design mitigations for reducing the overall risk of an uncontrolled fire that were consistent with the AC's guidance, the uncontained engine failure resulted in a subsequent fire.

- **Need for separate engine fire checklist procedures for ground operations and in-flight operations.** American Airlines' engine fire checklist for the Boeing 767 (which was based on Boeing's engine fire checklist procedure) delayed the flight crew from initiating the evacuation checklist, shutting down the left engine, and commanding an evacuation. The engine fire checklist did not differentiate between an engine fire in flight and an engine fire while the airplane was on the ground and did not include a step, for an engine fire on the ground, to shut down the unaffected engine or perform the evacuation checklist sooner. Also, the engine fire checklist included a 30-second wait time between discharging the first fire extinguishing bottle and determining if the second bottle would also need to be discharged. Engine fire checklists that are specific to ground operations generally instruct flight crews to discharge both fire extinguisher bottles about the same time, which could be critical for containing a fire and/or commanding an evacuation.

- **Need for improved flight attendant training regarding assessing exits for evacuations and using interphone systems during emergencies.** As the evacuation was unfolding, three flight attendants stationed on the right side of the airplane blocked their assigned exits because they recognized that the engine fire would present a danger. A flight attendant stationed on the left side of the airplane blocked her assigned exit until the left engine was shut down. However, another flight attendant stationed on the left side of the airplane assessed the conditions outside the airplane yet opened the left overwing exit while the engine was still operating. The one serious injury that resulted during the evacuation occurred after a passenger evacuated using the left overwing exit. Once on the ground, the passenger stood up to get away from the airplane but was knocked down by the jet blast coming from the left engine.

  American Airlines 767-300-series airplanes are equipped with one of two interphone system models, which operate differently. After the accident airplane came to a stop, one flight attendant tried to use the interphone to alert the flight crew that the left engine was still operating but was unsuccessful because she operated the interphone incorrectly. Also, another flight attendant tried to use the interphone to make an announcement to the passengers but could not recall how to use the interphone. The NTSB could not determine, based on the available evidence, if the flight attendants' difficulty operating the interphone was directly related to training deficiencies or the stress associated with the situation. However, the interphone system model installed on the accident airplane was not installed on American Airlines' 767 simulators used for flight attendant training. Further, although company flight attendants were trained on interphone systems during initial training, airplane differences training, and recurrent training, the subject was presented during recurrent training without providing flight attendants with hands-on experience using an interphone during an emergency.

- **Need for research on the effects of evacuating with carry-on baggage.** Video taken during the evacuation and postaccident interviews with flight attendants indicated that some passengers evacuated from all three usable exits with carry-on baggage despite instructions to leave the bags. Although the NTSB has not identified any accident evacuations in which delays related to carry-on baggage caused injuries, passengers evacuating airplanes with carry-on baggage has been a recurring safety concern. The NTSB is not aware of any study that measured the potential delays associated with passengers retrieving and carrying baggage during an emergency evacuation. The results of such a study could help determine appropriate countermeasures to mitigate any potential safety risks.

- **Need for improved communication between flight and cabin crews during emergency situations, including evacuations.** The flight crew did not communicate with the flight attendants to relay its intent not to immediately evacuate. The flight attendants had both the evacuation signaling system and the interphone system available to them to alert the flight crew that an evacuation was underway, but none of the flight attendants activated the signaling system, and only two of the seven flight attendants attempted (unsuccessfully) to communicate with the flight crew using the interphone system. Even with an unfolding emergency, there should have been better communication between the flight and cabin crews.

  The NTSB has a long history of investigating accidents (including three other accident investigations within the last 2 years) in which communication between flight and cabin crews during an evacuation was inadequate and issuing related safety recommendations in response. However, the FAA has not yet acted on a 2009 safety recommendation to revise related guidance (issued in 1988) to reflect the most recent industry knowledge on the subject based on research and lessons learned from relevant accidents and incidents. In addition, the FAA has not yet established a multidisciplinary working group, in response to a 2016 recommendation, to develop best practices to resolve recurring evacuation-related issues. It is time for the FAA to emphasize the importance of ensuring that flight and cabin crew communications can facilitate safe and effective decision-making and action during emergency situations.

The NTSB determines that the probable cause of this accident was the failure of the HPT stage 2 disk, which severed the main engine fuel feed line and breached the right main wing fuel tank, releasing fuel that resulted in a fire on the right side of the airplane during the takeoff roll. The HPT stage 2 disk failed because of low-cycle fatigue cracks that initiated from an internal subsurface manufacturing anomaly that was most likely not detectable during production inspections and subsequent in-service inspections using the procedures in place. Contributing to the serious passenger injury was (1) the delay in shutting down the left engine and (2) a flight attendant's deviation from company procedures, which resulted in passengers evacuating from the left overwing exit while the left engine was still operating. Contributing to the delay in shutting down the left engine was (1) the lack of a separate checklist procedure for Boeing 767 airplanes that specifically addressed engine fires on the ground and (2) the lack of communication between the flight and cabin crews after the airplane came to a stop.

As a result of this investigation, the NTSB makes safety recommendations to the FAA, Boeing, and American Airlines.

1. Factual Information

1.1 History of Flight

On October 28, 2016, about 1432 central daylight time, American Airlines flight 383, a Boeing 767-323, N345AN, had started its takeoff ground roll at Chicago O'Hare International Airport (ORD), Chicago, Illinois, when an uncontained engine failure in the right engine and subsequent fire occurred.[1] The flight crew aborted the takeoff and stopped the airplane on the runway, and the flight attendants initiated an emergency evacuation. Of the 2 flight crewmembers, 7 flight attendants, and 161 passengers on board, 1 passenger received a serious injury and 1 flight attendant and 19 passengers received minor injuries during the evacuation. The airplane was substantially damaged from the fire. A section of the high-pressure turbine (HPT) stage 2 disk burst and penetrated through the inboard section of the right wing and was recovered in a United Parcel Service (UPS) warehouse about 2,935 ft from the location where the uncontained engine failure occurred. The airplane was operating under the provisions of 14 *Code of Federal Regulations* (*CFR*) Part 121. Visual meteorological conditions prevailed at the time of the accident.

Flight 383 was a scheduled passenger flight to Miami International Airport (MIA), Miami, Florida.[2] The flight crew's duty day began in ORD at 1320, with a scheduled departure time to MIA 1 hour later. The captain was the pilot flying, and the first officer was the pilot monitoring.

The captain taxied the airplane to runway 28R for a takeoff from the intersection of the runway with taxiway N5. Runway 28R was 13,000 ft long and 150 ft wide, and the available length from the N5 intersection was 9,750 ft.

According to the cockpit voice recorder (CVR), at 1430:57, the tower controller cleared the airplane for takeoff, and the first officer acknowledged this instruction.[3] At 1431:19, the CVR recorded a sound similar to increasing engine rpm, and the flight data recorder (FDR) indicated that the engines achieved takeoff power at 1431:24.[4] During a postaccident interview, the flight

[1] (a) All times in this report are central daylight time unless otherwise noted. (b) An uncontained failure of a turbine engine "is any failure which results in the escape of rotor fragments from the engine or APU [auxiliary power unit] that could result in a hazard," according to Federal Aviation Administration (FAA) Advisory Circular (AC) 20-128A, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure."

[2] This flight was the first of two planned sequences that day for the flight crewmembers; they were also scheduled to fly from MIA to ORD. On the day before the accident, the flight crew flew one sequence, from MIA to ORD. The captain reported that he and the first officer had flown together several times before that flight, most recently at the beginning of October 2016.

[3] The airplane was equipped with an L-3/Fairchild FA2100-1020 solid-state CVR, which records at least the last 2 hours of digital audio. The CVR records audio information from five channels—the captain's, first officer's, and observer's audio panels; a mixed crew audio panel; and the cockpit area microphone. Each of the channels contained either excellent- or good-quality audio information, and a transcript was prepared for the final 2 minutes 42 seconds of the recording. (See appendix B for the transcript and descriptions of excellent- and good-quality audio.) The transcript begins at 1430:29, just before the airplane turned onto runway 28R, and ends at 1433:12.

[4] The airplane was also equipped with an L-3/Fairchild FA2100 256 wps FDR. The recorder was in good condition, and the data were extracted normally from the recorder using the manufacturer's recommended procedures.

crew described the engine spool-up (as thrust advanced to the predetermined reduced power setting for takeoff) as "normal." At 1431:32, the first officer made a routine callout indicating that the airplane's airspeed was 80 knots.

FDR data showed that, at 1431:43.4 and with the airplane's airspeed indicating 128 knots, the longitudinal acceleration decreased suddenly from 0.23 to 0.13 G, and variations in the vertical acceleration increased in magnitude, consistent with a sudden engine imbalance causing a vibration force on the airframe.[5] About the same time, the CVR recorded a "bang" sound and the captain's statement "whoa." Both flight crewmembers reported hearing the sound and feeling the airplane drift to the right. At that time, the airplane was about 3,300 ft from the N5 intersection. The captain initiated the rejected takeoff maneuver; FDR data showed that the throttles were moved to idle power at 1431:45.[6] One second later, the autobrakes, which for takeoff had been selected in the "RTO" (rejected takeoff) position, activated.[7] At that time, the airplane's airspeed was 134 knots, which was also the calculated takeoff decision speed (V_1). The auto speedbrakes activated about 2 seconds after the autobrakes.[8] In a postaccident statement, the captain indicated that he rejected the takeoff because he thought that the airplane was "unable/unsafe to fly."[9]

At 1431:50, the first officer contacted the air traffic control (ATC) tower and stated that the airplane would be "stopping on the runway," and the tower controller responded, "roger roger fire," which was the flight crew's first indication that a fire had begun. The first officer asked the controller if he saw any smoke or fire, and the controller stated, "yeah, fire off the right wing."[10] At 1432:00, the CVR recorded the first officer stating, "okay, send out the [fire] trucks," and a

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About 56 hours of operational data were retained on the recording medium, including about 11 minutes of data from the accident flight, from 1422:15 to 1433:09.

[5] (a) G is a unit of measurement of acceleration and deceleration. One G is equivalent to the acceleration caused by the earth's gravity (about 32.2 ft/sec^2). (b) FDR data indicated that, between 1431:21 and 1431:37, the airplane reached a steady longitudinal acceleration of about 0.25 G. Between 1431:37 and 1431:43, the longitudinal acceleration began to slowly decrease. When the longitudinal acceleration decreased suddenly at 1431:43, the vertical acceleration also decreased, from 1.14 to 0.97 G. The vertical acceleration before that time had basically been steady—between 0.98 and 1.02 G.

[6] The CVR recorded a sound similar to throttles contacting idle stops and a sound similar to a decrease in engine rpm.

[7] Autobrakes are selected in the RTO position during takeoff to provide maximum braking in the event of a rejected takeoff. During a postaccident interview, the captain described the performance of the RTO autobrake system as an "aggressive stop."

[8] During that time, the FDR recorded the flight's maximum airspeed—135 knots—which decreased by 15 knots by 1431:49.

[9] American Airlines *767 Operations Manual, QRH* (*Quick Reference Handbook*) indicated that a rejected takeoff was a "non-normal maneuver." According to the *QRH*, "the captain has the sole responsibility for the decision to reject the takeoff. The decision must be made in time to start the rejected takeoff maneuver by V_1. If the decision is to reject the takeoff, the captain must clearly announce 'REJECT,' immediately start the rejected takeoff maneuver, and assume control of the airplane." The *QRH* also stated that a takeoff should be rejected between 80 knots and V_1 if an engine failure, fire, or fire warning occurred or if the airplane was unsafe or unable to fly and that "the crew member observing the non-normal situation will immediately call it out as clearly as possible."

[10] National Transportation Safety Board (NTSB) investigators sat in the first officer's seat in an exemplar American Airlines 767 airplane to determine whether the right wing and right engine could be viewed from that position. The investigators found that the right wingtip was visible only when the occupant's head was pressed against the closed right-side cockpit window. The right engine was not visible with the right-side cockpit window closed. The right engine was visible with the window opened to allow the occupant to look outside the fuselage.

sound similar to the engine fire warning. FDR data showed that the engine indicating and crew alerting system (EICAS) warning message "ENG FIRE R" had annunciated at the same time and that the airplane had decelerated to an airspeed of 35 knots.[11] The tower controller indicated that he would send emergency vehicles, and the captain called for the engine fire checklist (which included five memory items) at 1432:04.1, 20.6 seconds after the CVR recorded the "bang" sound. FDR data showed that the airplane came to a stop at 1432:09.8, which was 26.4 seconds after the right engine failure. The captain reported that he could smell smoke "as soon as [the airplane] came to a stop."

As part of the engine fire checklist, the fuel switch for the right engine was shut off. Also, the first officer pulled the right engine fire handle, and he later rotated the handle to release the contents of one of the fire extinguisher bottles into the right engine.[12] The left engine remained at idle power. At 1432:41, the captain stated, "oh look at the smoke—check out the smoke."

The CVR recording indicated that, at 1432:45, the captain called for the evacuation checklist; the first officer acknowledged the instruction about 1.5 seconds later. The first officer announced the items on the evacuation checklist, and the captain accomplished the items. The second and third steps in the checklist depressurized the airplane, and the captain stated, during a postaccident interview, that it took "a long time" for the airplane to depressurize.[13] While performing the checklist, the captain could hear "commotion" outside the cockpit door and realized that the flight attendants had begun an evacuation. The captain stated that, after completing the fourth step in the checklist—to shut down the left engine—he made an announcement to the cabin to evacuate and activated the emergency evacuation signal switch.[14] The captain then completed the remaining steps of the evacuation checklist and exited the cockpit, at which time both flight crewmembers observed "a lot of smoke" in the cabin.

After exiting the cockpit, the flight crewmembers were met by the lead flight attendant, who informed them that all passengers and the other flight attendants were off the airplane. (Section 1.5.2 describes the evacuation.) The first officer then evacuated the airplane, followed by the lead flight attendant and the captain. After evacuating the airplane, the captain used his personal cell phone to contact American Airlines dispatch to obtain the total count of occupants on board

[11] Also at 1432:00, the master WARNING light (on the glareshield in front of each pilot) illuminated.

[12] The left and right engine fire handles (for the left and right engines, respectively) were located on the engine fire control panel, which was located on the center console in the cockpit (as shown in section 1.6.1.1). According to American Airlines' *767 Operations Manual, QRH*, "Fire Protection," the airplane was equipped with two fire extinguisher bottles. One or both bottles, which contained halon, could be discharged into either engine. The FDR parameter for the right engine fire extinguisher bottle activated at 1432:12. (The FDR records when the fire handle is pulled for the first time; the FDR does not record when each fire extinguisher bottle discharges.) Postaccident examination of the fire extinguisher bottles showed that, according to the data in their labels, each weighed about 24 pounds at the time of installation. The weight of both bottles after removal from the airplane was about 10.5 pounds.

[13] According to the CVR, the first officer announced the checklist item to depressurize the airplane at 1432:57. (This issue is further discussed in section 2.2.1.) The first officer announced the next evacuation checklist item—to cut off the fuel control switches—at 1433:07.

[14] At 1433:10, the CVR recorded the first officer prompting the captain (as part of the evacuation checklist) to make a public address (PA) system announcement to evacuate the passenger cabin; this transmission was interrupted by the sound of a "thunk" 1 second later. The evacuation signal switch was on the emergency evacuation command panel, which was located on the overhead panel above the captain's head. The signal was intended to alert the flight attendants to evacuate the cabin.

for first responders. The 20 injured passengers were transported to local hospitals to receive treatment, and all were released within 24 hours.[15]

The fire was extinguished by aircraft rescue and firefighting (ARFF) vehicles. According to ARFF, aqueous film-forming foam was first applied within 2 minutes 51 seconds after notification of the fire.[16] Most of the fire damage was contained to the right engine, the right wing, portions of the right fuselage, and the right horizontal stabilizer. Figure 1 shows the accident airplane after the fire was extinguished.

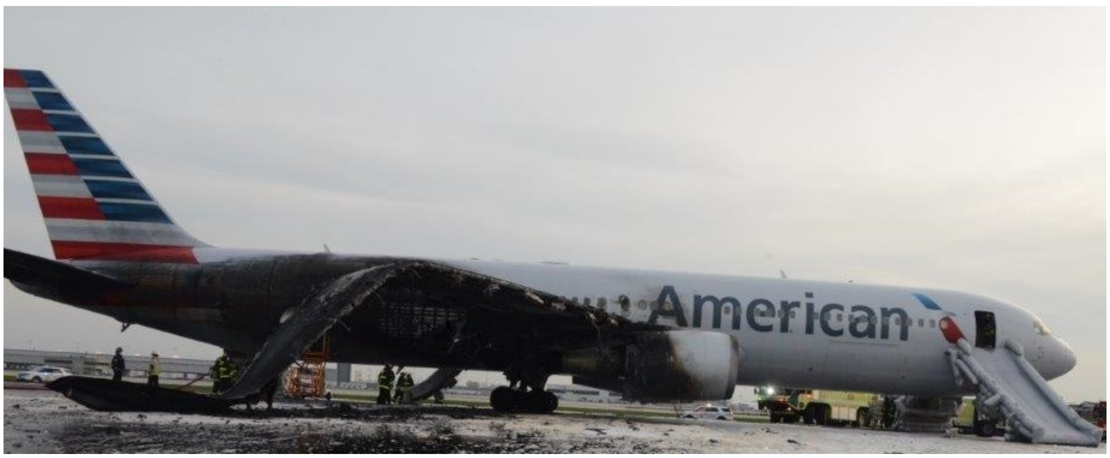

Figure 1. Right side of airplane after uncontained engine failure and subsequent fire.

The airplane's final position on runway 28R was about 5,975 ft from the N5 intersection (where the takeoff roll began) with about 3,775 ft of runway remaining. Braking marks from the left and right main landing gear tires were observed on the runway surface starting about 3,961 ft from the N5 intersection. The braking marks continued for about 2,284 ft to the airplane's final position on the runway.

1.2 Personnel Information

1.2.1 The Captain

The captain, age 61, held an airline transport pilot certificate with a multiengine land rating and an FAA first-class medical certificate dated May 4, 2016, with no limitations. The captain received a type rating for the Boeing 757 and 767 on March 31, 1995.

The captain was employed at Trans World Airlines (TWA) from January 1986 to April 2001 and has been employed by American Airlines since May 2001 (when AMR Corporation, the parent company of American Airlines, acquired TWA). He had been a captain on

[15] The flight attendant who received a minor injury was not transported to the hospital but instead went to the ORD medical office.

[16] According to the Bureau of Operations, Chicago Fire Department, 21 vehicles (including 8 ARFF units) and 56 personnel responded to the crash/fire alert on runway 28R.

the 767 for about 2.5 years before the accident.[17] The captain estimated that he had accumulated about 17,400 hours of total flight time, including about 4,000 hours on the 767 and about 1,500 hours as 767 pilot-in-command. He had flown about 157, 59, 12, and 3 hours in the 90, 30, and 7 days and 24 hours, respectively, before the accident. The captain's last line check occurred on October 21, 2015, and his last recurrent ground training occurred on March 20, 2016. FAA records indicated no accident or incident history or enforcement action.

The captain stated that he had never experienced an engine fire or performed a rejected takeoff during his career (except during simulator training). He also stated that he had never performed the evacuation checklist or commanded an evacuation on an actual flight.

72-Hour History

According to postaccident interviews and company records, on October 25, 2016, the captain's duty day started at 1400 eastern daylight time (EDT).[18] He departed from BOS at 1502 EDT and arrived at Philadelphia International Airport, Philadelphia, Pennsylvania, at 1703 EDT and then deadheaded to Charlotte-Douglas International Airport (CLT), Charlotte, North Carolina, arriving at 2043 EDT. Afterward, he flew from CLT to JFK, arriving at 2338 EDT. He went to sleep about 0100 EDT on October 26.

The captain did not recall his wakeup time on October 26, but he thought that he received 7 to 8 hours of sleep during the night. He left the hotel between 1400 and 1430 EDT and began his duty day at 1440 EDT. He flew from JFK to MIA, arriving at 1829 EDT. He described his duty day as "easy." He spent the night at his residence near MIA. He did not recall the time that he went to sleep.

On October 27, the captain awoke about 0900 EDT and began his duty day at 1550 EDT. He and the first officer departed MIA at 1706 EDT, arriving in ORD at 1943. The captain arrived at the hotel before 2000, got something to eat, and then used his computer until about 0000 on October 28 before going to sleep. The captain awoke between 0800 and 0900. He departed the hotel about 1235 for ORD, where his duty day began at 1320.

The captain reported no problems falling or staying asleep in the days before the accident. He woke up each day feeling rested, including on the morning of the accident. His normal sleep pattern when off duty was to go to sleep between 2300 and 0000 and wake up about 0700. He did not take any prescription or nonprescription medicine in the 72 hours before the accident that might have affected his performance on the day of the accident. He did not use tobacco products or illicit drugs, and his only alcohol consumption during the time period was during dinner on October

[17] Company records indicated that the captain upgraded to that position on the 767 on January 7, 2014. Before that time, he was an MD-80 captain; he received a type rating for the DC-9 (a variant of which is the MD-80) on July 13, 1998.

[18] The captain flew a 3-day trip from October 24 to 26. On October 24, his duty day started at 1726 EDT. He flew from MIA to John F. Kennedy International Airport (JFK), Jamaica, New York, arriving at 2021, and then he deadheaded (traveled as a nonrevenue passenger) to General Edward Lawrence Logan International Airport (BOS), Boston, Massachusetts, arriving at 2346 EDT. He arrived at a hotel and went to sleep between about 0100 and 0130 EDT on October 25. The captain awoke between 0900 and 1000 EDT that day and left the hotel about 1330 EDT to begin his duty day.

27.[19] He considered his health to be “pretty good” and had no changes in his health, finances, or personal life in the 12 months before the accident that would have affected his performance on the day of the accident.

1.2.2 The First Officer

The first officer, age 57, held an airline transport pilot certificate with a multiengine land rating and an FAA first-class medical certificate dated May 3, 2016, with a limitation that required him to possess glasses for near and intermediate vision. (During a postaccident interview, the first officer stated that he was wearing his glasses during the attempted takeoff.) The first officer received a type rating for the Boeing 757 and 767 on June 14, 2014.

The first officer was employed at TWA between December 1995 and April 2001 and then American Airlines beginning in May 2001 (when AMR Corporation acquired TWA). He was furloughed in July 2003, recalled from furlough in March 2008, furloughed again in February 2010, and recalled from furlough again in December 2010.[20] The first officer estimated that he had accumulated about 22,000 hours of total flight time, including about 1,600 hours on the 767. He had flown about 116, 78, 13, and 3 hours in the 90, 30, and 7 days and 24 hours, respectively, before the accident. The first officer’s last line check occurred on February 15, 2015, and his last recurrent ground training occurred on September 5, 2016. FAA records indicated no accident or incident history or enforcement action.

72-Hour History

According to postaccident interviews and company records, the first officer was off duty from October 24 to 26, 2016.[21] The first officer could not recall his sleep/wake times for the 3 days before the accident flight. On October 27, he commuted from his home in Tampa, Florida, to MIA and started his duty day at 1550 EDT. He flew from MIA to ORD with the captain, arriving at 1943. He recalled going to sleep shortly after arriving at the hotel and not having any trouble falling or staying asleep. He reported feeling rested when he awoke on October 28. His duty day began at 1320.

The first officer stated that he usually slept about 7 hours each night and that he normally went to sleep early and woke up early. He did not take any prescription or nonprescription medication in the 72 hours before the accident that might have affected his performance on the day of the accident. He did not use tobacco products or illicit drugs and did not consume alcohol during the time period.[22] He considered his health to be a “10 out of 10.” He had no changes in his health, finances, or personal life in the 12 months before the accident that would have affected his performance the day of the accident.

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[19] The results of postaccident drug and alcohol screening for the captain were negative.

[20] During the first officer’s first furlough from American Airlines, he worked at Atlantic Southeast Airlines as a first officer and then a captain on the Bombardier CL-65.

[21] The first officer was on duty from October 20 to 23.

[22] The results of postaccident drug and alcohol screening for the first officer were negative.

1.2.3 The Flight Attendants

The flight was operated with seven flight attendants. Table 1 shows each flight attendant's position, initial new hire date, and last recurrent training date before the accident. Section 1.5 provides information about the flight attendants' seating positions within the cabin and their actions before and during the evacuation.

Table 1. Flight attendant position, initial new hire date, and last recurrent training date.

Flight attendant (FA) position	Initial new hire date	Last recurrent training date
FA 1—Lead	April 1988	April 2016
FA 2	November 1998	November 2015
FA 3	November 2014	November 2015
FA 4	July 1991	March 2016
FA 5	October 1989	July 2016
FA 6	April 1984	April 2016
FA 7	November 1989	October 2016

The lead flight attendant was the primary liaison between the captain and the flight attendants. According to American Airlines *Flight Manual* Part I, "Flight Attendant/Purser Briefing," dated October 1, 2016, the lead flight attendant is responsible for promptly informing the captain of "all on-board cabin emergencies, irregular issues, passenger concerns, and cabin discrepancies."

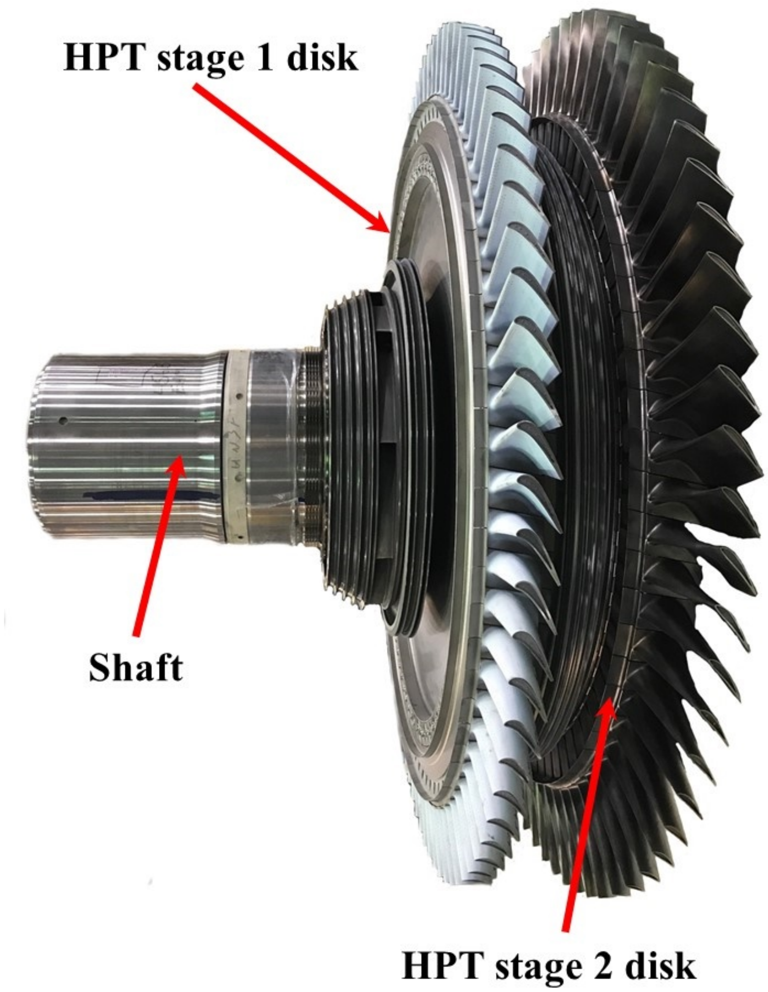
1.3 Airplane and Engine Information

Boeing delivered the airplane involved in this accident, serial number 33084, to American Airlines on April 30, 2003; American Airlines records showed that the airplane was registered as N345AN on the same date. At the time of the accident, the airplane had 50,632 total flight hours and 8,120 total flight cycles.[23] The airplane was equipped with two General Electric (GE) CF6-80C2B6 turbofan engines, with one engine mounted under each wing. The No. 1 (left) engine had accumulated 46,822 total hours and 7,299 total cycles, and the No. 2 (right) engine had accumulated 68,785 total hours and 10,984 total cycles.

The CF6-80C2B6 is a dual-rotor, high-bypass ratio turbofan engine. The low-speed rotor (N1) consists of a large diameter fan and four low-pressure compressor booster stages that are interconnected to a five-stage low-pressure turbine rotor. The high-speed rotor (N2), which is located between the fan rotor/booster and the low-pressure turbine rotor, consists of a 14-stage high-pressure compressor and a 2-stage HPT. The HPT rotor drives the high-pressure compressor rotor by converting the combustor exhaust gas flow into mechanical force. The HPT stage 1 disk has 80 blades, the HPT stage 2 disk has 74 blades, and each blade has its own retaining post.[24] Figure 2 shows an HPT rotor for a CF6-80C2B6 engine.

[23] A flight cycle is one complete takeoff and landing sequence.

[24] For more information about the CF6-80C2B6 engine, see the Powerplants factual report in the docket for this accident investigation, DCA17FA021, at the NTSB's website (www.ntsb.gov).



Source: American Airlines.

Figure 2. HPT rotor.

1.3.1 High-Pressure Turbine Stage 2 Disk Manufacturing Process

The HPT stage 2 disk installed on the right engine was made of alloy 718 (a wrought nickel-based alloy). The material used to manufacture the disk for GE was produced by TDY Industries LLC doing business as ATI Specialty Materials (ATI SM) in 1997 at the company's Monroe, North Carolina, facility. ATI SM used a triple-melt process to produce an ingot (a mass of metal cast into a specific size or shape) per GE specifications.[25] Afterward, ATI SM converted

[25] GE first used alloy 718 in the 1970s, and the material underwent a double-melt process at that time. In the early 1980s, GE started using a triple-melt process for some part applications manufactured with alloy 718. In the mid-1990s, GE began using the triple-melt process for all of its critical life-limited rotating parts manufactured with alloy 718.

ingots to billets (larger diameter bars) using thermal and mechanical processes and inspected the billets for internal defects using an ultrasonic inspection procedure.

1.3.1.1 Triple-Melt Process

ATI SM’s triple-melt process consisted of vacuum induction melting, electroslag remelting, and vacuum arc remelting, as described below. After completion of the triple-melt process, an ingot undergoes a billet conversion process, which is also described below.

Vacuum Induction Melting

The first step of the triple-melt process, vacuum induction melting, is also referred to as the master heat. Vacuum induction melting uses an induction furnace in a vacuum chamber to (1) combine raw material to establish the desired chemistry and (2) refine the material by removing impurities. Melting the raw material in a vacuum reduces the oxygen and nitrogen content, thus inhibiting the formation of oxides and nitrides, which are detrimental to the mechanical properties of the alloy. After the material is completely melted and agitated, in-process samples are taken until the desired chemistry has been achieved. The molten material is then poured into a series of vertical molds, creating a series of ingots that function individually as an electrode for the next step in the triple-melt process.

Electroslag Remelting

The second step of the triple-melt process, electroslag remelting, establishes the cleanliness of the material. This step involves (1) continuously melting an ingot (which functions as an electrode) through a molten bath of electrically conductive and chemically reactive slag and (2) collecting the purified material in a water-cooled mold. A stub, referred to as a stinger, is welded to the ingot to provide a current path to complete the electrical circuit and structurally support the ingot.

As the ingot melts, droplets are created that descend through the superheated slag layer, and impurities dissolve or bind with the reactive elements within the slag layer and float toward the top. When the droplets reach the bottom of the water-cooled mold, they solidify, creating a new ingot that builds up from the bottom of the mold and moves the slag layer up the side of the mold.

A slag skin layer also builds up between the new ingot and the water-cooled mold, which helps reduce the formation of oxides. The skin layer limits the rate at which heat can be removed from the newly formed ingot, which negatively affects the macrostructure of the material. As a result, before the ingot undergoes the next step in the triple-melt process, the top and bottom of the ingot are removed to reduce the possibility of contamination, and any scale on the outside of the ingot (the slag skin layer in this case) is also removed.[26]

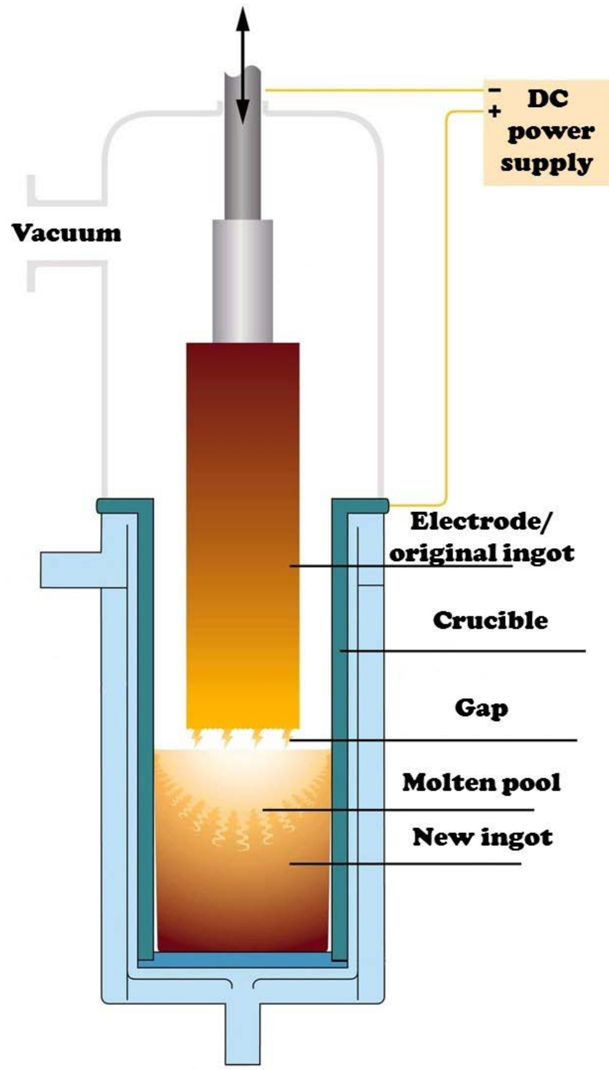
[26] Material defects are most likely to form in the top and bottom of the ingot because the temperature is the least stable in these areas during the melting and subsequent cooling/solidification of the ingot.

Vacuum Arc Remelting

Although the final step in the triple-melt process, vacuum arc remelting, further refines the cleanliness of an ingot, the main purpose of this process is to establish the desired macrostructure for the ingot material. Similar to electroslag remelting, vacuum arc remelting involves continuously melting an original ingot (which functions as an electrode), collecting the molten material in a water-cooled mold, and forming a new ingot. Unlike electroslag remelting, vacuum arc remelting is a direct current process conducted under a vacuum and does not use a molten slag layer.

The original ingot is lowered into the mold until an arc is struck between the electrode and the bottom of the mold. The high-temperature arcing melts the original ingot. As molten droplets fall through a gap, dissolved gases are removed, and unwanted contaminants are vaporized. The molten droplets collect at the bottom of the mold, where they resolidify and form the new ingot, as shown in figure 3.[27] The position of the original ingot is controlled to keep the melt rate constant as the new ingot builds up from the bottom of the mold. Similar to electroslag remelting, after the vacuum arc remelting process is completed, the top and bottom of the ingot are removed, and any scale on the outside of the ingot is also removed.

[27] Figures showing the vacuum induction melting and the electroslag remelting processes appear in the Powerplants factual report in the docket for this accident investigation, DCA17FA021.



Source: ATI SM.

Figure 3. Vacuum arc remelting process.

Billet Conversion Process

The billet conversion process replaces the original non-uniform coarse grain structure of an ingot with a new recrystallized (finer) grain structure. During this process, the ingot is subjected to a series of heat treatments and axial, transverse, and radial forging operations until the material has reached the desired size, shape, and microstructure. At the end of this process, the material becomes a billet.

1.3.1.2 Ultrasonic Inspection Process

After completion of the conversion process, a billet is prepared for ultrasonic inspection, which is a nondestructive inspection method for detecting surface and subsurface anomalies and determining the position, shape, and possibly the size of those anomalies. ATI SM uses a longitudinal wave water immersion, pulse-echo ultrasonic inspection technique in which the billet is submerged in a water tank and rotated while two transducers move longitudinally along the length of the billet. The rotation of the billet ensures that its entire diameter is inspected by the combination of the two transducers. The technique involves a pulsed sound wave from a transducer that propagates through the material and reflects off any discontinuity, such as a void (an internal cavity), crack, or variation in material density, providing an echo back to the transducer.

The location of a discontinuity can be determined by comparing the amount of time for the echo to return to the transducer with the normal reflective wave from a known discontinuity. Although the size of a discontinuity can be determined by the strength (amplitude) of the echo return, this information must also be correlated with a known defect size. The advantage of this technique is the ease of moving the transducer along the material while both remain acoustically coupled.[28] Figure 4 shows a representation of a longitudinal wave scan.

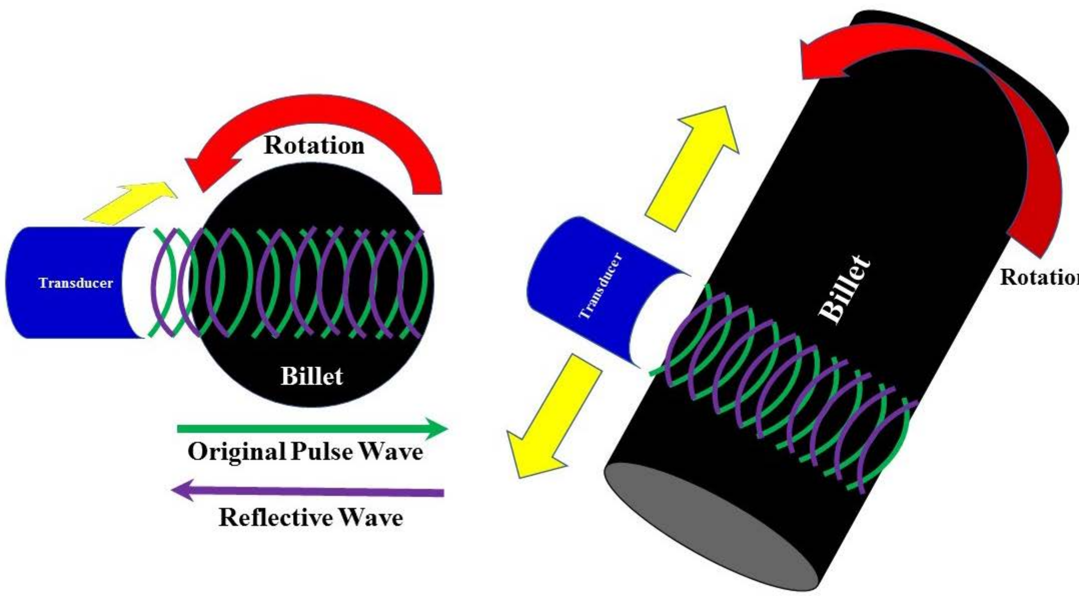


Figure 4. Longitudinal wave scan used during ultrasonic inspections.

Before the ultrasonic inspection, the top and bottom of a billet are cut off because these areas are where defects are most likely to have formed. Additional cuts at the top and bottom of the billet are made for visual macroscopic inspection. The final steps before the ultrasonic inspection are a machining operation termed "peeling" and polishing to enhance the effectiveness of the inspection. ATI SM uses the requirements of GE specification P3TF15, titled "Ultrasonic Inspection of Billet – Immersion," class C and class E, for the billets.[29] As part of the inspection process, any identified defects are cut out of the billet material for evaluation, and an ultrasonic

[28] The immersion transducer uses the water to facilitate the transmission of acoustic waves from the transducer to the material to be inspected. The transducer cables are electrically sealed and waterproof.

[29] GE specification P3TF15 called for the surface finish for the polishing step to be 125 microinches or better, which "will normally ensure inspectability." A microinch (μin) is equal to one-millionth of an inch. Class C refers to alloy 718 (fine grain), and class E refers to general applications (high sensitivity).

billet map sheet is created for each billet to provide the location of any defects that were cut out of the material.

1.3.1.3 Manufacture History of Accident HPT Stage 2 Disk

According to ATI SM production records related to the accident HPT stage 2 disk, the triple-melt process produced five ingots, designated as FA94-1 through -5, from the master heat, and the ingot designated as FA94-2 was the one from which the HPT stage 2 disk was manufactured. ATI SM stated that the furnaces that were used to produce these ingots were still in use at the company's facility (as of November 2017). Ingot FA94-2, which became billet FA94-2, was forged into a 10-inch-diameter round. The ultrasonic inspection technique that ATI SM used for billet FA94-2 was the same as that in use as of November 2017, and the equipment that was used for inspecting the billet was the same design as the equipment in use as of November 2017.[30] Review of the ultrasonic billet map sheet for FA94-2 showed no defects or rejections in the billet material.[31]

Two companies, in addition to ATI SM, were involved in manufacturing the HPT stage 2 disk that was delivered to GE: Wyman-Gordon of Houston, Texas, and Motoren- und Turbinen-Union GmbH (MTU) of Germany. Once billet FA94-2 was deemed acceptable (that is, it passed all required inspections), ATI SM cut the billet to the lengths specified by Wyman-Gordon. Review of the ATI SM certification test sheet (used to certify billets) for FA94-2, dated June 17, 1997, indicated that (1) the metallography, microstructure, and grain size were acceptable per specifications; (2) an ultrasonic inspection was performed with no defects found; and (3) macroscopic inspection results were acceptable.

ATI SM sent the billet to Wyman-Gordon, which further cut the billet into nine pieces, with each piece representing the precise length of material needed to manufacture the intended part. These pieces were press forged, heat treated, and rough machined. Wyman-Gordon certified the forging on August 8, 1997, and sent the forged pieces to MTU for additional inspections and final machining.

MTU performed ultrasonic inspections (with the pulse-echo technique, similar to ATI SM) on "sonic-shape" forged pieces using its own work instructions, which GE approved.[32] MTU's work instructions met GE specification P3TF1, titled "Ultrasonic Inspection," class A longitudinal

[30] The transducers for the ultrasonic equipment need to be replaced periodically to prevent calibration issues resulting from deterioration.

[31] For FA94-1, the ultrasonic billet map showed a "macro-rejectable" defect in the bottom of the billet, so additional material was removed. For FA94-3, the ultrasonic billet map showed a "sonic-rejectable" indication in the top of the billet, so material containing the indication was removed, and the defect was located and identified. For FA94-4, the ultrasonic billet map showed a sonic-rejectable indication in the top of the billet, so material containing the indication was removed, but the indication could not be identified after the material was removed. For FA94-5, the ultrasonic billet map showed a macro-rejectable indication in the bottom of the billet, so additional material was removed.

[32] MTU performed pre-machining and cleaning operations before the ultrasonic inspection; those operations produced the forging shape configurations (referred to as sonic-shape pieces) for the inspection.

and circumferential shear ultrasonic requirements.[33] Afterward, additional machining, shot peening, a final visual and dimensional inspection, and a high-sensitivity fluorescent penetrant inspection (FPI), per a GE specification, were performed. Review of the MTU final inspection sheet for the HPT stage 2 disk, dated February 3, 1998, indicated that the completed disk was acceptable. In March 1998, MTU sent the HPT stage 2 disk to GE, which installed the disk in the CF6-80C2B6 turbofan engine that was eventually installed on the right side of the accident airplane. The engine serial number (ESN) for the right engine was ESN 690-373.

1.3.2 Accident Engine Maintenance Events

On April 30, 1998, Boeing delivered a 767 airplane to American Airlines with ESN 690-373 (including the HPT stage 2 disk involved in this event) installed; that airplane was registered as N392AN. On March 25, 2007, American Airlines removed ESN 690-373 from N392AN and sent it to the company's Tulsa, Oklahoma, engine maintenance facility to, among other things, accomplish the mandatory inspection requirements of FAA Airworthiness Directive (AD) 2002-07-12, which were to be performed on the HPT stage 2 disk at "each piece-part opportunity."[34] To satisfy the AD's HPT stage 2 disk inspection requirements, maintenance personnel performed FPIs and eddy current inspections (ECI) of the HPT stage 2 rim bolt holes and the disk bore. Initial FPI results revealed that the bolt holes needed repairs, which were made; follow-up FPI results revealed no other disk anomalies. Maintenance personnel reinstalled the HPT stage 2 disk into the same engine and, on September 16, 2007, installed ESN 690-373 in company 767 airplane N386AA.

On January 15, 2011, American Airlines removed ESN 690-373 from N386AA and sent it to the company's Tulsa maintenance facility for scheduled heavy maintenance. Among other things, maintenance personnel removed the HPT stage 2 disk from the engine and performed all mandatory inspections as well as visual and dimensional inspections. Among the mandatory inspections performed were those required by AD 2009-04-10, which superseded A 2002-07-12.[35] Regarding the CF6-80C2 HPT stage 2 disks, AD 2009-04-10 had the same ECI and FPI requirements as those mandated by AD 2002-07-12, and maintenance personnel documented no anomalies when performing those inspections. Maintenance personnel reinstalled the HPT stage 2 disk into the same engine and, on May 12, 2011, installed ESN 690-373 in the right engine position of the accident airplane (N345AN).

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[33] GE specification P3TF1 called for a surface finish of 90 microinches for longitudinal wave and circumferential shear wave, which "will usually provide ultrasonic inspection with acceptable surface noise effects." Class A refers to immersion ultrasonic inspection.

[34] FAA AD 2002-07-12, "General Electric Company CF6-80A, CF6-80C2, and CF6-80E1 Series Turbofan Engines" (67 *Federal Register* 17279, April 10, 2002), effective May 15, 2002, stated the following: "within the next 30 days after the effective date of this AD, revise the manufacturer's Life Limits Section of the Instructions for Continued Airworthiness…and for air carrier operations revise the approved continuous airworthiness maintenance program" by adding the mandatory inspections detailed in the AD for life-limited rotating engine parts. According to the AD, "piece-part opportunity" meant that "the part has accumulated more than 100 cycles-in-service since the last piece-part opportunity inspection, provided that the part was not damaged or related to the cause for its removal from the engine" (FAA 2002).

[35] FAA AD 2009-04-10, "General Electric Company CF6-80A, CF6-80C2, and CF6-80E1 Series Turbofan Engines" (74 *Federal Register* 7995, February 23, 2009), effective March 30, 2009, incorporated additional inspection requirements (FAA 2009).

On November 11, 2013, American Airlines removed ESN 690-373 from the airplane for reliability improvement program tasks while at the company's Tulsa maintenance facility. Maintenance personnel did not disassemble the HPT rotor and thus did not inspect the HPT stage 2 disk. On December 4, 2013, maintenance personnel reinstalled ESN 690-373 in the right engine position of the accident airplane, where it remained through the time of the accident.

As previously stated, the right engine had accumulated 10,984 total cycles since new. The HPT stage 2 disk has a life limit of 15,000 cycles when installed on the CF6-80C2B6 engine. Thus, at the time of the accident, the HPT stage 2 disk had 4,016 cycles of in-service life remaining. Also, since the time of the right engine's shop visit in January 2011 (the last time before the accident that the HPT stage 2 disk was removed from the engine and inspected), the engine had accumulated 19,139 hours and 3,057 cycles.

1.3.3 Postaccident Engine Observations

The HPT stage 2 disk of ESN 690-373 (right engine) was recovered on scene in four fragments, as shown in figure 5. About 96% of the disk, including the entire disk bore, was recovered.[36] As mentioned in section 1.1, one disk fragment (labeled "A" in figure 5), which weighed about 56.6 pounds, was recovered on the airport property in a UPS warehouse located about 2,935 ft south of the airplane's position on the runway where the uncontained engine failure occurred.[37]

[36] After the accident, 71 of the 74 blade retaining posts in the HPT stage 2 disk were recovered. In addition, smaller pieces of engine debris were recovered at or near the location on the runway where the uncontained engine failure occurred.

[37] The disk fragment penetrated the roof of the UPS warehouse and was found on the floor.

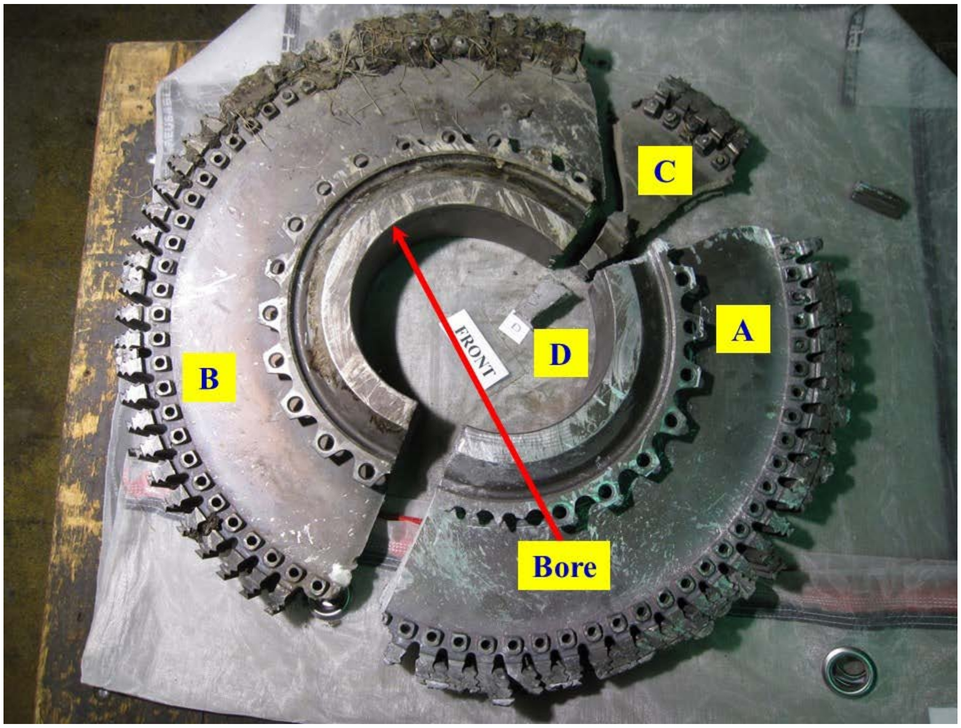

Figure 5. Main fragments of the HPT stage 2 disk (forward side).

The other three disk fragments (labeled “B,” “C,” and “D” in figure 5) were recovered on the airport property north of runway 28R. These three disk fragments were located 475 ft (fragment D), 1,365 ft (fragment B), and 1,500 ft (fragment C) from the airplane’s location on the runway where the uncontained engine failure occurred. Specifically, fragment B, which weighed about 83.1 pounds, was recovered in the grassy area near a taxiway; fragment C, which weighed about 6.6 pounds, was recovered on another taxiway; and fragment D, which weighed about 0.2 pound, was recovered on the overrun area at the departure end of runway 15.[38] Figure 6 shows the disk fragment locations overlaid on a map of the airport.

[38] According to GE, without blades or thermal shield attachment bolts, the HPT stage 2 disk weighs about 153 pounds. The disk fragment weights in this section reflect the weight with blade shanks and attachment bolts removed when possible.

Figure 6. Disk fragment locations.

On-scene examination of the right wing (inboard of the right engine pylon) revealed two distinct penetration holes.[39] One hole (referred to as hole 1) was located forward of the front spar in the leading-edge panel; the other hole (referred to as hole 2) was located aft of the wing front spar. Figure 7 shows holes 1 and 2.

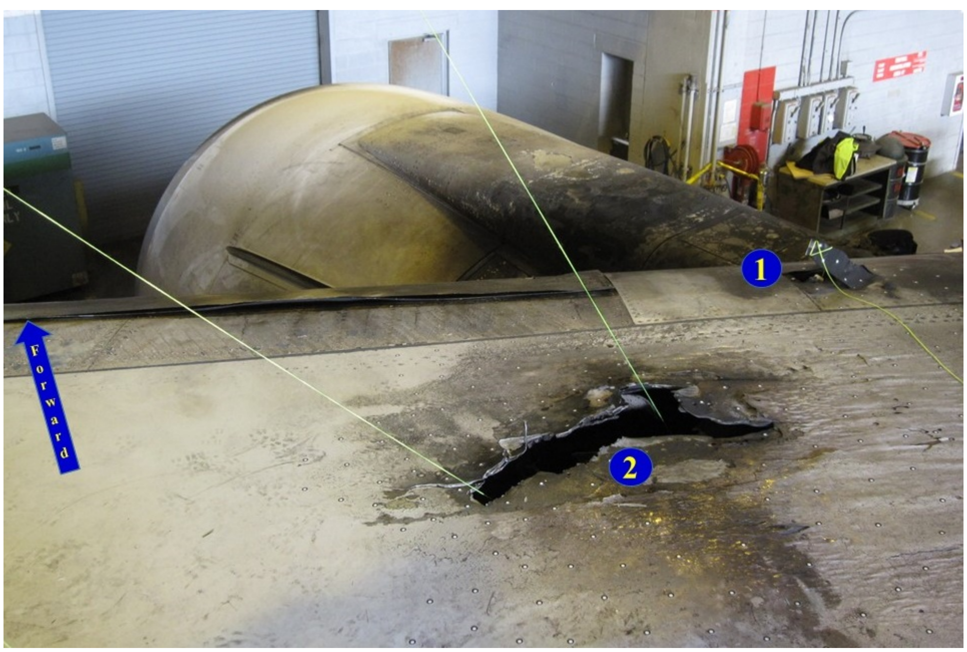

Figure 7. Holes located forward and aft of the right wing front spar.

[39] All right wing impact damage from exiting HPT stage 2 disk or engine debris was observed inboard of the right engine pylon.

The on-scene examination also revealed the following:

- fragments of the ruptured HPT stage 2 disk, along with blade and vane fragments, penetrated through the HPT case and right engine nacelle structure;
- small engine hardware fragments impacted the right side of the fuselage and the left and right main landing gear doors;
- small engine hardware fragments penetrated the left engine nacelle, with no engine damage observed;
- a disk fragment, along with smaller engine hardware fragments, impacted the right engine, right wing, and portions of the right fuselage, severing the main engine fuel feed line and breaching the right-wing fuel tank, which led to a fuel-fed fire; and
- another disk fragment, along with smaller engine hardware fragments, created multiple impact scars on runway 28R.[40]

1.3.4 Metallurgical Examinations

The NTSB's Materials Laboratory in Washington, DC, examined the three largest HPT stage 2 disk fragments (A, B, and C; see figure 5). Visual examination found a discolored (heat-tinted) region on the fracture surfaces separating fragments A and B.[41] The discolored region was at the forward end of the disk bore region, as indicated in figures 8 and 9, and this region was identified as the location where the fracture originated.

[40] The main impact scar was a gouge that was consistent with the impact from exiting HPT stage 2 disk fragments. The gouge was oriented about 30° forward of the direction of airplane travel (relative to the HPT stage 2 plane of rotation) and in the general direction where three separate fragments of the HPT stage 2 disk were located (north of runway 28R). The gouge measured about 33 inches long, 8 inches wide, and 2 inches deep and was located about 32 ft to the right of the runway 28R centerline.

[41] The fracture surfaces comprised right and left sides. The right sides were on disk fragment A, and the left sides were on disk fragment B.

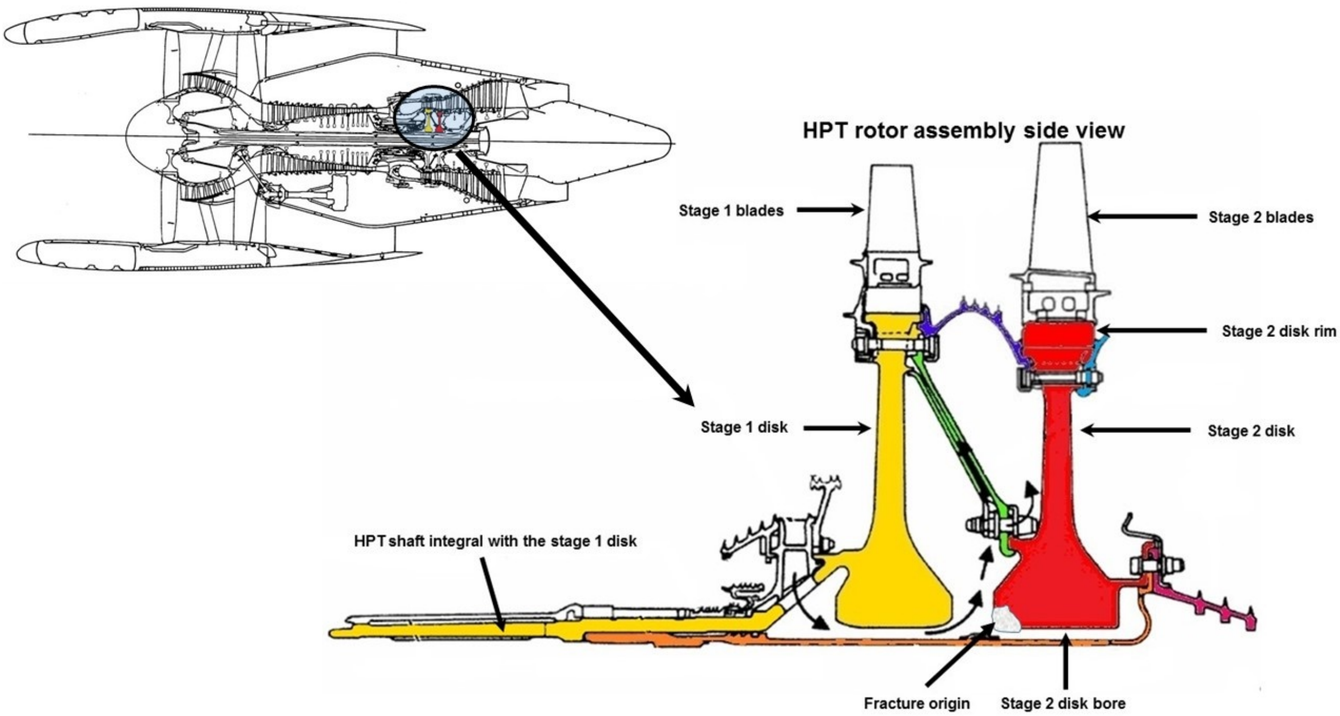

Figure 8. Engine cross-section and fracture origin location.

Figure 9. Fracture surface from disk fragment A.

Metallurgical examination of the fracture surfaces revealed multiple subsurface microstructural discontinuities with multiple cracks initiating along the boundary of the discontinuities. The discontinuities, which had a dark gray appearance, were elongated in the direction of, and aligned with, the grain structure pattern produced during forging. The discontinuities spanned a total length of about 0.78 inch, with the largest of the discontinuities measuring about 0.43-inch-long by 0.07-inch-wide and having an inclination of about 26º from the bore centerline.

Multiple cracks had initiated along the upper and lower edges of the discontinuities and progressed toward the disk rim and disk bore. Scanning electron microscope (SEM) images of the fracture surface revealed relatively coarse striations at regularly spaced intervals, consistent with crack growth by low-cycle fatigue, followed by a transition to cyclic tensile crack growth and then tensile overstress.[42] The net size of the cracked region immediately before the disk fracture (given the size of the discolored region) ranged from about 0.47 to 0.93 inch in the radial direction and about 0.96 inch to 1.13 inches in the axial direction and encompassed an area of about 0.82 square inch.

SEM examination of the discontinuities on the fracture surface showed that the discontinuities were regions of discrete micron-sized oxide particles, referred to as stringers, embedded in a material consistent with alloy 718. A polished and acid-etched metallurgical cross-section through the largest of these features showed that these oxide stringers surrounded and were interspersed in a discrete underlying region where the alloy 718 grain size was coarser than the surrounding material. The coarse grain region beneath the discontinuity exhibited a white-etched appearance compared with the surrounding fine grain material due to the acid etch. The stringers and coarse grain region collectively formed a subsurface anomaly referred to as a "discrete dirty white spot" that measured about 0.15 by 0.10 inch.[43] Figure 10 shows the discrete dirty white spot, and figure 11 shows a close-up view of one of the stringers.

[42] Striations are linear features on a fatigue fracture surface that indicate how far a crack advanced with each stress cycle. The NTSB selected three of six cracks for striation density measurements to estimate the number of low-cycle fatigue crack growth cycles before the disk ruptured. In airplane engines, low-cycle fatigue is associated with one striation per flight cycle. For information about the NTSB's work in this area, see section 1.4.1.

[43] If stringers are present, a white spot is "dirty"; if stringers are absent, a white spot is "clean." Section 1.7.1 provides information about white spot formation as it related to the manufacturing process for the HPT stage 2 disk.

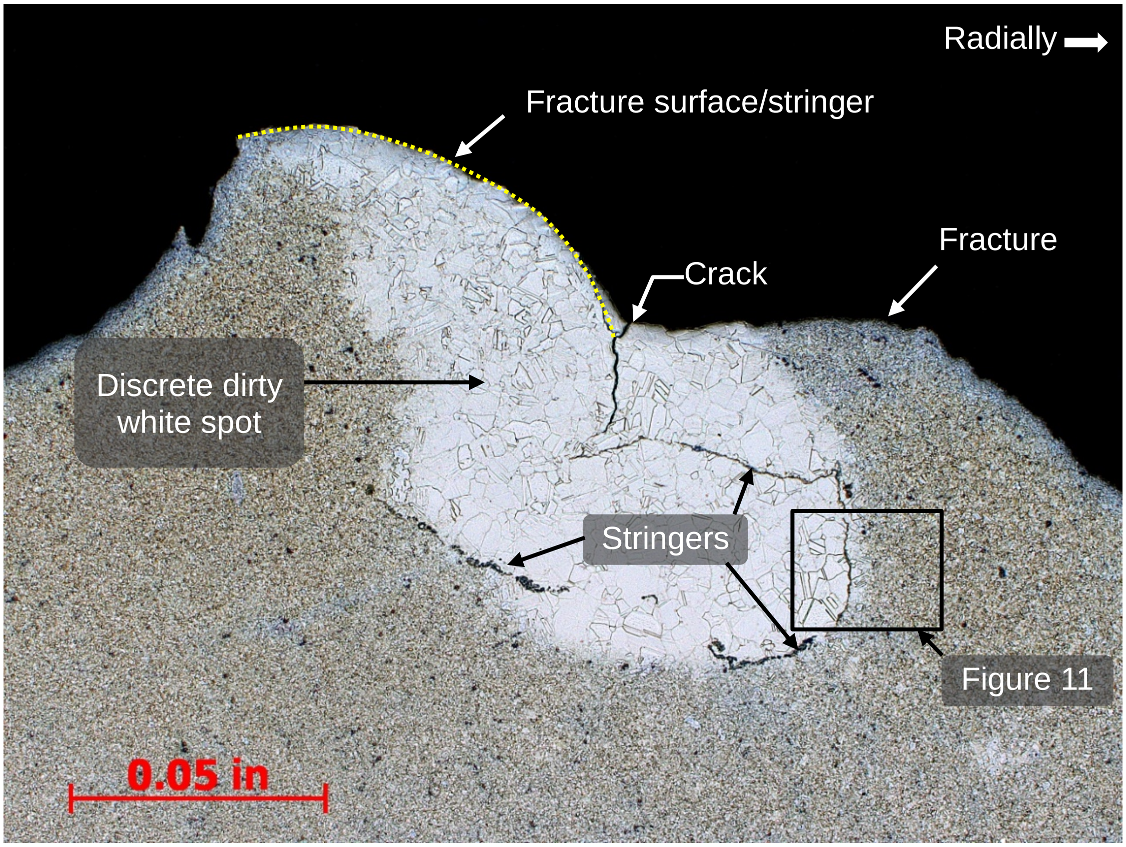

Figure 10. Discrete dirty white spot in fracture surface.

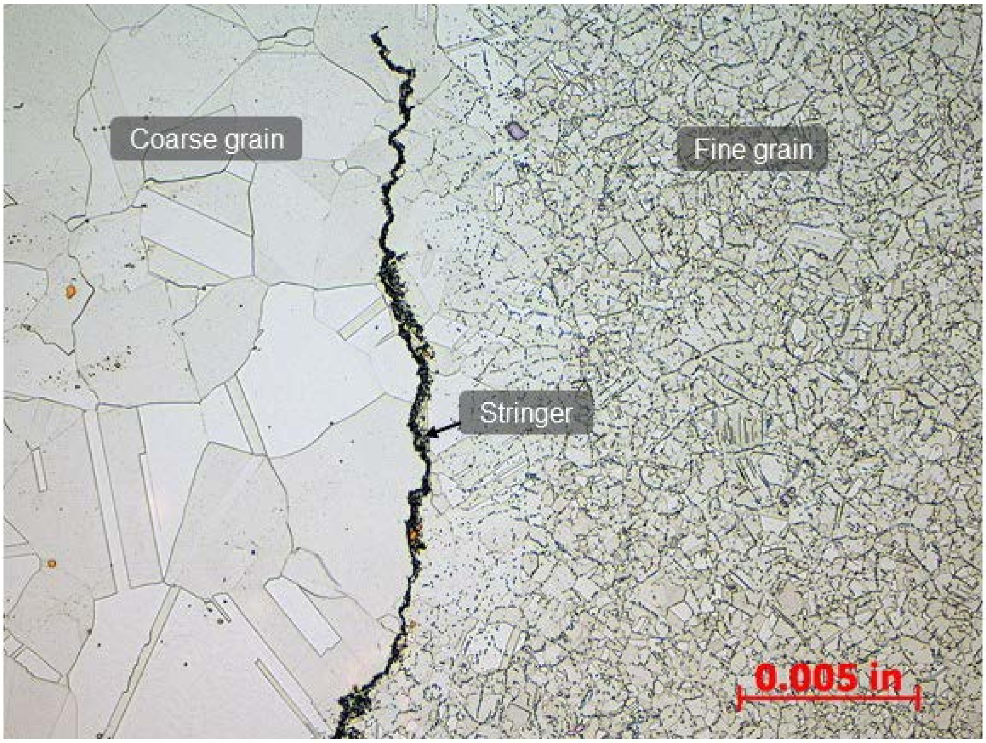

Figure 11. Stringer in material microstructure.

GE Aviation's Materials Laboratory in Evendale, Ohio, performed additional metallurgical examinations on the disk segments and produced a report detailing its findings (Morales 2017). This work included additional striation density measurements (discussed in section 1.4.1), hardness measurements, microprobe chemical analysis of the discrete dirty white spot, additional cross-section metallography, and bulk alloy chemistry. The report stated that the hardness, chemistry, and grain size of the material away from the discrete dirty white spot was within the blueprint requirements for the disk and that GE's cross-sections through the discrete dirty white spot found stringers with no voids.

GE and ATI SM conducted a study of discrete dirty white spots "to better understand their ultrasonic response characteristics." The report detailing the study results is discussed in section 1.4.2.

1.4 Tests and Research

1.4.1 Number of Flight Cycles in Low-Cycle Fatigue Regions

As previously stated, the NTSB documented the presence of multiple fatigue cracks that initiated at a discrete dirty white spot in the forward bore region of the HPT stage 2 disk. The NTSB and GE estimated flight cycles for a total of six cracks, numbered 1 through 6, as shown in figure 12. The cracks exhibited striated features consistent with low-cycle fatigue.

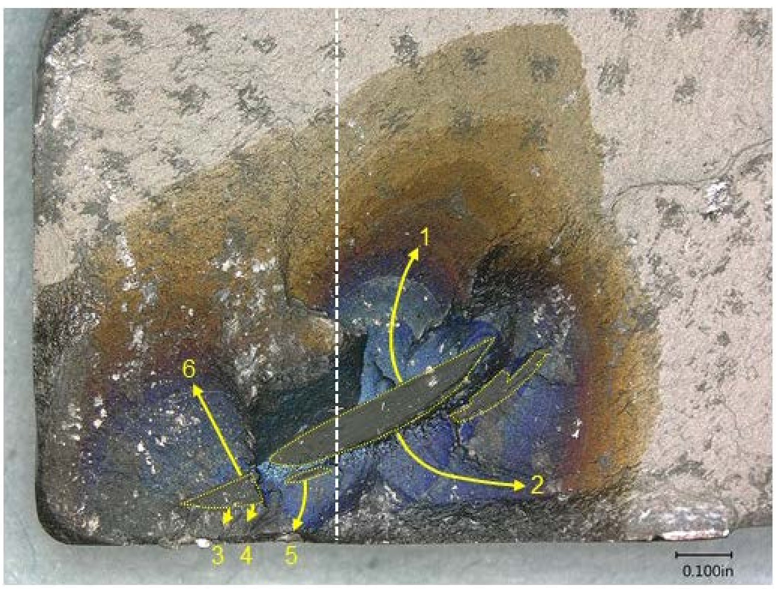

Figure 12. Fatigue cracks that initiated from discrete dirty white spot.

The NTSB selected cracks 1, 2, and 6 for a study to estimate the number of flight cycles in each low-cycle fatigue region. (The NTSB focused on these cracks for the study because they did not emerge from the surface.) SEM images were taken for each of the cracks (along the path of crack progression up to the transition to cyclic tensile crack growth), and striation densities were measured on those images to estimate the number of cycles from crack initiation to the HPT stage 2 disk failure. The study assumed that one striation correlated with one flight cycle and that the forces during takeoff, when the stresses on the HPT stage 2 disk would be at their highest, caused the crack to progress. The study results showed that cracks 1, 2, and 6 progressed by low-cycle fatigue for about 5,700, 5,600, and 3,700 cycles, respectively.

GE made striation density measurements for all six cracks, which showed that the greatest striation count, assuming one striation per mission/flight cycle, was about 7,000 cycles before the disk ruptured in tensile overload. This striation density measurement estimate was for crack 6, which progressed outward and did not reach the bore of the disk. GE's estimates for cracks 1 and 2 were 6,000 and 5,900 low-cycle fatigue crack growth cycles, respectively. (The NTSB notes that striation density measurements can be affected by subjectivity in measuring the striation densities and interpreting the results.) GE's striation density measurement estimates for cracks 3, 4, and 5 indicated that the cracks progressed by low-cycle fatigue for 1,400, 1,200, and 3,200 cycles, respectively.

1.4.2 Ultrasonic Response Characteristics of Discrete Dirty White Spots

As stated in section 1.3.4, GE and ATI SM conducted a study of discrete dirty white spots to better understand their ultrasonic response characteristics. GE provided the NTSB with a report on the results of the study.

ATI SM selected and characterized six discrete dirty white spots found by ultrasonic inspection of alloy 718 billets during the 2.5 years before the study was completed (in April 2017). According to GE's report, the sample represented "a typical range of sizes, shapes, stringer distribution, and radial position observed historically." GE performed further characterization of the six discrete dirty white spots, including metallographic examination. Voids/cracks were found in five of the six discrete dirty white spots; findings for one discrete dirty white spot were inconclusive.

The report concluded that voids/cracks in discrete dirty white spots might provide a reflection surface that is conducive to ultrasonic detection (GE 2017). Specifically, the report compared one of the sample discrete dirty white spots with the discrete dirty white spot found on the HPT stage 2 disk from the accident airplane. The sample discrete dirty white spot had multiple voids along a stringer, which made detection via ultrasonic inspection likely. The discrete dirty white spot on the HPT stage 2 disk from the accident airplane showed no voids, and, as previously stated, ultrasonic detection performed during manufacturing of the billet did not detect any anomalies.

1.5 Survival Aspects

The airplane was configured with 2 flight crew seats (and a cockpit jumpseat, which was unoccupied during the accident flight), 10 flight attendant jumpseats (3 of which were unoccupied), and 206 passenger seats.[44] The airplane had four door exits and four overwing exits. Figure 13 shows the airplane configuration and the seating positions within the cabin for the seven flight attendants.

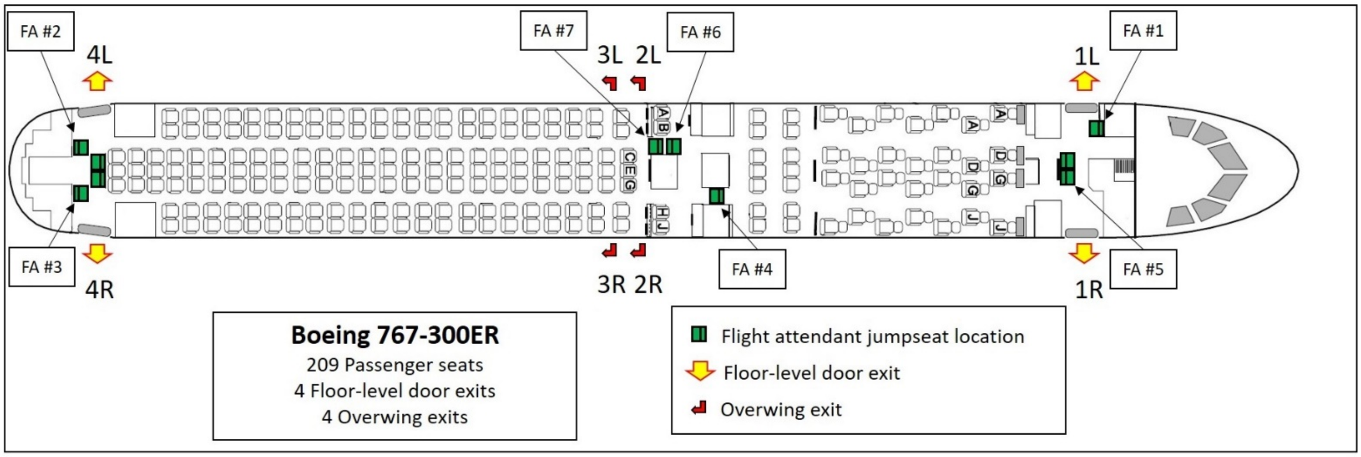

Figure 13. N345AN configuration.

1.5.1 Interphone Communication System

The airplane's interphone communication system comprised a flight crew interphone and five flight attendant interphones, which enabled voice communications to and from the flight deck and five flight attendant locations (1L, 1RC, 2R, 4L, and 4R jumpseats). The interphones were also used to make PA announcements and enable communication between flight attendant locations.

American Airlines 767-300-series airplanes have two different interphone models: the "classic" model, shown in figure 14a, which was installed on 767C-300ER airplanes delivered before January 2003, and the "new" model, shown in figure 14b, which is installed on 767N-300ER airplanes delivered beginning in January 2003. The accident airplane, delivered in April 2003, had the new model interphone system installed.

[44] The three unoccupied jumpseats were at the 1LC (left center), 4LC, and 4RC (right center) positions.

Figure 14a. Classic model interphone.

Figure 14b. New model interphone.

The classic model interphone has a key pad with four keys (buttons) to call locations within the airplane. The new model interphone has a key pad that resembles a standard telephone key pad. On the back of the new model interphone is a list of 10 communication options for making calls to various locations within the airplane. According to American Airlines flight attendant interphone procedures, although the classic and new model interphones both required flight attendants to activate the interphone buttons slowly and pause between each high/low chime to allow the chiming cycle to complete, the procedures for placing routine and emergency calls between the cockpit and the cabin differed between the models.[45]

Section 1.5.2 describes the experience of three flight attendants with the interphone during the emergency. Also, section 1.6.3.2 discusses flight attendant training, including the use of simulators. The classic model interphone was installed on one of two Boeing 767 simulators used for flight attendant training. The other 767 simulator had a nonfunctioning mockup of the new model interphone.

1.5.2 Evacuation

After the airplane came to a stop (1432:10), the flight attendants began evacuating the airplane. FDR data showed that, at 1432:20 (10 seconds after the airplane came to a stop), the left overwing exit opened. The forward left (1L) and forward right (1R) cabin doors opened 18 and 22 seconds later, respectively. At 1432:48 (38 seconds after the airplane came to a stop), the aft left (4L) cabin door opened. The left engine was shut down at 1433:09.

American Airlines provided the NTSB with two videos of the accident airplane that were taken by witnesses. One video was 2 minutes 28 seconds long, and the other video was 57 seconds long. Both videos show only the left side of the airplane. Also, the videos do not show the time that the last passenger evacuated via the left overwing exit slide. From the available information on those videos, the NTSB determined the timeline of evacuation events shown in table 2.

Table 2. Evacuation events shown on videos of left side of airplane.

Elapsed time (min:sec)	Event
0:00	Airplane comes to a stop.
0:15	Left overwing exit opened.
0:19	Left overwing exit slide fully deployed.
0:31	First occupant evacuated via left overwing exit slide.
0:31	1L door opened.
0:37	1L slide fully deployed.
0:40	4L door opened.
0:44	First occupant evacuated via 1L slide.
0:46	4L slide fully deployed but initially unusable—blown aft by left engine. (Slide remained attached to airplane.)
1:09	4L slide repositioned forward unassisted.
1:11	4L slide fully deployed and usable.
1:25	First occupant evacuated via 4L slide.
2:02	Airport operations vehicle arrives.
2:11	Last occupant evacuated via 1L slide.
2:21	Last occupant evacuated via 4L slide.

Note: The FDR "door open" signal occurred 2 to 5 seconds before the left overwing exit and the 1L and 4L doors were observed to open. The FDR door open signal is driven by a door proximity sensor that indicates that a door was unlocked or that a door handle changed position. As a result, the FDR door open signal would not be expected to occur at the same time as opening of the overwing exit and doors, which is why the FDR showed that the left overwing exit opened 10 seconds after the airplane came to a stop and the video showed that the left overwing exit opened 15 seconds after the airplane came to a stop.

[45] For example, for a routine call to the flight deck, flight attendants were to press the "Pilot" button twice on the classic model interphone or enter "31" on the new model interphone. Also, for an emergency call to the flight deck, flight attendants were to press the "Alert" button four times on the classic model interphone or enter "#4" on the new model interphone.

The NTSB conducted postaccident interviews with the flight attendants, who reported that, after hearing a loud noise (described as a "bang" or a "boom") and feeling the airplane "shudder," "shake," and "fishtail," passengers began moving from the right to the left side of the airplane while it was still moving down the runway. Once the airplane came to a complete stop, passengers started rushing toward the exits and urged the flight attendants to open the doors so that the passengers could evacuate. Table 3 summarizes the flight attendants' actions before and during the evacuation.[46] Two flight attendants reported that they were not able to properly use the interphone. These two flight attendants also reported the 4L door slide could not be immediately used after it deployed because it was blown aft before the left engine had been shut down. (The slide remained attached to the airplane.) In addition, two flight attendants reported passengers evacuating with baggage despite being directed to leave their bags behind.

Table 3. Summaries of flight attendant evacuation actions.

Flight attendant position and location	Evacuation actions
FA 1(lead)/1L jumpseat	After the airplane came to a complete stop, flight attendant 1 stood up to assess his area and waited for a call from the cockpit. Passengers started to rush the 1L door area, requesting him to open the door so that they could exit the airplane. He recalled picking up the interphone but did not remember if he called the cockpit. After he saw a "haze of smoke" aft of the first-class cabin, he opened the 1L door and initiated the evacuation. He continued the evacuation until all passengers had exited. He told the flight crew that the cabin was clear and then exited from the 1L door.
FA 2/4L jumpseat	Flight attendant 2 saw flames coming from the right wing. She reported that passengers were immediately at the 4L door, pleading to get off the airplane. She attempted to contact the flight crew about the left engine but was unsuccessful because she selected the wrong button on the interphone. Passengers were continuing to plead with her to let them off the airplane. She continued to hold off passengers to allow more time for the flight crew to shut down the left engine. The cabin began filling with smoke, and she was concerned because the airplane was heavy with fuel, so she decided to allow passengers to evacuate from the 4L door. The slide deployed but was blown aft because the left engine was still running. She and flight attendant 3 held back passengers until the engine stopped running and the slide stabilized itself, and then they began the evacuation. Once flight attendant 2's area was clear, she exited the airplane from the 4L door.
FA 3/4R jumpseat	Flight attendant 3 reported that the cabin was "lit up" on the right side of the airplane back to the 4R door. Before the airplane came to a stop, passengers were screaming, climbing over seats, and moving to the left side of the airplane. He picked up the interphone to make a PA announcement instructing passengers to remain calm, but he did not make the announcement because he could not recall how to use the interphone. He moved to the 4L door area to assist flight attendant 2 as passengers asked them to open the door so that they could get out of the airplane. He and flight attendant 2 were waiting to hear from the captain and for the left engine to shut down before they began the evacuation. While they were waiting, the cabin began to fill with smoke, so they decided to open the 4L door. Once the door was opened, he saw the slide blowing. Once the slide stabilized, he evacuated passengers until his assigned area was clear and then exited from the 4L door.
FA 4/2R jumpseat	Flight attendant 4 reported that she heard a loud explosion and saw fire. Passengers jumped up out of their seats, even though the airplane was still moving. She shouted at the passegers, "remain seated" and "heads down," but they continued to rush toward her jumpseat. The airplane came to a complete

[46] For more information, see the flight attendant interviews (Survival Factors Attachment 1) in the docket for this accident investigation, DCA17FA021.

Flight attendant position and location	Evacuation actions
	stop, and she instructed the passengers to “get out.” Her exit was unusable, so she ran to the first-class cabin area, saw that the forward doors were open, and redirected passengers to the front of the airplane. Passengers were trying to get their bags out of the overhead bins, so she told them repeatedly, “don’t take anything with you.” She went to the 2L overwing exit and saw flight attendant 7 evacuating passengers out of the window exits, so she also directed passengers to those exits. A passenger came toward her exit with a bag; she told him to leave the bag, but he did not follow directions and evacuated with the bag over his head. Her location in the cabin was getting smoky, and she feared that the airplane would explode, so, after checking for passengers, she evacuated from the 2L overwing exit.
FA 5/1RC jumpseat	Flight attendant 5 was waiting for the flight crew to tell the flight attendants what had happened during the takeoff attempt when passengers started rushing toward her shouting, “fire, open the door.” She did not initially see fire but noted that flight attendant 1 had opened the 1L door after seeing smoke in the cabin. Flight attendant 5 assessed the conditions using the 1R door window, saw no fire, and opened the door. She then saw fire outside and blocked the exit by holding up her hands to stop passengers from using that exit. She shouted at passengers to use the 1L door and continued blocking the 1R door. Once all passengers had evacuated, she exited from the 1L door.
FA 6/2L jumpseat	After the airplane came to a complete stop, flight attendant 6 looked out a window on the right side of the airplane and saw fire. She turned around toward the 2L overwing exit. Flight attendant 7 was opening that exit, so she started directing passengers to the open exits. A passenger came to the area with a large bag, and flight attendant 6 instructed the passenger to leave the bag and evacuate the airplane. The passenger did not listen, so flight attendant 6 tried to take the bag away from the passenger. The flight attendant realized that the struggle over the bag was causing a delay in the evacuation, so the passenger evacuated the airplane with her bag. Once the area was clear, flight attendant 6 exited from the 2L overwing exit.
FA 7/3L jumpseat	Flight attendant 7 saw a “plume of fire” over the right wing and black smoke and reported that passengers started jumping out of their seats while the airplane was still moving. He yelled, “stay down,” but the passengers did not listen. Once the airplane came to a complete stop, he opened the 2L overwing exit, even though it was flight attendant 6’s assigned exit, and started commanding passengers to evacuate out the window exits on the left side of the airplane. Flight attendant 7 also directed passengers forward toward the first-class section. The cabin was starting to fill with “hazy gray smoke,” and he thought that the interior panels were burning and could see the window glass melting on the right side. After the passengers had evacuated, he exited from the 2L overwing exit.

The NTSB also interviewed four passengers from the flight. One of these passengers, who occupied a seat near the 3L overwing exit, reported that everything appeared to be normal during the takeoff roll until he heard a loud “bang” and saw what appeared to be “orange sparks.” He also reported that the flight attendant sitting in front of him instructed passengers, in a forceful yet calm manner, to sit down. As soon as the airplane came to a stop, he opened the exit. He stated that he had not heard an evacuation command but was “very focused” on getting the exit open.

In addition, the NTSB interviewed the passenger who sustained the serious injury during the evacuation. The passenger exited the airplane using the left overwing exit slide. He reported that, after reaching the ground, he stood up to get away from the airplane and was “blown over” by the jet blast coming from the back of the left engine. He also reported that, as he stood up again and ran to a grass strip next to the runway, he felt pain in his back.

1.6 Organizational Information

1.6.1 American Airlines Flight Crew Manuals

1.6.1.1 Engine Fire Checklist

The American Airlines *B767 Operations Manual, QRH* included a checklist procedure (dated March 11, 2015) for an engine fire (or engine severe damage or separation) occurring on the ground or in flight. This checklist was based on the checklist in Boeing's *767 Flight Crew Operations Manual QRH* for the same engine emergencies. The first five items on the checklist, which detailed actions to be taken immediately in response to the engine emergency, were to be performed from memory. The remaining 11 items on the checklist, which were to be accomplished using the checklist, included actions related to configuring the airplane for landing. The five memory items, as well as the messages and conditions, on the checklist were as follows (bold face type indicated in original):

Messages: L ENGINE FIRE R ENGINE FIRE

Condition: One or more of these occur:

- Engine fire warning
- Airframe vibrations with abnormal engine indications
- Engine separation

1. A/T ARM switch………………………………………………. OFF

2. Thrust lever
(affected side)……………………… confirm……….…………………Idle

3. FUEL CONTROL switch
(affected side)…………………….…confirm……….…………...CUTOFF

4. Engine fire switch
(affected side)……………………….confirm………………………... Pull

5. **If** the engine fire warning light is illuminated:

   Engine fire switch
   (affected side)……………...…Rotate to the stop and hold for 1 second

If after 30 seconds the engine fire warning light stays illuminated:

Engine fire switch
(affected side)……………Rotate to the other stop and hold for 1 second

Figure 15 shows the engine fire switches, also referred to as engine fire handles, as described in steps 4 and 5 of the checklist.

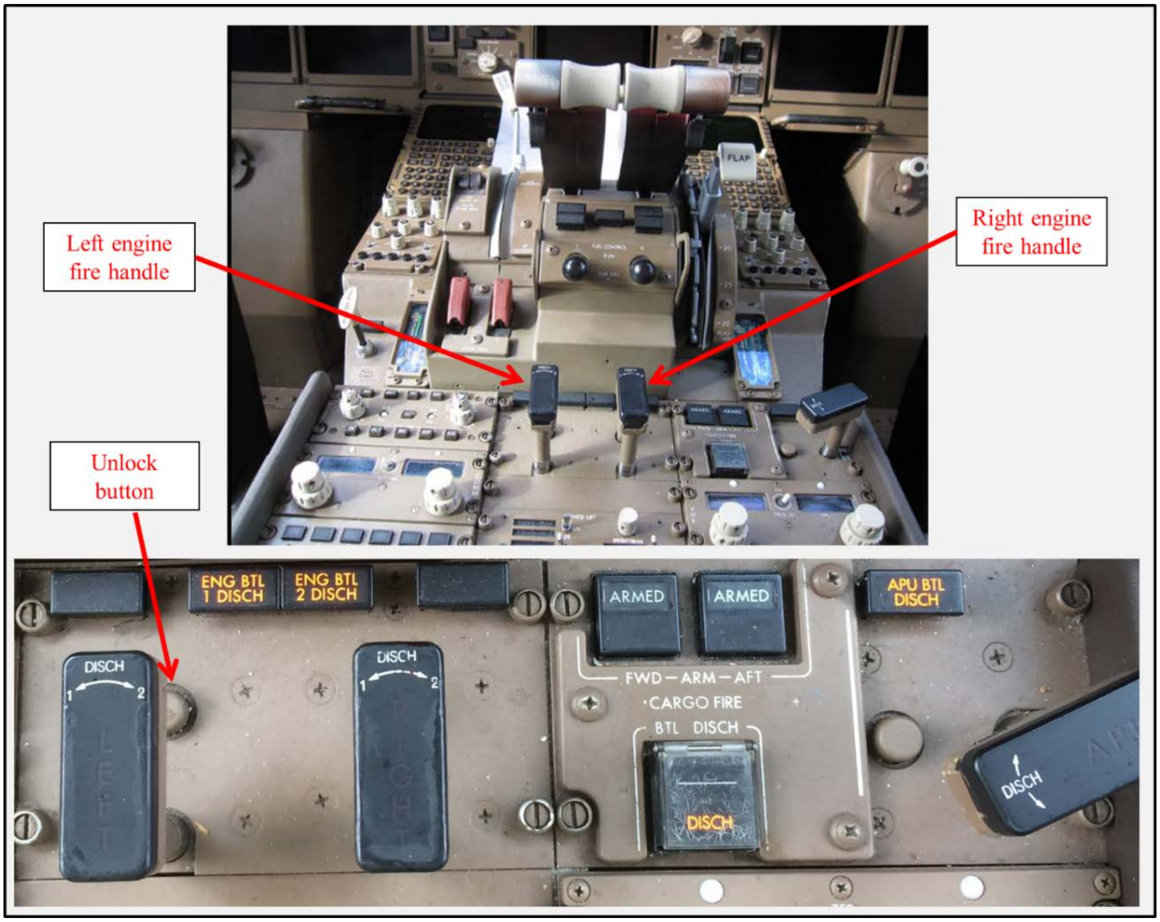

Figure 15. Engine fire handles.

Note: Only the unlock button for the left engine fire handle is labeled. A similar unlock button appears forward of the right engine fire handle.

1.6.1.2 Evacuation Guidance

The American Airlines *B767 Operations Manual, QRH* (dated April 7, 2016) provided the following evacuation guidance in the "General Information" section (bold face type indicated in original):

After an airplane has landed following a significant in-flight event, the potential exists for a passenger or Flight Attendant initiated evacuation. If an immediate

> evacuation is not required, it is important to assure the passengers and Flight Attendants that the situation is under control. Make an immediate PA commanding:
>
> **'This is the Captain. Remain Seated. Remain Seated. Remain Seated.'**
>
> If an evacuation might be required after further assessment, consideration should be given to configuring the aircraft for a potential evacuation. (Steps such as shutting down the engines should be considered to avoid the potential passenger injuries which might occur if the aircraft is not configured and the situation deteriorates or an inadvertent passenger or Flight Attendant evacuation takes place.)

The guidance also stated that the "primary evacuation signal" was the announcement, over the PA system, **"This is the Captain. Evacuate. Evacuate. Evacuate"** (as shown in step 5 of the evacuation checklist in section 1.6.1.3).

The American Airlines *B767 Operations Manual, QRH* also provided the following evacuation decision-making guidance under "General Information":

> In a non-normal situation, the Captain must decide whether or not to conduct a passenger evacuation. The Captain must balance the hazard of passenger evacuation against the hazard of remaining on board. It is not feasible to establish a rigid set of rules regarding evacuation since there are many situational variables.
>
> The Captain must evaluate a specific situation, apply good judgment, and reach the best decision given the information available. The emergency evacuation is a powerful tool. Use it cautiously.
>
> The Captain should consider the following:
>
> - The decision to evacuate should be deliberate after carefully weighing the risks in evacuating against the risks of remaining on board.
> - The most hazardous event is fire or smoke within the pressurized area of the airplane (cabin or cargo compartment).
> - Smoke or flames in the engines, APU, or wheel assembly areas will normally burn out quickly and not endanger the cabin. Request ARFF equipment, pull the Fire Switch, discharge fire suppression agent as appropriate, carefully monitor the area and communicate with crash vehicle crews and tower. Time and conditions permitting, clear the active runway. Evacuate the passengers if the fire does not extinguish in a reasonable time or appears to be spreading.
>
> Whatever the decision, be specific and unambiguous in conveying your intent to the Flight Attendants.

The *QRH* provided the following evacuation-related information related to the role of the flight attendants under "General Information":

> Since most accidents occur on takeoff and landing, the Flight Attendants are instructed to be alert to clues of an emergency situation, such as unusual impact forces, noises, smoke, fire, or abnormal airplane attitudes. After the airplane stops, the Flight Attendants will assess the situation and, if the need for an evacuation is obvious, will initiate the evacuation without waiting for instructions from the cockpit. A DOOR EICAS message indicates that the evacuation has started.

In addition, the American Airlines *Flight Manual* Part I, "Non-normal and Emergency" (dated October 1, 2016), stated the following regarding flight attendant-initiated emergency evacuations:

> When an aircraft has come to a stop in an obvious life-threatening situation (fire, dense smoke in the cabin, crash), Flight Attendants are authorized to initiate an evacuation without awaiting instructions from the flightdeck. Flight Attendants will attempt to communicate with the flightdeck if at all possible. If contact with the flightdeck is not possible, or if life threatening conditions still exist, Flight Attendants will make an independent decision and operate all usable exits.

1.6.1.3 Evacuation Checklist

The American Airlines 767 evacuation checklist procedure (dated April 7, 2016), appeared on the back cover of the company's *B767 Operations Manual, QRH*. The checklist was to be announced by the first officer, performed by the captain, and verified by the first officer. The steps of the checklist were as follows (bold face type indicated in original):

> Condition: Evacuation is needed.
>
> **Note**: Light override is available.
>
> 1. Parking brake……………………………….……………………...…Set
>
> 2. Cabin altitude MODE SELECT………………………………...MAN[47]
>
> 3. CABIN ALTITUDE MANUAL control……………..…Hold in CLIMB
>
> **Note**: Hold in CLIMB until the outflow valve indication shows fully open to depressurize the airplane.

[47] The 767 pressurization system has automatic and manual operating modes. The 767 pressurization panel, located on the cockpit panel above the first officer's seat, includes the cabin altitude mode select switch, which can be set to the AUTO 1, AUTO 2, or MAN (manual) setting.

4. FUEL CONTROL switches (both)…………………….………CUTOFF

5. PA……………………………….....……...........**“This is the Captain. Evacuate, Evacuate, Evacuate.”**

6. Evacuation COMMAND Switch
(as installed)…………………………………………..………...ON

7. ATC……………………………………………………………Notify

8. Engine and APU
fire switches (all)……………………….……………. Override and pull

9. **If** an engine or APU fire warning occurs:
Related fire switch………………..Rotate to the stop and hold for 1 second

1.6.1.4 Evacuation Duties

The American Airlines *B767 Operations Manual, QRH* contained the following information (dated March 11, 2015) regarding the flight crew’s responsibilities during an evacuation:[48]

> Cockpit crewmembers will assist in the evacuation after completing required cockpit duties and should wear their hats to identify themselves as authorities to the passengers.
>
> <u>Captain – Assist in cabin</u>
>
> - After checklist is complete, immediately proceed to forward cabin and assess conditions.
> - Assist and direct evacuation. Pay attention to utilization of slides; use megaphone, if required, to maintain orderly and rapid passenger evacuation. Instruct Flight Attendants to leave airplane when their areas are clear.
> - Check entire cabin to ensure that all passengers have evacuated. Exit via any usable rear entry door.
> - Assemble passengers away from airplane.
> - Ensure that one or more crewmembers remain with the passengers until relieved by station personnel.

[48] The *QRH* also described “concurrent flight attendant duties,” including, once outside the airplane, assembling passengers away from the airplane. Both flight crewmembers stated that, after evacuating the airplane, they saw the flight attendants moving the passengers away from the airplane. Other concurrent flight attendant duties were making a passenger count and reporting the count to the captain.

<u>First Officer – Assist outside airplane</u>

- After checklist is complete, immediately proceed to forward cabin and assess conditions.
- Take Halon fire extinguisher (if possible).
- Exit via first usable door and assist outside as necessary.
- Assemble passengers away from airplane.

1.6.2 American Airlines Flight Attendant Manual

American Airlines *Flight Service Inflight Manual* included the following information (dated December 24, 2016) under the heading “General Principles of Evacuation”:

- If an emergency situation develops, be prepared to evacuate the aircraft. Stay alert to clues that may signal a possible emergency.
  - Unusual noises
  - Impact forces
  - Fire, sparks, or smoke
  - Abnormal aircraft attitude
  - The need to evacuate may not always be obvious. FAs must evaluate the level of danger and clearly communicate any conditions that may warrant an evacuation.
- Do not initiate an evacuation until the aircraft has come to a complete and final stop.
  - Be prepared for more than one impact.
  - Be alert to any sense of motion, i.e., any sense of movement out the window, or outside noises if vision is impaired.
- Begin evacuation command immediately upon signal from the flightdeck.
  - If one FA initiates an evacuation, all FAs must initiate evacuation procedures immediately by shouting evacuation commands.

The guidance also states that it is “critical” for flight attendants to update the captain if cabin conditions warrant an evacuation because the flight crew might be unaware of life-threatening situations, such as excessive smoke and/or fire. The guidance further stated, “if the aircraft is on the taxiway and time permits, notify the flightdeck prior to initiating the evacuation.”

Further, the guidance included a table labeled "Evacuation Procedures." The table comprised nine procedural steps, including "on aircraft such equipped, turn on [evacuation] signaling system" (step 3) and "prior to opening an exit, assess conditions outside to determine if exit and escape route [are] safe" (step 4). Examples of unsafe conditions were provided, including "fire or dense smoke" and "engine(s) still operating."

Under the heading "FA and Flightdeck Crew Authority" (dated January 27, 2016), the flight attendant manual includes the following information:

> In a life-threatening situation, e.g., fire, smoke, impact forces, or abnormal aircraft attitude, and when the aircraft has come to a complete stop, FAs have the authority to initiate an evacuation without awaiting instructions from the flightdeck.
>
> - FAs will attempt to communicate with the flightdeck prior to evacuation, if possible.
> - If contact with the flightdeck is not possible, FAs will make an independent decision regarding evacuation and operate all usable exits.

The flight attendant manual further indicated that, during land evacuations, flight attendants are to command passengers to "come this way" toward usable door and overwing exits and "leave everything."

Under the heading "767 Evacuation Signaling System" (dated March 11, 2015), the flight attendant manual stated that signaling system control panels were located in the cabin on most flight attendant jumpseats and in the cockpit.[49] In addition, the manual included a section on interphone calls. This information (also dated March 11, 2015) described how to place and answer calls. As previously stated, depending on their delivery date, 767 airplanes had one of two interphone models—either the classic or the new model—and the procedures for placing calls using each model are described in section 1.5.1.

1.6.3 American Airlines Training

1.6.3.1 Flight Crew Training

According to the American Airlines *Flight Training B757/767 Instructor Guide – Qualification Training*, 12 days of ground school training were followed by 10 days of simulator training. The simulator training was divided into simulator sessions, which were further divided into various types of special purpose operational training, and concluded with a maneuvers validation, line-oriented flight training, and a line operational evaluation.

[49] According to Boeing, the evacuation signaling system control panels have a COMMAND switch, an EVAC (evacuation) light, and a horn. Boeing indicated that, when the COMMAND switch is placed in the ON position, the EVAC light illuminates and the horn sounds at each location with system control panels, including the cockpit.

One special purpose operational training session titled "Rejected Takeoff (First Look), Evacuation" comprised the following maneuvers:[50]

- *Takeoff*

  — Contingencies: Rejected Takeoff

- *Takeoff*

  — Contingencies: Engine Fire

- *Takeoff*

  — Contingencies: Evacuation

This training scenario involved either a cargo fire or an engine fire. During the training, the flight crew was expected to perform a fire checklist and not initiate an evacuation until a flight attendant called the cockpit to alert the flight crew of smoke in the cabin.

1.6.3.2 Flight Attendant Training

American Airlines uses two training facilities for company flight attendant training: Flagship University and the Flight Academy, both of which are in Fort Worth, Texas. American Airlines instructors conduct the training.

Initial new-hire training and recurrent (annual) training followed advanced qualification program guidelines. Flight attendants received classroom instruction, web-based instruction, hands-on door operation training in normal and emergency modes, and hands-on emergency equipment training. Instructor-facilitated, scenario-based simulator training included full-scale evacuations. In addition, American Airlines trained its flight attendants on the use of the evacuation signaling system.

1.6.4 American Airlines Operating Manual—Engine Fire Warning System

According to American Airlines' 757/767 *Operating Manual*, "Systems," two detector loops in each engine nacelle provide fire detection. Under normal circumstances, both loops must detect a fire condition to cause an engine fire warning. An engine fire would be annunciated by the following:

- sounding of the fire bell,
- illumination of the master WARNING light,

[50] American Airlines described "first look" maneuvers as "maneuvers which are NOT briefed during the RTS [recurrent training–simulator] briefing period but are flown by each pilot in the simulator and are defined to give some indication of whether the interval between training sessions may be too long to maintain proficiency in rarely exercised critical tasks" (capitalization indicated in original).

- display of the EICAS warning message ENG FIRE (left or right),
- illumination of the engine fire switch (left or right) fire warning light (on the center pedestal),
- illumination of the engine FUEL CONTROL (left or right) switch fire warning light (on the center pedestal), and/or
- unlocking of the engine fire handle (left or right) to activate the fire extinguisher bottle(s).[51]

1.6.5 Boeing

The Boeing 767 *Airplane Flight Manual* included emergency procedures for responding to an engine fire, severe engine damage, or an engine separation. The procedures, which the FAA approved on May 12, 2005, stated that the following actions should be taken if an engine fire has occurred:

Thrust Lever…………………………………………...…….…CLOSE
Fuel Control Switch………………………………..…………CUTOFF
Engine Fire Switch…………..…………………………………...PULL

If fire warning light remains illuminated:

Engine Fire Switch…………………………….....…………..ROTATE

After 30 seconds, if fire warning light remains illuminated:

Engine Fire Switch……………..ROTATE TO REMAINING BOTTLE

APU (if available)……..………………………………………...START

Prepare for one-engine inoperative landing.

This procedure (except for the last step) applied to engine fires that occurred on the ground and during flight. The related checklist procedure in Boeing's *767 Flight Crew Operations Manual QRH* (dated August 16, 2013) was based on the information in the *Airplane Flight Manual*. The engine fire checklist procedure that American Airlines used (see section 1.6.1.1) was based on the checklist procedure in Boeing's 767 QRH.

[51] To prevent an accidental activation of the fire extinguishing system, each fire handle is locked in its down (non-activated) position by a solenoid-operated mechanical interlock device connected to the fire handle's shaft. A pilot can manually release a handle's mechanical interlock by pressing a button located on the engine fire control panel forward of the fire handle (see figure 15). The engine fire detection system can also automatically release the mechanical interlock when the system detects an engine fire or overheat condition. Once the mechanical interlock is released, a pilot can pull and rotate the engine fire handle.

1.6.6 Federal Aviation Administration

1.6.6.1 Advisory Circular 20-128

Title 14 *CFR* 25.903(d)(1) states that, for turbine engine installations, "design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case." According to the accident airplane's FAA type certificate data sheet, the Boeing 767-300 was certified on September 22, 1986. At that time, FAA Order 8110.11, *Design Considerations for Minimizing Damage Caused by Uncontained Aircraft Turbine Engine Rotor Failures,* issued on November 19, 1975, was in effect. The order described, among other things, design considerations for critical systems (including fuel systems) to minimize the damage that uncontained engine debris could cause.

On March 9, 1988, the FAA issued AC 20-128, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure." (FAA Order 8110.11 was canceled on May 1, 1988; AC 20-128 contained much of the same information as the order.) AC 20-128 defined various fragment spread angles (based on historical engine failure events) and the area of the airplane that would likely be impacted by uncontained fragments resulting from an uncontained engine failure.[52] The AC also included a figure that further explained fragment spread angles. The figure showed that, for a rotor burst event, an airframe manufacturer was expected to assume that large disk fragments would exit the engine at an angle that was ± 3° fore and aft from the center of the plane of rotation and that smaller disk fragments would exit the engine at an angle that was ± 5° fore and aft from the center of the plane of rotation. (These same fragment exit trajectories were specified in FAA Order 8110.11.)

On March 25, 1997, the FAA issued AC 20-128A in response to Safety Recommendation A-90-170 (see section 1.7.3.1). The revised AC provided more recent information regarding rotor bursts and blade release fragment trajectory data so that airframe manufacturers could take appropriate design precautions to minimize the hazards to the airplane and its occupants. The fragment spread angle information remained the same as in the previous version of the AC.[53] The AC described accepted design precautions for uncontrolled fire, loss of thrust, loss of airplane control, passenger and crew incapacitation, and structural integrity and indicated that airplane designs would be evaluated against proven design practices for each.[54]

In May 1999, the FAA issued a report titled *Large Engine Uncontained Debris Analysis*. According to the report's abstract, the objective of the analysis was to "define the debris, size, weight, exit velocity, and trajectory that can be used to update [AC] 20-128A." The abstract stated that the results of the analysis showed that, according to the debris trajectories that were examined,

[52] A fragment spread angle is "the angle measured, fore and aft, from the center of the plane of rotation initiating at the engine or APU shaft centerline."

[53] AC 20-128A stated that an alternative engine failure model, with a single large one-third piece of disk having a fragment spread angle of ± 5°, could be used for analysis. As part of the investigation of the American Airlines flight 383 accident, Boeing used this more conservative model to perform a trajectory analysis, as discussed in section 2.1.

[54] AC 20-128A included accepted design precautions to reduce the overall risk of an uncontrolled fire for fuel tanks located in impact areas, as discussed in section 2.4.3.

"the trajectories defined in AC 20-128A are too narrow and should be expanded significantly." Further, the abstract stated the following: "during an uncontained event the aircraft is subjected to multiple 'small' fragment impacts, not just a single impact. It is the combined effects from the small fragments that pose the highest hazard potential to the aircraft" (FAA 1999). In addition, the report indicated that the Aviation Rulemaking Advisory Committee (ARAC) 25.903(d)(1) Task Group was revising the engine uncontainment fragment model defined in AC 20-128A.

On November 2, 2001, the FAA issued a notice of new task assignment for the ARAC regarding transport airplanes and engine issues (66 *Federal Register* 56729, November 9, 2001). The notice indicated that the new task assignment included the following actions:

- reviewing the acceptable design precautions for showing compliance with the regulations described in AC 20-128A, including 14 *CFR* 25.903(d)(1), and developing additional design precautions to mitigate shortfalls that the ARAC previously identified (which, according to the FAA, were associated with difficulties getting manufacturers to fully comply with the AC for minimizing the uncontained engine debris fragment threat);

- developing a report that recommends the requirements for minimizing the hazards from uncontained engine debris; and

- recommending revisions to AC 20-128A and developing additional advisory materials to address issues resulting from changes to the regulations (FAA 2001).

The notice stated that the ARAC accepted the task and assigned it to the Powerplant Installation Harmonization Working Group. The notice also stated that the task was required to be completed no later than November 7, 2003. In an undated letter signed by the manager of the FAA's Transport Airplane Directorate, Aircraft Certification Service, the FAA informed the Assistant Chair of the Transport Airplane and Engine Issue Group of a moratorium regarding certain ARAC taskings of the group. The FAA's letter stated the following:

> During the November 2002 Harmonization Management Team Meeting, industry requested that the FAA consider placing a moratorium on certain lower priority ARAC taskings while the FAA, Joint Aviation Authorities (JAA), and Transport Canada (TCCA), worked to develop a joint rulemaking priority list…to conserve resources until a final rulemaking priority list could be implemented.

The FAA agreed with industry's request and identified tasks to be placed under the moratorium. These tasks included those associated with the Powerplant Installation Harmonization Working Group. As a result, work related to the actions in the November 2001 new task assignment ceased. As of December 2017, AC 20-128A had not been updated.

1.6.6.2 Inspection Techniques for Nickel Billets

In September 2005, the FAA issued a report titled *Inspection Development for Nickel Billet—Engine Titanium Consortium Phase II*.[55] According to the report, the purpose of the consortium's Phase II program was to "develop higher-sensitivity inspection methods for nickel (Ni) billets that could be used to reduce the occurrence of melt-related defects in Ni forgings and, therefore, lower the engine failure risk" (FAA 2005). Alloy 718 was evaluated using a 10-inch-diameter billet and a multizone ultrasonic inspection procedure.

The program established an overall goal of "four times improvement over the current conventional method," which was achieved. Specifically, the report stated that the multizone inspection procedure exceeded the program goal of a No. 1 flat-bottom hole for alloy 718 by a minimum of 3.5 times and was a minimum of 31 times more sensitive at the billet center than the current inspection requirements.[56] The report also stated that a factory assessment showed that the multizone inspection procedures were "more sensitive" than the current inspection procedures in detecting surface blemishes. In addition, the report stated that a factory demonstration produced conclusive results showing that, for alloy 718, the multizone inspection procedures could detect indications that would be missed by current inspection procedures (FAA 2005).

Multizone inspection procedures, as well as phased array inspection procedures (another high-sensitivity ultrasonic inspection technique), were compared with current inspection procedures for a 5-inch-diameter billet, which is another typical billet diameter, made of another nickel alloy. The multizone inspection achieved a sensitivity of about a No. 0.5 flat-bottom hole throughout most of the billet depth, which exceeded the current inspection sensitivity by about 20 times at the billet center. The phased array inspection achieved a sensitivity of about a No. 0.75 flat-bottom hole.

1.6.6.3 Definition of Stealth Anomalies

In April 2008, the FAA issued a report titled *Turbine Rotor Material Design—Phase II*, which addressed "the threat of material or manufacturing anomalies in high-energy rotating

[55] The FAA established the Engine Titanium Consortium in 1993 as a result of a recommendation from the agency-sponsored titanium rotating components review team (which was formed in response to Safety Recommendation A-90-167—see section 1.7.3.1). The consortium consisted of a team of researchers from academia and industry. According to the FAA, the objective of the consortium was to provide the FAA and engine manufacturers "with reliable and cost-effective new methods and/or improvements in mature methods for detecting cracks, inclusions, and imperfections in titanium material and components." Phase I, which was completed in 1998, focused on "developing and understanding the fundamental material properties of titanium and hard alpha defects as they relate to their response to ultrasonic interrogation, developing tools for the detection of fatigue cracks…and developing and applying tools to assess the reliability of inspection of anomalies." The FAA also stated that the work of the consortium had been expanded to include critical engine rotating components made of nickel alloys.

[56] A flat-bottom hole is a machined hole, the bottom of which is perpendicular to the beam of the transducer used for the inspection. The reflective wave height is proportional to the area of the bottom of the hole or the square of the diameter of the hole. Billets with a 10-inch diameter are typically inspected to a sensitivity of a No. 2 flat-bottom hole, which is 2/64 inch (0.031 inch) in diameter. A No. 1 flat-bottom hole is 1/64 inch (0.016 inch) in diameter. Thus, reducing from a No. 2 to a No. 1 flat-bottom hole resulted in a "four times improvement" in sensitivity during inspections because of the change in the area of the hole.

components" (FAA 2008). Under the heading "Definition of Stealth Anomalies," the report stated the following:

> Historically, a number of rotor disk fracture and cracking events have originated from embedded anomalies, which, although they were substantial in size, were undetected by production inspections. These anomalies have been called 'stealth' anomalies due to their ability to evade inspection detection; i.e., the reflected signal is small relative to the inclusion size.

The report also described different types of stealth anomalies, including the following:

> [A] category of stealth anomaly comprises those types that are ductile and well bonded, making them less likely to have cracking and voiding during ingot and billet conversion. The lack of cracking and voiding, combined with a similarity in elastic modulus and density to the parent alloy, renders them indistinguishable from the parent alloy for sonic detection. These anomalies…form a zone of material that is substantially weaker in tensile and fatigue capability than base metal [FAA 2008].

1.6.6.4 Notice of Proposed Rulemaking

GE performed a study of ultrasonic inspection indication rates from the mid-1990s to 2016 using samples from its suppliers of alloy 718 and determined that there were fewer indications in samples manufactured in 2000 and later due to processing improvements that had been implemented before those samples were manufactured. As a result, on June 29, 2017, GE issued Service Bulletin (SB) 72-1562, "CF6-80C2 Stage 1 and Stage 2 HPTR [High Pressure Turbine Rotor] Disk Ultrasonic Inspection," for HPT stage 1 and 2 disks manufactured before 2000.[57] A revised SB was issued on July 28, 2017, because of changes to two paragraphs and an appendix listing the serial and part numbers of affected disks.[58]

On September 1, 2017, the FAA issued a notice of proposed rulemaking (NPRM) titled "Airworthiness Directives; General Electric Company Turbofan Engines" (82 *Federal Register* 42261, September 7, 2017). The NPRM stated that the FAA proposes to adopt a new AD for certain GE CF6-80-series turbofan engines, including the CF6-80C2B6, as a result of the uncontained failure of an HPT stage 2 disk. The NPRM also stated that the proposed AD would require ultrasonic inspections for cracks in HPT stage 1 and stage 2 disks at each piece-part opportunity in accordance with GE's SB 72-1562. Further, the NRPM stated that, if the unsafe condition were not corrected, "uncontained HPT disk release, damage to the engine, and damage to the airplane" could result (FAA 2017). In an October 13, 2017, letter to the Department of Transportation, the NTSB expressed its full support for the proposed AD.

[57] CF6-80C2 HPT stage 1 and 2 disks have similar stress/volume characteristics, so GE decided to have stage 1 disks inspected in addition to stage 2 disks.

[58] SB 72-0869, "CF6-80A Stage 2 HPTR Disk Ultrasonic Inspection," was issued on August 22, 2017. The FAA indicated that the part numbers referenced in the appendix of revised SB 72-1562 applied to CF6-80C2 and CF6-80A engines.

1.7 Additional Information

1.7.1 Discrete White Spot Formation

In the nickel alloy manufacturing industry, it is generally accepted that discrete white spot formation is an inherent, yet infrequent, characteristic of the vacuum arc remelting process (described in section 1.3.1.1 and depicted in figure 3). A discrete white spot forms typically when a solid piece of either the original or the newly created ingot detaches from the outer edge, falls through a molten liquid layer, and becomes incorporated in the newly created ingot before the piece becomes completely molten. Although electroslag remelting and vacuum arc remelting (the second and third steps of the triple-melt process, respectively) both involve an original ingot that is consumed and a new ingot that is formed, discrete white spots are less likely to occur in an electroslag remelting ingot than in a vacuum arc remelting ingot. Specifically, according to a member of the Advanced Metallurgical Group in the Netherlands, with the electroslag remelting process, the molten superheated slag prevents the formation of crown material (solidified material above the liquid level) and gives the small detached pieces more time to become molten before solidification in a newly created ingot.[59]

Discrete white spots could be harmful depending on their overall size, chemistry, and grain size and the presence of oxide/nitride clusters, which can cause cracks to form during the forging process at the billet conversion stage or during the final forging stage. Data indicated that discrete white spots formed less frequently (based on the number of ultrasonic test inspection indications) using a triple-melt process than a double-melt process, even though both processes include vacuum arc remelting (Moyer et al. 1994).

Ultrasonic test inspection data showed that many indications in superalloys (high-performance alloys) were cracks associated with discrete white spots. Those discrete white spots with clusters of oxide, nitride, and/or carbonitride (a carbon and nitrogen compound) particles were considered to be discrete dirty white spots (Jackman et al. 1994).

1.7.2 Master Heat FA94

As stated in section 1.3.1.1, vacuum induction melting—the first step of the triple-melt process—is also referred to as the master heat, and the ingots that were produced during this process, designated as FA94-1 through -5 (with the HPT stage 2 disk manufactured from FA94-2), were part of a group collectively referred to as Master Heat FA94.

A total of 36 parts, including the HPT stage 2 disk, were produced from Master Heat FA94.[60] At the time of the accident, 8 of the 36 parts (not including the HPT stage 2 disk) were in an operating status, available for installation into an engine/airplane, or scrapped but

[59] For more information, see ALD Vacuum Technologies' web page on electroslag remelting (http://web.ald-vt.de/cms/vakuum-technologie/anlagen/electroslag-remelting-esr/, accessed January 10, 2018). (ALD Vacuum Technologies is a member of the Advanced Metallurgical Group.)

[60] Six parts were manufactured from FA94-1. Nine parts were manufactured from FA94-2. Seven parts were manufactured from FA94-3. Eight parts were manufactured from FA94-4. Six parts were manufactured from FA94-5.

not destroyed; all 8 parts were sent to GE for inspection.[61] GE performed high-resolution ultrasonic inspections on all eight parts using a technique that had a greater detection sensitivity than what was available at the time that the parts were produced. GE did not find defects in any of the eight parts.

GE reviewed the production records for Master Heat FA94 and compared the records with those for other ingots/billets that ATI SM produced for GE during that same time period. GE did not identify any information in the records to indicate that Master Heat FA94 had a different potential for white spot formation than other master heats that were produced about the same time. Also, GE did not identify any information in the records to indicate that ingot FA94-2 had a different potential for white spot formation than the other ingots of Master Heat FA94.[62]

1.7.3 Previous Related Safety Recommendations

1.7.3.1 Recommendations From United Airlines Flight 232 Accident

On July 19, 1989, United Airlines flight 232, a DC-10-10, experienced a catastrophic failure of the No. 2 tail-mounted engine during cruise flight when the separation, fragmentation, and forceful discharge of stage 1 fan rotor assembly parts led to the loss of the three hydraulic systems that powered the airplane's flight controls. The flight crew experienced severe difficulties controlling the airplane, which subsequently crashed during an attempted landing at Sioux Gateway Airport, Sioux City, Iowa. Of the 285 passengers and 11 crewmembers aboard, 110 passengers and 1 flight attendant died.[63]

As a result of this accident, the NTSB made the following recommendations to the FAA on December 14, 1990:

> Intensify research in the nondestructive inspection field to identify emerging technologies that can serve to simplify, automate, or otherwise improve the reliability of the inspection process. Such research should encourage the development and implementation of redundant ('second set of eyes') inspection oversight for critical part inspections, such as for engine rotating components. (A-90-167)

> Analyze the dispersion pattern, fragment size and energy level of released engine rotating parts from the July 19, 1989, Sioux City, Iowa, DC-10 accident and include

[61] Of the remaining 27 parts produced from Master Heat FA94 (not including the HPT stage 2 disk), 19 had been destructively scrapped, and 8 were being used in industrial power generation applications and were not removed for inspection.

[62] The Powerplants Group also reviewed the records for Master Heat FA94 and ingot FA94-2 and found no anomalies or deviations from the approved production process.

[63] The NTSB determined that the probable cause of this accident was "the inadequate consideration given to human factors limitations in the inspection and quality control procedures used by United Airlines' engine overhaul facility which resulted in the failure to detect a fatigue crack originating from a previously undetected metallurgical defect located in a critical area of the stage 1 fan disk that was manufactured by General Electric Aircraft Engines. The subsequent catastrophic disintegration of the disk resulted in the liberation of debris in a pattern of distribution and with energy levels that exceeded the level of protection provided by design features of the hydraulic systems that operate the DC-10's flight controls" (NTSB 1990).

> the results of this analysis, and any other peripheral data available, in a revision of AC 20-128 for future aircraft certification. (A-90-170)
>
> Create the mechanism to support a historical data base of worldwide engine rotary part failures to facilitate design assessments and comparative safety analysis during certification reviews and other FAA research. (A-90-172)

Regarding Safety Recommendation A-90-167, on September 16, 1991, the FAA stated that, in May 1991, its Engine and Propeller Directorate sponsored a titanium review conference, during which the titanium rotating components review team report (dated December 14, 1990) was released to industry and public participants. According to the FAA, the report identified several recommendations regarding manufacturing process control, manufacturing inspection, in-service inspection, design procedures, research and development, and FAA policy and guidance. The FAA also indicated that several agency initiatives defined in the titanium rotating components review team report encompassed the nondestructive evaluation aspects of rotating components. As a result, on April 2, 1992, the NTSB classified the recommendation "Closed—Acceptable Action."[64]

Regarding Safety Recommendation A-90-170, on June 19, 1997, the FAA stated that it issued AC 20-128A on March 25, 1997. According to the FAA, the AC presented a method of compliance with the requirements of 14 *CFR* 23.901(f), 23.903(b)(1), and 25.901(d)(1), which addressed design precautions to minimize the hazards to an airplane in the event of an uncontained engine or APU failure. On the basis of the FAA's action, the NTSB classified the recommendation "Closed—Acceptable Action" on August 26, 1997.

Regarding Safety Recommendation A-90-172, on September 10, 1998, the FAA stated that it would maintain an uncontained turbine engine debris characterization and mitigation database within the aircraft catastrophic failure prevention program. The FAA also stated that these data would be available for future design assessments, safety analyses, and research. As a result, the NTSB classified this recommendation "Closed—Acceptable Action" on December 8, 1998.

In January 2010, the Aerospace Industries Association (AIA) issued a report titled *High Bypass Ratio Turbine Engine Uncontained Rotor Events and Small Fragment Threat Characterization 1969-2006*. The report was developed by an AIA working group comprising experts from transport-category airplane manufacturers and high-bypass turbofan manufacturers; the FAA did not participate.[65] The report addressed, among other things, high-bypass turbofan disk bursts, their effects, and related trend analysis. According to the executive summary of the report, the data published in the report were collected from AIA's rotor burst database for high-bypass turbofan engines, which AIA indicated was consistent with the intent of Safety Recommendation A-90-172 (AIA 2010).[66] (As indicated in this section, AIA was not the recipient

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[64] As previously stated, the FAA established the Engine Titanium Consortium in response to one of the recommendations of the titanium rotating components review team.

[65] Although the FAA was not a member of the working group, the report indicated that the FAA was represented on the data collection process team.

[66] According to the AIA report, data from the association's rotor burst database for high-bypass turbofan engines showed that, between 1969 and 2006, 58 nacelle uncontained disk events occurred; 46 of these events involved first-generation engines (designed in the late 1960s), and 12 of the events involved second-generation engines

of that recommendation, and the FAA did not ask AIA to take action in response to the recommendation.)

1.7.3.2 Communication and Coordination Among Flight and Cabin Crews

Safety Recommendation A-16-26

On October 6, 2016, the NTSB issued Safety Recommendation A-16-26 as a result of its investigation of the March 5, 2015, accident involving Delta Air Lines flight 1086, an MD-88 that was landing at LaGuardia Airport in New York, New York, when it departed the left side of the runway, contacted the airport perimeter fence, and came to rest with the airplane's nose on an embankment next to Flushing Bay. The NTSB's investigation determined that the captain did not convey a sense of urgency to evacuate the cabin and that the flight attendants were confused about the timing of the evacuation. The investigation also determined that the evacuation began about 12 minutes after the airplane came to a stop and that more than 17 minutes had elapsed between the time that the airplane came to a stop and the time that the passengers were off the airplane (NTSB 2016). As a result of that accident and the lack of FAA action to fully address recurring evacuation communication, coordination, and decision-making problems, the NTSB issued Safety Recommendation A-16-26, which asked the FAA to do the following:[67]

> Develop best practices related to evacuation communication, coordination, and decision-making during emergencies through the establishment of an industry working group and then issue guidance for 14 *Code of Federal Regulations* Part 121 air carriers to use to improve flight and cabin crew performance during evacuations.

On December 27, 2016, the FAA stated that it understood the importance of crewmember communication, coordination, and decision-making related to emergency evacuations and, as such, was considering the establishment of a working group to examine these issues and make recommendations. The FAA indicated that the working group would include representatives from the Air Line Pilots Association, the Association of Flight Attendants, the Association of

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(designed in the 1980s). No events involved third-generation engines (designed in the 1990s). The data also showed that more than 90% of the disk bursts occurred during takeoff or initial climb. Although the AIA report noted the "low incidence of disk uncontainment demonstrated by the 2nd/3rd generation fleet," the data on which this finding was based were for nacelle uncontained disk events. The American Airlines flight 383 accident was the first rotor burst event involving a second-generation (CF6-80C2) engine. Section 2.4.3 describes an uncontained engine failure involving a third-generation engine.

[67] The final report on the investigation of the accident involving Delta Air Lines flight 1086 stated that the accident "demonstrated problems with evacuation communication, coordination, and decision-making. The NTSB has investigated other accidents in which similar problems occurred and made related safety recommendations." These investigations included the accidents involving (1) a Tower Air 747 at Jamaica, New York, on December 20, 1995 (DCA96MA029); (2) a Delta MD-88 at Pensacola, Florida, on July 6, 1996 (DCA96MA068); (3) a Northwest Airlines DC-9 and a Northwest Airlines A319 at Minneapolis, Minnesota, on May 10, 2005 (CHI05MA111A and CHI05MA111B); and (4) an American Airlines MD-82 at St. Louis, Missouri, on September 28, 2007 (DCA07MA310, cited in the discussion for Safety Recommendation A-09-27 later in this section). The final report also cited the NTSB's June 2000 safety study on emergency evacuations of commercial airplanes (discussed in section 1.7.3.3), which found continuing communication and coordination problems among flight and cabin crewmembers during airplane evacuations.

Professional Flight Attendants, Airlines for America, and the FAA's Flight Standards Service. On March 27, 2017, the NTSB classified Safety Recommendation A-16-26 "Open—Acceptable Response" pending the establishment of the working group and the development of the recommended best practices.

Safety Recommendation A-09-27

On May 19, 2009, the NTSB issued Safety Recommendation A-09-27 as a result of its investigation of the September 28, 2007, accident involving American Airlines flight 1400, an MD-82 that experienced an in-flight engine fire during a departure climb from Lambert St. Louis International Airport, St. Louis, Missouri, and made a successful emergency landing on one of the airport's runways. The NTSB found that, during the emergency situation, the flight attendants did not relay potentially pertinent information to the captain in accordance with company guidance and training. In addition, the NTSB found that the flight crew considered initiating an evacuation but did not communicate with the cabin crew to obtain and exchange information (NTSB 2009).[68] Safety Recommendation A-09-27 asked the FAA to do the following:

> Revise Advisory Circular 120-48, "Communication and Coordination Between Flight Crewmembers and Flight Attendants," to update guidance and training provided to flight and cabin crews regarding communications during emergency and unusual situations to reflect current industry knowledge based on research and lessons learned from relevant accidents and incidents over the last 20 years.[69]

On August 28, 2012, the FAA stated that it was revising AC 120-48 to update the guidance regarding communications during emergency and unusual situations to reflect current industry knowledge based on lessons learned. The FAA indicated that it anticipated issuing the revised AC in 2013.

On March 18, 2014, the NTSB stated that, according to its conversations with the FAA, the issuance of revised AC 120-48 was delayed by work associated with a final rule, but the FAA indicated that it still intended to issue the revised AC. As a result, Safety Recommendation A-09-27 remained classified "Open—Acceptable Response" pending completion of that action.[70]

In its final report on the Delta Air Lines flight 1086 accident, the NTSB noted that the FAA had still not issued revised AC 120-48. Also, given the inadequate communication and coordination among the Delta flight and cabin crewmembers that the NTSB's investigation found, the NTSB reiterated Safety Recommendation A-09-27 and reclassified it "Open—Unacceptable Response."

[68] After a discussion with ARFF personnel, the flight crew decided not to evacuate, but the ARFF incident commander decided to deplane the passengers about 30 minutes later after heat and smoke were observed coming from a damaged engine.

[69] The NTSB noted that this AC had not been updated since its issuance in July 1988 and thus did not reflect industry knowledge that was current at the time that the safety recommendation was issued.

[70] Safety Recommendation A-09-27 was initially classified "Open—Acceptable Response" on April 2, 2010.

In a March 27, 2017, letter to the FAA, the NTSB stated that the FAA's December 23, 2016, letter about recommendations from the Delta flight 1086 investigation did not include any actions that were planned or taken in response to Safety Recommendation A-09-27. The NTSB noted that the FAA stated that, as part of the response to Safety Recommendation A-16-25, it was reviewing AC 120-48 and was considering needed revisions.[71] The NTSB stated that the FAA should consider the requested actions in Safety Recommendation A-09-27 in any revisions to AC 120-48 and that Safety Recommendation A-09-27 remained classified "Open—Unacceptable Response."

1.7.3.3 Retrieval of Carry-On Baggage

On July 14, 2000, the NTSB issued Safety Recommendation A-00-88 as a result of the findings in its safety study, *Emergency Evacuation of Commercial Airplanes*. Specifically, the NTSB found that "the training that flight attendants receive with regard to passengers retrieving carry-on luggage does not address what to do when passengers do not follow the command to leave everything behind" (NTSB 2000). The NTSB also determined that techniques for handling passengers who do not listen to flight attendants' instructions during evacuations needed to be addressed. Safety Recommendation A-00-88 asked the FAA to "develop advisory material to address ways to minimize the problems associated with carry-on luggage during evacuations."

On November 8, 2000, the FAA stated that, on July 24, 2000, it issued AC 121-29B, "Carry-On Baggage," which provided information in plain language regarding compliance with carry-on baggage regulations.[72] The FAA also stated that the AC indicated that operators were required to provide crewmember training that included the handling of carry-on baggage during an emergency. In addition, the FAA stated that it would issue a flight standards handbook bulletin for air transportation that included guidance for principal operations inspectors (POI) about the handling of carry-on baggage during an emergency. On July 25, 2001, the NTSB classified Safety Recommendation A-00-88 "Open—Acceptable Response" pending the issuance of the bulletin.

On July 30, 2001, the FAA stated that FAA Order 8400.10, *Air Transportation Operations Inspector's Handbook*, paragraph 1984, was revised to direct POIs to encourage their assigned certificate holders to ensure that specific procedures were included in crewmember manuals and training programs about the handling of carry-on baggage during an emergency.[73] The FAA stated that this information should provide flight attendants with clear direction and guidance to minimize

[71] Safety Recommendation A-16-25 asked the FAA to "require 14 *Code of Federal Regulations* Part 121 operators to provide (1) guidance that instructs flight attendants to remain at their assigned exits and actively monitor exit availability in all non-normal situations in case an evacuation is necessary and (2) flight attendant training programs that include scenarios requiring crew coordination regarding active monitoring of exit availability and evacuating after a significant event that involves a loss of communications." This recommendation was classified "Open—Acceptable Response" on March 27, 2017.

[72] According to AC 121-29B, the FAA did not make any substantive changes to the guidance in AC 121-29A.

[73] FAA Order 8400.10 was canceled in October 2007. FAA Order 8900.1, *Flight Standards Information Management System*, was issued in August 2008. Volume 3 of FAA Order 8900.1, "General Technical Administration," chapter 23, "Flight Attendant Training and Qualification Programs," states that POIs "should work with their assigned certificate holders to ensure that they have specific procedures in the appropriate crewmember manuals and training programs that address the handling of carry-on baggage during an emergency and provide their F/As [flight attendants] with clear direction and guidance."

the identified problems associated with carry-on luggage. As a result of this revision, the NTSB classified Safety Recommendation A-00-88 “Closed—Acceptable Action” on January 3, 2002.

2. Analysis

The flight crew was properly certificated and qualified in accordance with federal regulations and company requirements. A review of the flight crew's work and sleep schedules and recent activities showed no evidence of factors that could have adversely affected the performance of either crewmember on the day of the accident.

The airplane was properly certificated, equipped, and maintained in accordance with federal regulations. No evidence indicated any structural, engine, or system failures before the uncontained engine failure occurred.

This analysis discusses the accident sequence, flight crew checklist issues, flight and cabin crew evacuation-related issues, and the manufacture and inspection of the HPT stage 2 disk and related guidance.

2.1 Accident Sequence

The right engine failure occurred when the CVR recorded a "bang" sound, at which time the airplane's airspeed was 128 knots. Both flight crewmembers then felt the airplane drift to the right, and the captain thought that the airplane was unsafe to fly. At that time, no warnings were being annunciated in the cockpit to indicate to the flight crew that an uncontained engine failure had occurred or that a fire had subsequently begun. The captain moved the throttles to the idle position when the airspeed was 130 knots and began the rejected takeoff maneuver. The start of the rejected takeoff maneuver occurred 1.2 seconds after the "bang" sound. The RTO autobrakes activated when the airspeed was 134 knots, which was also V_1 for the flight. According to the American Airlines *B767 Operations Manual, QRH*, the decision to reject the takeoff must be made in time to start the maneuver by V_1.

The first officer informed the tower controller that the takeoff was being rejected, and the tower controller notified the flight crewmembers of a fire, which was their first indication of the fire. The airplane stopped on the runway about 26 seconds after the "bang" sound. The NTSB concludes that the captain made a timely decision to reject the takeoff and performed the maneuver in accordance with company training and procedures.

The uncontained engine failure resulted from an HPT stage 2 disk rupture (rotor burst). The HPT stage 2 disk was recovered in four fragments (shown in figure 5 in section 1.3.3). One disk fragment and other exiting engine debris fragments (for example, blades, static hardware, or HPT stage 2 disk posts) impacted and penetrated through the inboard section of the right wing, creating two separate holes (shown in figure 7 in section 1.3.3). Disk fragments "B," "C," and "D" were recovered outboard of the right engine (to the north of the airplane); as a result, they could not have caused the damage observed inboard of the engine.

In addition, disk fragments B, C, and D were likely part of a single disk piece that had fractured into three separate fragments after impacting the runway. Specifically, an impact ground scar/gouge was observed about 32 ft to the right of the runway 28R centerline (outboard of the right engine location). This ground scar/gouge was consistent with impact from a single HPT stage

2 disk fragment. Thus, this disk fragment was most likely intact as it exited the right engine and nacelle and impacted runway 28R, creating the observed ground scar/gouge and fracturing into three pieces. The overstress fractures on disk fragments B, C, and D were consistent with a hard impact, which would be expected given the exit velocity, size, and weight of the disk fragment before it fractured.

Disk fragment "A" was recovered about 2,935 ft south of the uncontainment location at a UPS building. Hole 1 (located in the inboard section of the right wing forward of the front spar) was too small for disk fragment A to fit through, and the edges of the hole exhibited tearing and ripping that were consistent with impact from smaller debris with less momentum, such as that from exiting engine debris fragments. The trajectory of the released debris showed that the debris did not impact the front spar but instead continued upward and exited the top of the leading-edge panel.

The trajectory for the disk fragment causing the damage to the inboard section of the right wing aft of the front spar (hole 2) showed that the fragment entered the dry bay through the lower wing skin, severed the main engine fuel feed line, severed rib No. 6 (part of the inboard dry bay boundary), and continued through the upper wing skin.[74] To create this damage, a large disk piece with significant energy would be needed. Disk fragment A weighed about 57 pounds and represented more than one-third of the disk. Thus, hole 2 was created by disk fragment A of the HPT stage 2 disk.

Disk fragment A did not cause the impact damage observed on the fuselage, landing gear doors, and left engine nacelle; the cause of that damage was consistent with smaller exiting engine debris fragments. If disk fragment A, which was found intact, had struck the fuselage, landing gear doors, or left engine nacelle, the fragment would have created a sizeable hole due to the exit velocity, size, and weight of the fragment. Also, Boeing's trajectory analysis, which estimated the exit angle for the disk fragment that departed the right engine and penetrated through the right wing, determined that the disk fragment exited the engine about 4.3° aft of the HPT stage 2 disk rotation plane and that the fragment passed over the fuselage.

The NTSB concludes that the right engine experienced an uncontained HPT stage 2 disk rupture during the takeoff roll. The HPT stage 2 disk initially separated into two fragments. One fragment penetrated through the inboard section of the right wing, severed the main engine fuel feed line, breached the fuel tank, traveled up and over the fuselage, and landed about 3,000 ft away. The other fragment exited outboard of the right engine, impacting the runway and fracturing into three pieces.

Postaccident observations of the HPT stage 2 disk fragments found that the fracture surfaces in the forward bore region of the disk exhibited a heat-tinted appearance. High-magnification optical examination of the fracture surfaces revealed the presence of dark gray subsurface material discontinuities with multiple cracks initiating along the edges of the discontinuities. Examination of the material underneath the largest discontinuity, which was about

[74] The dry bay, which contains no fuel, is a compartment in each main fuel tank that is located directly above each engine in the forward part of the fuel tank.

0.43 inch in length and 0.07 inch in width and was inclined about 26° to the bore centerline, revealed a discrete region underneath the discontinuity that appeared white compared with the surrounding material. Surrounding and interspersed within this region were stringers of micron-sized oxide particles referred to collectively as a “discrete dirty white spot.”[75]

The multiple cracks that had initiated along the edges of the discontinuities propagated radially inward toward the bore and outward toward the disk rim and blade slots. Under SEM examination, the cracks exhibited striations that slowly increased in spacing as the crack length increased, which was consistent with low-cycle fatigue.[76] (Outside of the heat-tinted region, the fractures exhibited features consistent with overstress.) The NTSB concludes that the HPT stage 2 disk failed because of multiple low-cycle fatigue cracks that initiated from an internal material anomaly, known as a discrete dirty white spot, which formed during the processing of the material from which the disk was manufactured. Section 2.4 provides more information about the HPT stage 2 disk failure.

2.2 Checklist Issues

2.2.1 Decision to Perform Engine Fire Checklist

The flight crew received aural and visual engine fire warnings after the captain’s decision to reject the takeoff.[77] Given these warnings, the flight crew began the 16-step engine fire checklist, the first 5 steps of which were memory items.[78] Step 3, which was accomplished about 4 seconds after the captain called “checklist,” instructed the flight crew to cut off the fuel control switch on the affected side (in this case, the right side), which shut down that engine. Step 5 instructed the flight crew to rotate the engine fire switch (shown in figure 15) to its stop and then wait 30 seconds to see if the engine fire warning light remained illuminated. If the light was still illuminated, the engine fire switch was to be rotated to its other stop.[79]

FDR data showed that the handle for the right engine fire extinguisher was pulled about 8 seconds after the captain called “checklist.” About 23 seconds after the handle was pulled, the captain asked the first officer if he had discharged the fire extinguisher bottle, and the first officer

[75] Metallurgical cross-sections that GE prepared indicated that the discrete dirty white spot was a single anomaly measuring about 0.74 inch in length and that the oxide stringers exposed by the fracture were part of that anomaly.

[76] The highest low-cycle fatigue cycle counts that the NTSB and GE obtained (when measuring the striation densities of multiple cracks as a function of crack size) were about 5,700 and 7,000 cycles, respectively, before the disk failed. The difference between the estimates was likely due to the subjectivity in measuring the striation densities and interpreting the results.

[77] At 1432:00, the CVR recorded a sound similar to the EICAS engine fire warning, and the FDR recorded the ENG FIRE R and master WARNING annunciations at the same time. These warnings occurred 15 seconds after the captain rejected the takeoff and 10 seconds before the airplane came to a stop.

[78] At 1432:04, the CVR recorded the captain stating “ok, let’s run the uh checklist”; about 11 seconds later, the first officer stated, “checklist for engine fire.” Commanding the engine fire checklist was consistent with American Airlines’ special purpose operational training for rejected takeoffs and evacuations (see section 1.6.3.1), which both flight crewmembers had received.

[79] The engine fire checklist applied to in-flight operations as well as ground operations. This issue is discussed further in section 2.2.2.

replied that he "pushed it twice." The first officer then realized that he had pulled but not rotated the engine fire switch, at which time he accomplished that step.

Because of the wind at the time (from 180° at 10 knots) in relation to the airplane's location on runway 28R, the smoke was blowing away from the cockpit, and the flight crew could not readily see the amount of smoke coming from the right engine. Also, postaccident observations in an exemplar 767 airplane demonstrated that the first officer would not have been able to see the right engine and most of the right wing when looking out the cockpit right-side window from his seat. Thus, at that point, the flight crew was unaware of the severity of the fire.[80] The flight crew was also unaware that the cabin was beginning to fill with smoke.

About 4.5 seconds after the first officer discharged the fire extinguisher bottle in the right engine, the captain stated, "oh look at the smoke—check out the smoke." The captain stated, during a postaccident interview, that he recognized that continuing the engine fire checklist would not be appropriate because the airplane was on the ground. He called for the evacuation checklist, which had nine steps, about 4 seconds after seeing the smoke. The captain stated that, while performing the evacuation checklist, he heard commotion outside the cockpit door and realized that the cabin was being evacuated. The fourth step of the evacuation checklist instructed the flight crew to cut off the fuel control switches to shut down both engines.

Although the right engine had already been shut down as part of the engine fire checklist, shutting down the left engine did not occur until the flight crew depressurized the airplane (the third evacuation checklist step), which the captain reported took a long time, even though the airplane had not yet been in flight.[81] (The NTSB notes that, at this point, the exits would have been opened, so the cabin would have already been depressurized.) FDR data showed that the left engine was shut down about 59 seconds after the airplane came to a stop, and video evidence showed that the left engine spooled down about 10 seconds later.

The NTSB concludes that the captain's decision to perform the engine fire checklist was appropriate given his training, the information provided by ATC, and the fire warnings in the cockpit. However, the design of the engine fire checklist delayed initiating the evacuation checklist, shutting down the left engine, and commanding an evacuation from the cockpit.

2.2.2 Engine Fire Checklist Design

American Airlines' engine fire/engine severe damage or separation checklist for the Boeing 767 did not differentiate between an engine fire in flight or an engine fire while the airplane was on the ground. As stated previously, step 3 of the checklist instructed the flight crew to cut off

[80] During a postaccident interview, the first officer stated that, after evacuating the airplane, he was "surprised" to see flames on the right side of the airplane because he expected to see a small fire.

[81] Although only two of the nine items on the evacuation checklist are associated with depressurizing the airplane, the captain thought that the evacuation checklist was "slow and cumbersome" because of the "large portion" of time needed to depressurize the airplane. In an October 2017 e-mail, Boeing indicated that, before the airplane's takeoff rotation, the cabin pressure would be less than 0.05 psig above the ambient pressure, and the amount of time needed to depressurize the airplane would be "very short." The CVR transcript showed that, at 1432:57, the first officer called "cabin altitude mode selector manual?" to which the captain replied "OK." At 1433:01, the first officer called "cabin altitude control hold in climb." About 4 seconds later, the captain replied, "okay. What about the—." At 1433:07, the first officer called "fuel control switches both cutoff."

the fuel control switch on the affected side to shut down that engine. For an engine fire during flight, shutting down the affected engine only would be appropriate because the unaffected engine would be needed for continued flight; the items on the checklist after the first five memory items included actions related to configuring the airplane for landing. However, for an engine fire on the ground, the checklist did not include a step to shut down the unaffected engine or direct the flight crew to perform the evacuation checklist after the engine fire checklist memory items.

Also, as stated previously, step 5 of the engine fire checklist consisted of rotating the engine fire switch to its stop, holding for 1 second so that a fire extinguisher bottle could discharge its contents (halon) to suppress the fire, and then waiting 30 seconds. If the engine fire warning light remained illuminated, the engine fire switch was to be rotated to its other stop and held for 1 second, which would discharge the second halon bottle.

A Boeing fire specialist stated that the 30-second wait period in between discharging halon bottles was necessary because it would allow pilots time to deploy a secondary means to suppress an engine fire if it reignited due to hotspots within the engine core. The fire specialist also stated that the wait period would likely not be required on the ground; however, that information was not included in the checklist.

American Airlines based the engine fire/engine severe damage or separation checklist on Boeing's 767 checklist procedure for the same emergencies. Boeing's engine fire checklist procedures for its other airplane models also appeared to be the same for an engine fire during flight or on the ground. However, other airplane manufacturers, including Airbus and Embraer, have a set of procedures for an engine fire on the ground and another set of procedures for an in-flight engine fire. American Airlines used both sets of procedures for its fleet of Airbus A319, 320, and 321 airplanes and Embraer E190 airplanes.

The American Airlines *A319/320/321 QRH* "ENG (1 or 2) FIRE (On Ground)" checklist (dated July 5, 2016) had six immediate action items to be accomplished. Those items did not have any associated wait times. After the last item was accomplished, the checklist directed the flight crew to accomplish the evacuation checklist, if required. Similarly, the American Airlines *E190 QRH* (dated May 31, 2016) showed seven items under the "ENG (1 or 2) FIRE, Severe Damage or Separation" checklist. The first item referred the flight crew to the "Engine Fire on the Ground Checklist" (dated January 3, 2017), which had five items to be accomplished. Those items also did not have any associated wait times. After accomplishing the last item on the checklist, the flight crew was directed to either "establish and communicate a plan" or "accomplish Evacuation."[82]

American Airlines' engine fire checklists that are specific to ground operations did not include the 30-second wait time between discharging a fire extinguishing bottle and determining if the second bottle would need to be discharged as well. That time could be critical in terms of containing a fire and/or commanding an evacuation. The NTSB concludes that engine fire checklists that specifically address ground operations would allow a flight crew to secure an engine

[82] The third step on the American Airlines *A319/320/321 QRH* nine-step evacuation checklist instructed pilots to depressurize the airplane if the pressurization system was in the manual operating mode. The eighth step on the American Airlines *E190 QRH* 12-step evacuation checklist was to "push in" the "pressurization dump" switch light; Embraer airplanes have a guarded "dump" switch light, which, upon pressing, would allow the outflow valves to quickly open, depressurizing the airplane.

and command an evacuation, if required, in a timelier manner than engine fire checklists that do not differentiate between ground and in-flight operations. Therefore, the NTSB recommends that Boeing work with operators as required to develop and/or revise emergency checklist procedures for an engine fire on the ground to expeditiously address the fire hazard without unnecessarily delaying an evacuation.

The NTSB also recommends that American Airlines, for all airplanes that it operates, review existing engine fire checklists and make changes as necessary to ensure that the procedures would expeditiously address engine fires occurring on the ground without unnecessarily delaying an evacuation. The NTSB notes that American Airlines' evacuation guidance for flight crews was focused on assessing the need for an evacuation occurring after landing because of "a significant in-flight event" rather than assessing the need, after a rejected takeoff, for an evacuation due to an engine fire and announcing the captain's intentions. American Airlines could mitigate this issue by implementing the recommended action. In addition, the NTSB recommends that the FAA, when approving the operating procedures of a 14 *CFR* Part 121 air carrier, require operators to develop and/or revise emergency checklist procedures for an engine fire on the ground to expeditiously address the fire hazard without unnecessarily delaying an evacuation.

2.3 Evacuation Issues

2.3.1 Evacuation Sequence

All seven flight attendants reported that they remained in position at their assigned exits after the airplane came to a stop. Passengers moved quickly toward the exits and were urging the flight attendants to open them. The flight attendants stated that they tried to delay the evacuation because they had not received instructions from the flight crew to evacuate. However, due to the severity of the fire and the passengers' panic, the flight attendants initiated an evacuation in accordance with their authority to do so in a life-threatening situation that involved fire and smoke. The flight attendants evacuated all 161 passengers, checked their assigned areas, and exited the airplane (except for the lead flight attendant, who waited for the flight crew before evacuating). The NTSB evaluated the flight attendants' actions during the evacuation.

The flight attendants assigned to the overwing exits (2L, 2R, and 3L) all observed fire on the right side of the airplane. Flight attendant 4, who was assigned to the right overwing exit, blocked the exit because of fire and smoke outside of the airplane, which was appropriate. Flight attendant 6 was responsible for operating the left overwing exit, and she was seated facing forward on the left-side aisle with flight attendant 7 seated behind her facing aft. During the evacuation, flight attendant 7 was responsible for elevating himself on a seat in the main cabin to provide flow control instructions to passengers, but instead he opened the left overwing exit at 1432:20 (10 seconds after the airplane came to a stop) and started evacuating passengers. Flight attendant 6 saw that flight attendant 7 had opened the exit, and she assumed his responsibility to direct passengers to usable exits. Video evidence showed that the left overwing exit slide was fully deployed 19 seconds after the airplane came to a stop and that the first occupant evacuated from that slide 12 seconds later, even though the engine did not fully spool down for another 38 seconds.

Flight attendants 1 and 5 were assigned to the forward cabin doors (1L and 1R, respectively). Flight attendant 1 (the lead flight attendant) decided to initiate an evacuation because smoke had started to fill the cabin and passengers were rushing toward the front of the airplane to evacuate. Consistent with company procedures, flight attendant 1 picked up the interphone to notify the flight crew that he was going to initiate an evacuation, but he did not later remember if he performed the step to call the flight crew. Flight attendant 1 opened the 1L door at 1432:38 (28 seconds after the airplane came to a stop) and evacuated passengers via the 1L door slide.

Flight attendant 5 opened the 1R door at 1432:42 (32 seconds after the airplane came to a stop) after flight attendant 1 initiated the evacuation, but she immediately blocked that exit because the engine fire would be too close to the 1R door slide. Flight attendants are trained to assess conditions outside of doors that they are operating by looking through a window in the doors. If all conditions are met (no smoke, fire, or airplane or ground debris), the doors can be opened, and the flight attendants can continue to assess the conditions outside of the airplane. It is possible that flight attendant 5 did not see the extent of the fire until the 1R door was fully opened because of the limited viewing area of the door window. Once the door was fully opened, she recognized that the fire would present a danger and took appropriate action to prevent passengers from using that exit.

Flight attendants 2 and 3, who were assigned to the aft cabin doors (4L and 4R, respectively), saw fire on the right side of the airplane. Because she could hear the left engine running, flight attendant 2 initially blocked her assigned exit, which was appropriate. She tried to contact the flight crew on the interphone to report that the left engine was running but had difficulty using the interphone. She opened the 4L door at 1432:48 (38 seconds after the airplane came to a stop).[83] Flight attendant 3 also blocked his exit because of smoke and fire outside the door, which was appropriate. He tried to use the interphone to make a PA announcement to calm passengers but also had difficulty using the interphone. (The difficulty that these flight attendants experienced with the interphone is discussed in section 2.3.2.1.)

Although the actions of flight attendant 7 in assessing and opening the left overwing exit did not slow the evacuation at this exit, performing flight attendant 6's assigned responsibilities was contrary to company procedures and training. Also, flight attendant 7 deviated from the evacuation procedures in the *Flight Service Inflight Manual*, which indicated that "prior to opening an exit, assess conditions outside to determine if exit and escape route [are] safe," and began evacuating passengers from the left overwing exit. However, after opening the left overwing exit, flight attendant 7 should have recognized, from the sound of the engine, that the exit would not be viable for an evacuation. (The sound of the engine would have been the primary cue to flight attendant 7 that the engine was still operating.) Given the location of the left overwing exit relative to the left engine, flight attendant 7 should have blocked the exit until the engine was shut down.

Flight attendant 7 stated that he assumed that the left engine was still running but not at "full blast mode" because the airplane had come to a stop. He also stated that his main concern was getting passengers off the airplane because of the fire. However, the evacuation guidance

[83] Flight attendant 2 decided eventually to allow passengers to evacuate from her assigned exit because the cabin was filling with smoke. However, she and flight attendant 3 had to hold passengers back until the slide stabilized; after deployment, the slide was blowing toward the back of the airplane because the left engine had not yet been shut down.

specifically indicated that "engine(s) still operating" was an unsafe condition. The one serious injury that resulted during the evacuation occurred after a passenger evacuated using the left overwing exit. Once on the ground, the passenger stood up to get away from the airplane but was knocked down by the jet blast coming from the left engine.

The NTSB concludes that the flight attendants made a good decision to begin the evacuation given the fire on the right side of the airplane and the smoke in the cabin, but the left overwing exit should have been blocked while the left engine was still operating because of the increased risk of injury to passengers who evacuated from that exit. Therefore, the NTSB recommends that the FAA develop and issue guidance to all air carriers that conduct passenger-carrying operations under 14 *CFR* Part 121 regarding (1) discussing this accident during recurrent flight attendant training to emphasize the importance of effectively assessing door and overwing exits during an unusual or emergency situation and (2) providing techniques for identifying conditions that would preclude opening exits, including an operating engine. The NTSB notes that a safety alert for operators (SAFO) could be an effective means for conveying this information to affected Part 121 carriers.[84]

2.3.2 Flight and Cabin Crew Communication

The American Airlines *B767 Operations Manual, QRH* guidance stated (in the General Information section) that, if an immediate evacuation is not required, the captain should make a PA announcement commanding "This is the Captain. Remain Seated. Remain Seated. Remain Seated" to assure the flight attendants and passengers that the situation was under control. The guidance did not require captains to consult with flight attendants before making this announcement. Although the flight 383 captain called for the engine fire checklist 5.7 seconds before the airplane came to a stop, an announcement communicating the captain's initial assessment that an immediate evacuation was not necessary would have provided awareness to the flight attendants of the flight crew's intentions. During postaccident interviews, three of the flight attendants reported that, after the airplane came to a stop, they expected an announcement from the cockpit.

It is understandable that the flight crew was focused on securing the right engine (given the engine fire warnings and the report of fire from ATC), and the NTSB recognizes that the flight crew's performance of the engine fire and evacuation checklists was consistent with American Airlines' training and procedures. Nevertheless, there would likely have been enough time, after the airplane came to a stop, for the captain to quickly instruct the flight attendants and passengers to remain seated. This statement could have then resulted in the flight attendants notifying the flight crew of the magnitude of the fire on the right side of the airplane and the need to shut down the engines.

Such communication between the flight and cabin crews would have been effective crew resource management (CRM). Also, the *QRH* provided the following flight crew evacuation guidance: "the Captain must evaluate a specific situation, apply good judgment, and reach the best decision given the information available." Communication from the flight attendants to the flight

[84] According to the FAA's website (www.faa.gov, accessed January 10, 2018), a SAFO "is an information tool that alerts, educates, and makes recommendations to the aviation community."

crew regarding the conditions inside the cabin and outside the airplane would have helped the captain make an informed decision about the timing of the evacuation.

The NTSB is also concerned that none of the flight attendants alerted the flight crewmembers about the evacuation. As previously stated, the flight attendants tried to delay the evacuation because they had not received evacuation instructions from the cockpit, but they initiated the evacuation, although the left engine was still running, due to the severity of the fire and the passengers' panic.

The American Airlines *Flight Service Inflight Manual* described the importance of having flight attendants update the captain if cabin conditions warrant an evacuation. Although the manual described the flight attendants' authority to initiate an evacuation in a life-threatening situation without awaiting instructions from the flight crew, the manual also stated that flight attendants were to attempt to communicate with the flight crew before the evacuation if possible. Because one (or possibly two) of the seven flight attendants attempted to contact the flight crew via the interphone (but were unsuccessful, as further discussed in the next section), there was adequate time for the flight attendants to communicate with the flight crewmembers and alert them about the evacuation.

During a postaccident interview, one flight attendant stated his opinion that it was not a priority to be on the phone if an engine fire occurred. If that were the case, the flight attendants could have activated the evacuation signaling system located on the flight attendant jumpseat control panels, which would have provided an aural and a visual alert in the cockpit. If any of the flight attendants had taken that action, the flight crewmembers would immediately have known that an evacuation was underway, and they could have reacted accordingly. American Airlines trained flight attendants to use the signaling system for an evacuation, and evacuation procedures in the flight attendant manual stated, "on aircraft such equipped, turn on signaling system," so it is unknown why none of the flight attendants used the system to alert the flight crew.

The captain reported that he became aware that a flight attendant-initiated evacuation was underway when he heard commotion outside the cockpit door. Although a "DOOR" message would have appeared on the EICAS screen when the cabin doors were opened, postaccident simulator testing showed that the messages would not have been visible on the EICAS screen for long because of the other displayed alerts resulting from the emergency. Also, because the flight crewmembers would have been focused on performing checklists, they would not likely have noticed the door alerts. Further, after the engines were shut down, the EICAS screen would not have been displaying alerts and other pertinent information.

During a postaccident interview, the captain stated that he learned from videos of the evacuation that the left engine was still running when the exits were opened. The captain also stated that, if he had that awareness when he heard the commotion, he would have shut down the left engine sooner. The flight attendants had both the evacuation signaling system and the interphone system available to them to communicate with the flight crew, but none of the flight attendants activated the signaling system, and the flight attendants who attempted communication using the interphone system were unsuccessful in reaching the flight crew.

Even with an unfolding emergency, there should have been better communication between the flight and cabin crews. The lack of communication resulted in the flight crew being unaware of the developing situation in the cabin and the flight attendants initiating an evacuation with the left engine still operating. If the left engine had been shut down earlier, the 4L slide would have been available for evacuation sooner because the slide would not have been affected by the jet blast coming from the engine.[85] Also, the only serious injury resulting from the evacuation (which, as previously stated, occurred when a passenger, once on the ground, was knocked down from the jet blast coming from the left engine) might have been avoided. The NTSB concludes that, if the flight crew or the flight attendants had communicated after the airplane came to a stop, the flight crew could have become aware of the severity of the fire on the right side of the airplane and the need to expeditiously shut down the engines.

Section 2.3.2.2 discusses recurring evacuation-related communication and coordination issues that the NTSB has found during multiple investigations. In this investigation, the flight attendants not alerting the flight crew that the cabin was being evacuated and the captain not announcing his intention not to immediately evacuate are examples of such issues.

2.3.2.1 Interphone Issues

During postaccident interviews, three flight attendants indicated that they attempted to use the interphone before the evacuation. Flight attendant 2 tried to use the interphone to contact the cockpit and alert the flight crew that the left engine was running but was unsuccessful because she pressed the wrong numbers. Flight attendant 3 tried to use the interphone to make an announcement in the cabin to calm the passengers but could not recall how to use the interphone. The NTSB could not determine if flight attendant 1 attempted to place a call to the cockpit and experienced difficulty with the interphone or picked up the interphone without actually placing a call.

Depending on their delivery date, American Airlines 767-300-series airplanes either have a “classic” model interphone system (shown in figure 14a) or a “new” model interphone system (shown in figure 14b). As a result, flight attendants who are qualified on the 767 airplane need to know how to use both interphone system models. The new model interphone, which was installed on the accident airplane, requires additional steps to operate compared with the classic model interphone. To use the new model interphone, the flight attendant would need to turn over the handset and read the communication options for the location within the airplane to be called and then input the symbol (if required) and/or number(s) for that location on the key pad. In contrast, the classic model interphone has a key pad with buttons labeled for the pilot and forward, mid-, and aft cabin locations. Also, both interphone models have a “push to talk” button, but, for initial calls that do not go through, the new model interphone requires flight attendants to reset the interphone by either placing the interphone back into its cradle or pressing the reset button before pressing the “push to talk” button.

During a postaccident interview, American Airlines’ manager of flight attendant training stated that flight attendants are trained on interphone systems during initial training, airplane

[85] Video evidence showed that, 46 seconds after the airplane came to a stop, the 4L slide was fully deployed but was unusable because it was blown aft by left engine. After the engine was shut down, the slide repositioned itself, and the first occupant evacuated from that slide 1 minute 25 seconds after the airplane came to a stop.

differences training, and recurrent training. However, during recurrent training, which the accident flight attendants received, the subject was presented via a web-based course and not through hands-on experience using an interphone during simulated emergencies. Also, the new interphone system was not installed on either of the 767 simulators used for flight attendant training. The NTSB could not determine, based on the available evidence, if the flight attendants' difficulty operating the interphone was directly related to training deficiencies or the stress associated with the situation.

Because the interphones on the accident airplane were located at the 1L, 1RC, 2R, 4L, and 4R jumpseats, flight attendants who regularly sit in the 2L and 3L jumpseats and the 1LC, 4LC, and 4RC jumpseats (which were unoccupied during the accident flight) would generally not have an opportunity to use the interphone except during training. The NTSB notes that flight attendants 2 and 3, who were located at flight attendant stations with an interphone and would likely have had experience using the interphone during operations, did not use the interphone properly during the emergency. The NTSB concludes that American Airlines did not adequately train flight attendants qualified on the Boeing 767 to effectively use the different interphone system models installed on the airplane during an emergency.

According to a September 2017 e-mail from American Airlines, the company planned to incorporate "hands-on training for the handset differences" in January 2018 for initial flight attendant training and in April 2018 for recurrent flight attendant training. American Airlines also stated that it "continues to work on providing a job aid in the interim to our Flight Attendants to further identify the differences in handsets."

In addition, paragraph (b)(2) of 14 *CFR* 121.417, "Crewmember Emergency Training," addresses training in the operation of emergency equipment but does not include the interphone system among the equipment required to be trained. It is important that flight attendants are fully knowledgeable about the interphones on every airplane for which they are qualified because flight attendants cannot access the cockpit quickly to speak directly with the flight crew during an emergency given the increased cockpit security that was implemented after the events of September 11, 2001. Further, not all flight attendants have routine experience using the interphone during actual flights; thus, it is also important for flight attendants to receive the necessary training that would allow them to successfully operate the interphone, regardless of the interphone system make and model, under the stress associated with an emergency situation.

At the time of the accident, American Airlines operated 13 different interphone systems across its airplane fleet, and the differences among interphone systems could affect evacuation communications during an emergency if company flight attendants were not familiar with, and comfortable operating, various interphone system models. Such a situation could also affect flight attendants at other air carriers as well as flight crews.[86] Therefore, the NTSB recommends that the FAA review the training programs of all 14 *CFR* Part 121 operators and make changes as necessary to ensure that the programs provide flight attendants and flight crews with training aids

[86] The American Airlines simulators used to train 767 flight crewmembers included only the classic model interphone.

and hands-on emergency scenarios that account for the different interphone systems that air carriers operate.

In December 2017, the United Kingdom's Air Accidents Investigation Branch (AAIB) issued its final report on the June 26, 2016, incident involving an American Airlines Airbus A330 at Heathrow Airport, London, England.[87] According to the report, the cabin filled with smoke after boarding due to the failure of the APU load compressor carbon seal, which allowed hot oil to enter the bleed air supply to the cabin. Several flight attendants attempted to contact the flight crew, but they used the normal interphone call function and not the emergency call function.[88] The flight crew did not respond to the flight attendants (possibly because the sound of the master warning blocked the tone associated with a normal interphone call from the cabin), and one of the flight attendants initiated a passenger evacuation while the airplane was still parked at the gate.

Similar to the NTSB's findings from the AA383 investigation, the AAIB found that the flight attendants were trained to operate interphones on several types of airplanes and that emergency calls were initiated in different ways depending on the airplane type. Because the interphone handset keypad layouts are not standardized and this lack of standardization might have been a factor in the flight attendants' inability to initiate an emergency call, the AAIB issued Safety Recommendation 2017-024, which asked the FAA to "regulate the operation of interphone handsets, including during emergency communications, so that it is standardised irrespective of aircraft type."[89]

The NTSB recognizes that a standardized interphone system design could minimize any confusion when using the interphone during an emergency. However, the NTSB also recognizes the difficulty that would be associated with standardizing the interphone system design among all airplane models so equipped. As a result, the NTSB issued Safety Recommendation A-18-8 because we believe that the most efficient and effective manner to address issues associated with flight attendants' use of the interphone would be to have the FAA work directly with Part 121 operators to ensure that their flight attendant training programs account for the different interphone systems that each air carrier operates.

2.3.2.2 Recurring Evacuation-Related Issues

The NTSB's report on the March 5, 2015, Delta Air Lines flight 1086 accident explained that we have a long history of investigating accidents involving inadequate evacuation-related communication and coordination and issuing safety recommendations to resolve these issues (NTSB 2016).[90] The report also noted that FAA efforts to fully address the issues had thus far been

[87] For more information, see "AAIB investigation into Airbus A330-323, N276AY" at the AAIB's website (accessed January 10, 2018).

[88] The NTSB notes that the flight attendants involved in this incident and the flight attendants aboard the flight 383 airplane received the same general interphone training (in addition to airplane-specific interphone training.)

[89] AAIB Safety Recommendation 2017-025 asked that the European Aviation Safety Agency take the same action as requested in Safety Recommendation 2017-024.

[90] The Delta flight 1086 report also identified inadequate evacuation decision-making as a recurring safety issue. For this accident, the captain made an appropriate decision to suspend the engine fire checklist and begin the evacuation checklist.

insufficient. As a result, the NTSB issued Safety Recommendation A-16-26, which advocated for a multidisciplinary approach to develop best practices to resolve recurring evacuation-related issues by focusing on analyzing data involving airplane evacuations and identifying ways to improve flight and cabin crewmember performance.

In response to this recommendation, the FAA stated that it was considering whether to establish a working group comprised of government and industry subject matter experts to examine recurring evacuation-related issues and make recommendations. In March 2017, the NTSB classified Safety Recommendation A-16-26 "Open—Acceptable Response."

The NTSB's report on the Delta flight 1086 accident also reiterated Safety Recommendation A-09-27, which asked the FAA to update the guidance and training provided to flight and cabin crews regarding communication and coordination during emergency and unusual situations to reflect current industry knowledge based on research and lessons learned. Safety Recommendation A-09-27 is currently classified "Open—Unacceptable Response" because the FAA has still not revised AC 120-48, "Communication and Coordination Between Flight Crewmembers and Flight Attendants," despite its correspondence indicating that the revised AC was anticipated in 2013. (The AC was last updated in July 1988.)

The NTSB is investigating two other accidents with emergency evacuation issues. On September 8, 2015, British Airways flight 2276, a Boeing 777-200 equipped with two GE90-85B engines, experienced an uncontained left engine failure during the takeoff ground roll and caught fire at McCarran International Airport in Las Vegas, Nevada. The fire was extinguished by ARFF personnel. The 157 passengers and 13 crewmembers evacuated on the runway via emergency exit slides. On October 29, 2015, Dynamic International Airways flight 405, a Boeing 767-200ER with 101 occupants aboard, was taxiing for departure at Fort Lauderdale-Hollywood International Airport in Fort Lauderdale, Florida, when fuel began leaking from the left engine, causing a fire.[91] Information in the dockets for these accidents indicated that both evacuations began while an engine was still operating, demonstrating that communication and coordination issues between flight and cabin crews continue to exist during airplane evacuations.

In its report on the September 2007 accident involving American Airlines flight 1400 in St. Louis, Missouri, the NTSB found that the safety risks posed by inadequate flight and cabin crew communications in emergency situations were not effectively addressed by AC 120-48. When the NTSB issued Safety Recommendation A-09-27 in May 2009, the AC guidance was more than 20 years old. The FAA has not taken any steps to satisfy the recommended action in the more than 8 years since the recommendation was issued. The FAA's failure to update the almost 30-year-old AC guidance, which does not reflect lessons learned from recent accidents and incidents and address communications challenges resulting from changes in cockpit access for cabin crewmembers after the events of September 11, 2001, is inconsistent with contemporary safety management practices and the FAA's responsibility for ensuring continual operational safety.

[91] The dockets for these accident investigations, DCA15FA185 (Las Vegas) and DCA16FA013 (Fort Lauderdale), can be accessed at the NTSB's website.

Actions to satisfy Safety Recommendations A-09-27 do not require rulemaking or any significant cost to industry or the FAA. The benefit of updating AC 20-148 to incorporate the latest industry knowledge regarding crew communications during emergency situations would be that operators could voluntarily incorporate this information into their training and guidance. More effective communications between flight and cabin crews during emergency situations would improve safety for the traveling public, and updated guidance would help mitigate the recurring evacuation-related safety issues that the NTSB has identified in numerous accident investigations, including four accident investigations within the last 2 years. In addition, the FAA has not updated the NTSB about the status of the working group requested in Safety Recommendation A-16-26, and a notice about the establishment of the working group had not been published in the *Federal Register* as of November 2017. It is time for the FAA to emphasize the importance of ensuring that flight and cabin crew communications can facilitate safe and effective decision-making and action during situations requiring an evacuation.

The NTSB concludes that the FAA's inadequate actions to improve guidance and training on communication and coordination between flight and cabin crews during emergency situations, including evacuations, could lead to negative consequences for the traveling public if this safety issue continues to be unresolved. Therefore, the NTSB reiterates Safety Recommendations A-09-27 and A-16-26. In addition, because the FAA has not established, or committed to establishing, a working group to address the actions in Safety Recommendation A-16-26 and has not provided another plan to improve flight and cabin crew communication and coordination during evacuations, Safety Recommendation A-16-26 is classified "Open—Unacceptable Response."

The AAIB's investigation of the June 2016 incident at Heathrow Airport also demonstrated evacuation-related communication and coordination problems between flight and cabin crews. The AAIB's report stated that the flight attendant who initiated the evacuation did not activate the evacuation signal (similar to the flight attendants aboard flight 383). However, another flight attendant went to the flight deck to report that an evacuation was underway, and the captain saw (from a reflection in the terminal building) that an aft emergency slide had been deployed. The captain then made an announcement to stop the evacuation because he thought that he had isolated the source of the smoke and wanted to prevent unnecessary injuries. However, the captain did not discuss the situation in the cabin with the flight attendants before making his announcement, which indicated "a breakdown in communication and co-operation between flight crew and cabin crew members."

The AAIB's report also indicated that the captain's announcement caused confusion. One of the flight attendants thought that the captain was not aware of the smoke in the cabin, so she shouted to the passengers to keep moving. Another flight attendant, who saw the captain standing in the flight deck, told the captain that the evacuation should continue because of "thick smoke" in the cabin, and the captain made a subsequent announcement indicating that the evacuation should continue via a jetbridge (which was in place before the evacuation). The AAIB's report concluded that "prompt and effective communication between the cabin and the flight deck might have avoided an evacuation" and that one reason for the initiation of the evacuation was that the flight attendants "did not receive specific instructions from the flight crew."

The AAIB noted that American Airlines had taken postincident actions in response to the communication and coordination shortcomings found during the investigation but that action was also needed by the regulator because other operators might be susceptible to similar shortcomings. As a result, the AAIB issued Safety Recommendation 2017-029, which asked the FAA to "require that flight and cabin crews participate in joint training to enhance their co-ordination when dealing with emergencies." The NTSB has made similar recommendations to the FAA, but joint evacuation exercises for flight and cabin crews are still not required.[92] The NTSB recognizes the benefits of joint flight and cabin crew evacuation training and notes that the actions requested in Safety Recommendation A-16-26 would also be an effective way to resolve evacuation-related communication and coordination issues.

2.3.3 Flight and Cabin Crew Evacuation Duties

According to postaccident interviews with the flight crewmembers, they completed the evacuation checklist, including the step in which the captain announced over the PA system that an evacuation was underway. The flight crewmembers then exited the cockpit and entered the forward cabin, which was filled with smoke, and were immediately met by the lead flight attendant, who told them that all passengers were off the airplane and that they needed to evacuate.[93] The flight crewmembers and lead flight attendant then exited the airplane through the 1L door. ARFF personnel requested the occupant count from the captain, who called dispatch to get the count. ARFF personnel then walked through the cabin and confirmed that all passengers and crew were off the airplane. After the captain received the occupant count from dispatch, ARFF compared that number with the count of occupants who were off the airplane; everyone was accounted for.[94]

The American Airlines *B767 Operations Manual, QRH* instructed the captain to conduct a walk-through of the entire cabin to ensure that all passengers evacuated and then to exit the airplane through a usable aft entry door. However, the captain did not check the cabin to verify the lead flight attendant's report that all passengers had exited the airplane, which was understandable because the captain reported that, upon exiting the cockpit, he could see "thick black smoke" and could not see farther than "about 2 feet" in front of him.[95]

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[92] Safety Recommendation A-92-74, issued as part of a special investigation report on flight attendant training and performance during emergency situations, asked the FAA to ensure that "all reasonable attempts" were made to conduct joint flight crew/flight attendant evacuation drills during recurrent training. In response, the FAA directed POIs to ensure that their assigned certificate holders were aware of the performance benefits that result when flight crews and flight attendants conduct emergency evacuation drills together. Because the FAA did not require air carriers to conduct joint exercises with flight attendants and flight crews, the NTSB classified Safety Recommendation A-92-74 "Closed—Unacceptable Action." Also, as part of our June 2000 safety study on emergency evacuations of commercial airplanes, the NTSB issued Safety Recommendation A-00-85, which again asked the FAA to require air carriers to conduct periodic joint evacuation exercises involving flight and cabin crews. The FAA responded that that most air carriers did not conduct joint emergency evacuation exercises and that the agency would not require such exercises. As a result, the NTSB classified Safety Recommendation A-00-85 "Closed—Unacceptable Action."

[93] Before this point, the lead flight attendant and another flight attendant had met in the middle of the airplane, and then the lead flight attendant went forward, and the other flight attendant went aft. Thus, it is not known if all flight attendants were off the airplane at that time.

[94] The NTSB does not know how long it took for the captain to learn the occupant count after he called dispatch.

[95] No company guidance indicated when a captain should not perform a walk-through of the cabin. However, the American Airlines manager of flight training and standards stated that a walk-through of the cabin should only be done if it would not compromise the safety of a captain.

After evacuating the airplane, the flight crew was responsible for helping assemble passengers away from the airplane, and the captain had the additional responsibility to ensure that at least one crewmember remained with the passengers. According to postaccident interviews, this was not done.

Although the captain was unable to verify that everyone was off the airplane due to smoke in the cabin, the captain's priority, after leaving the airplane, should have been to ascertain this information. However, the American Airlines *B767 Operations Manual, QRH* did not specify these postevacuation duties nor was there training that emphasized these duties. If these duties had been specified and trained, the captain might have been more likely to obtain an accurate passenger count from the flight attendants. Coordinating with flight attendants about the passenger count would have ensured, before ARFF personnel conducted its walk-though of the cabin, that all passengers were safely off the airplane or would have allowed ARFF to be promptly notified if the passenger count did not match the information provided by dispatch.

The American Airlines *B767 Operations Manual, QRH* stated that a concurrent flight attendant evacuation duty, after leaving the airplane, was to make a count and report it to the captain. The NTSB found no evidence indicating that the flight attendants accomplished this duty.

Even though this situation did not result in any adverse outcomes, the NTSB concludes that the flight crewmembers and flight attendants did not coordinate in an optimal manner once the passengers were evacuated.

2.3.4 Carry-On Baggage Issue

Video taken during the evacuation and postaccident interviews with flight attendants indicated that some passengers evacuated from all three usable exits with carry-on baggage. In one case, a flight attendant tried to take a bag away from a passenger who did not follow the instruction to evacuate without baggage, but the flight attendant realized that the struggle over the bag was prolonging the evacuation and allowed the passenger to take the bag. In another case, a passenger came to the left overwing exit with a bag and evacuated with it despite being instructed to leave the bag behind.

Passengers evacuating airplanes with carry-on baggage has been a recurring concern. In our June 2000 safety study on emergency evacuations of commercial airplanes, the NTSB stated that flight attendants had reported that their attempts to maintain a constant flow of passengers out an emergency exit "were often thwarted by passengers' insistence on retrieving their carry-on luggage before evacuating." Most recently, video from the British Airways event in Las Vegas and the Dynamic International Airways event in Fort Lauderdale showed passengers who evacuated with carry-on baggage despite the standard instruction to leave their baggage and similar items behind in the event of an emergency.

Flight attendants are trained to instruct passengers not to evacuate with carry-on baggage because doing so could potentially slow the egress of passengers during an evacuation and block an exit during an emergency. Although the NTSB's June 2000 safety study found that passengers exiting with carry-on baggage was "the most frequently cited obstruction to evacuation," the NTSB has not identified any accident evacuations in which delays related to carry-on baggage caused injuries. Also, the NTSB is not aware of any study performed to (1) measure the potential delays associated with passengers retrieving and carrying baggage during an emergency evacuation and (2) determine the appropriate countermeasures to mitigate any related potential safety risks.

As a result of findings from our safety study on emergency evacuations of commercial airplanes, the NTSB issued Safety Recommendation A-00-88, which asked the FAA to “develop advisory material to address ways to minimize the problems associated with carry-on luggage during evacuations.” In January 2002, the NTSB classified the recommendation “Closed—Acceptable Action” because the FAA had revised Order 8400.10 to direct POIs to encourage their assigned certificate holders to provide, in crewmember manuals and training programs, clear direction and guidance to minimize the problems associated with passengers evacuating with carry-on baggage during emergencies. (This information was subsequently incorporated into FAA Order 8900.1.)

In addition, AC 121-24C, “Passenger Safety Information, Briefing and Briefing Cards,” provides guidance to Part 121 carriers regarding the items that should be included in oral passenger briefings and on passenger briefing cards. Specifically, Appendix 1 states that oral briefings must be supplemented with briefing cards and that the content of the briefing cards should, among other things, “inform passengers that in an emergency situation, they should not bring carry-on baggage to the exit.” Further, AC 121-29B, “Carry-On Baggage,” states, in paragraph (k), that air carriers should provide training to all crewmembers regarding the carrier’s approved carry-on baggage program, including how to handle carry-on baggage during an emergency.

Although the FAA took action in response to Safety Recommendation A-00-88 to preclude passengers from evacuating with carry-on baggage and provided further related guidance in ACs 121-24C and 121-29B, the NTSB concludes that evidence of passengers retrieving carry-on baggage during this and other recent emergency evacuations demonstrates that previous FAA actions to mitigate this potential safety hazard have not been effective. Therefore, the NTSB recommends that the FAA conduct research to (1) measure and evaluate the effects of carry-on baggage on passenger deplaning times and safety during an emergency evacuation and (2) identify effective countermeasures to reduce any determined risks, and implement the countermeasures. The NTSB notes that the FAA’s Civil Aerospace Medical Institute has facilities, including a simulator with overhead bins, that would enable such research.

2.4 High-Pressure Turbine Stage 2 Disk Failure

As previously stated, the NTSB determined that the HPT stage 2 disk failed because of multiple low-cycle fatigue cracks that initiated from a discrete dirty white spot that was located near the forward bore region of the disk. The discrete dirty white spot formed during the processing of the alloy 718 ingot from which the disk was manufactured. The ingot was produced using ATI SM’s triple-melt process. The three steps of this process were vacuum induction melting (also referred to as the master heat), which established the alloy chemistry; electroslag remelting, which established the alloy cleanliness; and vacuum arc remelting, which established the alloy macrostructure. The ingot that was formed during this process then underwent a mechanical and thermal conversion process to create the billet, from which the final forged disk was produced.

A discrete dirty white spot is a known anomaly associated with the vacuum arc remelting process. The stringers of oxide and nitride particles associated with a discrete dirty white spot are known to act as initiation sites for fatigue cracks, significantly reducing the low-cycle fatigue life of alloy 718 (Jackman et al. 1994). The NTSB considered whether the discrete dirty white spot and the low-cycle fatigue cracks could have been detected during inspections, as discussed in sections 2.4.1 and 2.4.2. The NTSB also assessed the adequacy of FAA guidance about design precautions to minimize rotor burst hazards, as discussed in section 2.4.3.

2.4.1 Discrete Dirty White Spot Detection During Manufacturing

During the billet conversion process, the coarse grain structure of the ingot material is replaced by a fine grain structure. The large strains associated with the conversion process typically cause cracks and/or voids between stringers and the surrounding material. Ultrasonic inspections are performed to detect cracks and/or voids after the billet conversion process is completed.

In 1997, as part of the billet conversion process, ATI SM inspected the billet from which the final forged disk was produced. ATI SM conducted the inspection according to the requirements of a GE specification for ultrasonic inspections of billets. A comparison of the inspection requirements with ATI SM's ultrasonic test data (shown on the ultrasonic billet map sheet for Master Heat FA94) indicated that ATI SM's inspection was consistent with the required inspection procedures and that ATI SM's calibration of the equipment also met requirements.[96] ATI SM detected no anomalies during its ultrasonic inspection of the billet involved in this event, as shown by the ultrasonic billet map sheet for FA94-2. As of November 2017, ATI SM used the same ultrasonic technique and type of equipment to inspect billets.

MTU performed an ultrasonic inspection in 1998 after forging and before final machining. MTU inspected "sonic-shape" forged pieces using the company's work instructions for ultrasonic inspections, which GE approved. These instructions were consistent with a different GE specification for ultrasonic inspections than the one that ATI SM used.[97] GE's comparison of its inspection requirements with MTU's inspection records found that MTU's inspection was consistent with GE's inspection procedures. MTU found no anomalies during the ultrasonic inspection of the forged pieces that became the HPT stage 2 disk.

The ultrasonic techniques that ATI SM and MTU used during the manufacturing of the HPT stage 2 disk are consistent with the current industry standard for the inspection of nickel-based alloys. Such techniques have been effective in detecting anomalies in nickel-based alloys. The uncontained engine failure at ORD was the first failure of a GE nickel-based alloy 718 part due to a melt-related anomaly (the discrete dirty white spot). Also, according to the FAA, this event was the only occurrence in US commercial aviation of a triple-melt-related anomaly that resulted in a cracked or fractured part involving alloy 718.

[96] As previously stated, an ultrasonic billet map provides the location of any rejectable indications, nonrejectable indications, and areas where rejectable indications were cut out of the material.

[97] Although ATI SM and MTU used different GE specifications to conduct their ultrasonic inspections, both specifications were essentially identical regarding inspector qualifications, calibration standards and schedules, and reject thresholds, with only minor differences between the specifications noted.

During the mid-1990s, GE required the use of a triple-melt process for all its critical life-limited rotating parts manufactured with alloy 718. This and other manufacturing improvements since that time have been effective in reducing the overall number of anomalies detected during inspections. When an anomaly is detected, the material or part is not put into service. However, an FAA report on turbine rotor material design stated that "a number of rotor disk fracture and cracking events have originated from embedded anomalies, which…were undetected by production inspections" (FAA 2008). These anomalies, referred to as "stealth anomalies," included those that were "ductile and well bonded, making them less likely to have cracking and voiding during ingot and billet conversion." The report also stated that the lack of cracking and voiding, along with a similar density as the parent material, made this type of anomaly "indistinguishable from the parent alloy for sonic detection." In addition, the report stated that such anomalies "form a zone of material that is substantially weaker in tensile and fatigue capability than base metal."

This anomaly description is consistent with the anomaly (the discrete dirty white spot) found in the HPT stage 2 disk. Specifically, metallurgical examinations noted the lack of cracking and voids between the discrete dirty white spot and the parent (base) material; the discrete dirty white spot and the parent material had similar densities; and the fatigue cracks initiated at the interface of the discrete dirty white spot and the parent material, consistent with an area that is "substantially weaker in tensile and fatigue capability than base metal."

Given the history of effective manufacturing and inspection of alloy 718 triple-melt parts (one related in-service event in the United States since the mid-1990s), the similarity between the discrete dirty white spot on the HPT stage 2 disk and the description of a stealth anomaly, and the improbability that two independent manufacturing facilities did not detect the anomaly during separate ultrasonic inspections, the NTSB concludes that the discrete dirty white spot was most likely not detectable by the inspection methods used during production of the HPT stage 2 disk.

Some of the recommendations issued in response to the July 1989 United Airlines flight 232 accident in Sioux City have relevance to the circumstances of the American Airlines flight 383 accident (even though the Sioux City accident involved a manufacturing defect on a fan disk made of titanium). For example, after the Sioux City accident, the NTSB issued Safety Recommendation A-90-167, which asked the FAA to do the following:

> Intensify research in the nondestructive inspection field to identify emerging technologies that can serve to simplify, automate, or otherwise improve the reliability of the inspection process. Such research should encourage the development and implementation of redundant ('second set of eyes') inspection oversight for critical part inspections, such as for engine rotating components.

In response to this recommendation, the FAA established the Engine Titanium Consortium in 1993 to provide the FAA and engine manufacturers with "reliable and cost-effective" new methods, and improvements in existing methods, for detecting cracks and other defects in titanium material and components. Phase I of the consortium's work completed in 1998, and Phase II of the consortium's work, which focused on critical rotating parts made of nickel alloys, began in mid-1999. In September 2005, the FAA issued a report about nickel billet inspections, which presented the results of the Phase II work. The report findings indicated that enhanced inspection techniques, such as multizone and phased array inspections, could better detect indications than the conventional ultrasonic inspection techniques that were in use at the time, which were also the same techniques that were used in 1997 and 1998 when the HPT stage 2 disk was manufactured. These conventional ultrasonic inspection techniques are still in use for inspecting nickel billets.

The FAA’s report stated that, during the Phase I program, the multizone and phased array inspection methods were successful in detecting the same indications in titanium billets and that the multizone inspection method was being used for the commercial inspection of titanium parts.[98] However, the report also stated that the phased array inspection for nickel billets was based on “the current best knowledge of how to perform the inspection” and that “future work is needed to optimize this technique” (FAA 2005). Further, it is unknown whether either enhanced inspection technique would have detected the discrete dirty white spot found during the investigation of this accident.

Given that more than 12 years have passed since the FAA issued its report on the Engine Titanium Consortium’s work, the NTSB concludes that additional FAA and industry efforts are needed to determine if enhanced ultrasonic inspection methods are a best practice for inspecting nickel parts during manufacturing. Therefore, the NTSB recommends that the FAA establish and lead an industry group that evaluates current and enhanced inspection technologies regarding their appropriateness and effectiveness for applications using nickel alloys, and use the results of this evaluation to issue guidance pertaining to the inspection process for nickel alloy rotating engine components.

2.4.2 American Airlines Inspection of High-Pressure Turbine Stage 2 Disk

American Airlines performed an ECI and an FPI of the right engine HPT stage 2 disk during maintenance (shop visits) in March 2007 and January 2011, as mandated by ADs 2002--07-12 and 2009-04-10, respectively. Although both inspection techniques are used to detect cracks on a material surface, an ECI can also detect near-surface defects. The ECI procedure inspects the disk surface to a depth of about 0.013 inch. Internal cracks at greater depths would be undetectable using the ECI procedure. Maintenance records showed that no anomalies, including cracks, were detected in the disk bore during the ECI in March 2007.

In January 2011, American Airlines maintenance personnel performed an ECI and an FPI of the forward bore region of the HPT stage 2 disk; between that time and the disk failure, the right engine accumulated 3,057 cycles. The NTSB and GE made low-cycle fatigue flight cycle count estimates for six cracks that initiated from the discrete dirty white spot. Two of those cracks (referred to as cracks 1 and 6, as shown in figure 12) progressed away from the region where the ECI was conducted. The other four cracks (also shown in figure 12) progressed inward toward the bore.

[98] In August 2017, GE reported that it used multizone inspection techniques for cast and wrought titanium billets and forgings and ultrasonic inspection techniques for nickel billets and forgings. Also in August 2017, the FAA reported that its specifications included multizone inspection techniques for titanium parts only at the billet level because of experience indicating that essentially all material defects were detected during billet inspections.

One crack that progressed inward toward the bore, referred to as crack 2, started at an internal stringer discontinuity and progressed inward and aft until disk failure, at which point the crack propagated due to overstress. The NTSB estimated that the length of crack 2 at the time of the January 2011 inspection was about 0.07 inch.[99] The forward innermost edge of the largest discontinuity was located about 0.14 inch from the inner bore surface. As a result, it is unlikely that crack 2 had breached the surface at the time of the HPT stage 2 disk's last inspection.

The other three cracks that progressed to the inner bore surface, referred to as cracks 3, 4, and 5, started at the discontinuity and ended at the surface. GE estimated that the length of cracks at the time of the January 2011 inspection was about 0.03 inch for cracks 3 and 4 and about 0.07 inch for crack 5. However, it was not possible to determine when those cracks reached the surface because they stopped progressing at that point. What is known, according to the low-cycle fatigue flight cycle count estimates, is that cracks 3, 4, and 5 initiated at least about 1,400, 1,200, and 3,200 cycles, respectively, before the disk failure.[100] If the cracks had reached the surface at the time of the January 2011 shop visit, they should have easily been detectable by ECI because the cracks would have extended through the depth of the ECI (0.013 inch). Thus, it is unlikely that cracks 3, 4, and 5 had progressed to the surface at the time of the HPT stage 2 disk's last inspection.

Operators' engine maintenance programs, as part of continued airworthiness efforts, are intended to establish inspection intervals for critical life-limited rotating parts to identify defects, including cracks, so that corrective action can be taken. However, the inspection techniques mandated by ADs 2002-07-12 and 2009-04-10 were techniques for detecting surface (FPI) and near-surface (ECI) cracks and other anomalies. The discrete dirty white spot was a subsurface anomaly, and ECI and FPI were not capable of detecting the cracks that emanated from the anomaly because the cracks remained below the material's surface when American Airlines inspected the disk during the engine's January 2011 maintenance. As a result, the NTSB concludes that the fatigue cracks that initiated from the discrete dirty white spot were not detectable at the time of the HPT stage 2 disk's last inspection using the surface-based inspection techniques mandated by the applicable AD.

No engine maintenance between January 2011 and the time of the accident involved disassembling the HPT stage 2 disk; thus, American Airlines did not have another opportunity to inspect the disk before the accident. The NTSB concludes that, if a subsurface inspection technique, such as an ultrasonic inspection, had been required at the time of the HPT stage 2 disk's last inspection, the cracks that developed from the discrete dirty white spot should have been detectable because of the size of the cracks at that time and the sensitivity of ultrasonic inspection techniques.

As previously stated, the discrete dirty white spot found in the material of the HPT stage 2 disk is an example of a possible stealth anomaly. The detection of such anomalies during in-service inspections is important because of the possibility that those anomalies will not be detected during

[99] To make this estimate, the NTSB used a mathematical formula that included the low-cycle fatigue cycle count (5,600 cycles) and the number of cycles since the last inspection (3,057 cycles).

[100] The right engine had accumulated 10,984 total cycles since new. Thus, crack 3 could have initiated between 0 and 9,584 cycles since new, crack 4 could have initiated between 0 and 9,784 cycles since new, and crack 5 could have initiated between 0 and 7,784 cycles since new.

the billet and forging manufacturing stages. Ultrasonic inspections could be appropriate for in-service maintenance because they would provide maintenance personnel with a method to detect cracks emanating from internal material anomalies below a material's surface. (Enhanced inspection techniques, such as multizone and phased array, are intended for use during the billet and forging manufacturing stages.)

In September 2017, the FAA issued an NPRM that proposed an AD mandating the ultrasonic inspection of HPT stage 1 and 2 disks of GE CF6-80-series turbofan engines, consistent with the requirements of GE SB 72-1562. The proposed AD would be an appropriate step for ensuring the continued airworthiness of airplanes with those engines.[101] However, stealth anomalies can also affect other engines. Because the potential for an internal material anomaly cannot currently be eliminated during the manufacturing process, effective in-service inspection methods are essential; ECI and FPI are only effective once cracks breach the surface of a material. Therefore, the NTSB recommends that the FAA require subsurface in-service inspection techniques, such as ultrasonic inspections, for critical high-energy, life-limited rotating parts for all engines.

2.4.3 Guidance on Design Precautions to Minimize Rotor Burst Hazards

In March 1988, the FAA issued AC 20-128, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure." The FAA revised the AC in March 1997 in response to Safety Recommendation A-90-170, which was issued as a result of the Sioux City accident.

AC 20-128A provided rotor burst and blade release fragment trajectory data so that airframe manufacturers could integrate appropriate design precautions to minimize hazards to an airplane and its occupants. In May 1999, the FAA issued a report that provided the results of the agency's large engine uncontained debris analysis. The report defined the debris size, weight, exit velocity, and trajectory and noted that this information could be used to update AC 20-128A. The report determined that the trajectories included in AC 20-128A were "too narrow" and needed to be "expanded significantly" and that the "highest hazard potential" to an aircraft during an uncontained engine event was the combined effect from multiple small fragment impacts (and not a single impact). In addition, an FAA working group was tasked, in November 2001, to revise AC 20-128A, but this work ceased after a moratorium was imposed 1 year later (see section 1.6.6.1).

The Australian Transportation Safety Board (ATSB) issued a recommendation to the FAA resulting from its investigation of the November 4, 2010, accident involving an Airbus A380 that experienced an uncontained intermediate-pressure turbine disk rupture in a Rolls-Royce

[101] GE and ATI SM conducted a study of discrete dirty white spot samples from an alloy 718 billet produced between October 2014 and April 2017. These discrete dirty white spot samples, which were detected by ultrasonic inspection, were compared with the structure and characteristics of the discrete dirty white spot found on the HPT stage 2 disk from the accident airplane. The sample anomalies and the anomaly from the HPT stage 2 disk had similar structures and features except that at least one sample had voids/cracks along stringers. Even though no voids/cracks along stringers were found on the discrete dirty white spot associated with this accident, GE and ATI SM determined that voids/cracks along stringers could provide a reflection surface that is conducive to ultrasonic detection.

Trent 900 engine.[102] According to the ATSB, the failure in the No. 2 engine sent engine disk fragments through the left wing, which damaged some of the airplane's systems. Safety Recommendation AO-2010-089-SR-040 asked the FAA to do the following:[103]

> In cooperation with the European Aviation Safety Agency, review the damage sustained by Airbus A380-842, VH-OQA following the uncontained engine rotor failure overhead Batam Island, Indonesia, to incorporate any lessons learned from this accident into the advisory material.

The final report on the accident, issued in June 2013, stated that the amount of damage to the airplane resulting from the uncontained engine rotor failure "was greater than the modelling outlined in the advisory material," which provided a means of compliance with airframe certification standards. The advisory material included AC 20-128A.

In a December 2016 letter to the ATSB, the FAA stated that it was evaluating uncontained engine failure events, including the event referenced in the ATSB's recommendation, to understand the "failure effects" of these events. The FAA also stated that it would use that information to update AC 20-128A. The FAA further stated that its Technical Center tasked the US Naval Air Station China Lake to (1) update the uncontained engine debris model defined in the FAA's 1999 report on its large engine uncontained debris analysis and (2) develop computer modeling of more recent uncontained engine failures. The FAA indicated that a draft revision to AC 20-128A was expected by the end of 2016 and that it would provide the ATSB, by June 30, 2017, with an update of actions related to the recommendation. In August 2017, the FAA requested an extension to November 6, 2017, for responding to the ATSB. On December 6, 2017, the FAA responded to the ATSB, indicating that a draft revision of AC 20-128A was expected by the end of 2018.

During the 20 years since AC 20-128A was issued, the NTSB has investigated, participated in the investigation of, or become aware of at least 40 uncontained rotor burst events in addition to the one referenced in the ATSB's safety recommendation.[104] Also, AIA has a database of rotor burst events involving high-bypass turbofan engines that includes events between 1997 (the time that the AC was last updated) and 2006.[105] The lessons learned from all of these events would result in more robust guidance, including updated trajectory analyses, for airframe manufacturers to use when considering design mitigations for minimizing hazards resulting from uncontained engine failures.

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[102] For more information about this accident, including the final report, see "In-flight uncontained engine failure Airbus A380-842, VH-OQA, overhead Batam Island, Indonesia, 4 November 2010" at the ATSB's website (accessed January 10, 2018).

[103] ATSB Safety Recommendation AO-2010-089-SR-039 recommended that the European Aviation Safety Agency, in cooperation with the FAA, take the same action as requested in AO-2010-089-SR-040.

[104] This number was derived from a review of the NTSB's engine investigations as well as information from Boeing and engine manufacturers.

[105] AIA's database for high-bypass turbofan engines included events from 1969 to 2006. As stated in section 1.7.3.1, in January 2010, AIA issued a report describing uncontained rotor events involving high-bypass ratio turbine engines, which was based on data from the association's rotor burst database. AIA's report stated that these data could be used by "airplane designers and regulatory authorities to gain a common understanding of the rotor uncontainment threat."

AC 20-128A contains specific information about accepted design precautions to follow to reduce the overall risk of an uncontrolled fire if fuel tanks are located in impact areas. Specifically, the information stated that "dry bays or shielding" was an acceptable means of protection from the effects of fuel leakage for any fuel tanks "located above an engine or APU and within the one-third disc and intermediate fragment impact areas." The guidance also stated that the dry bays should be sized based on the manufacturer's analysis of "possible fragment trajectories through the fuel tank wall and the subsequent fuel leakage from the damaged fuel tank" so that fuel will not travel to an engine during in-flight or ground operations. The guidance further stated that a minimum drip clearance distance of 10 inches from potential ignition sources of the engine nacelle, for static conditions, would be acceptable.

Even though the size of the right wing dry bay and the drip clearance distance on the flight 383 accident airplane (a Boeing 767-300) were consistent with this guidance, the uncontained engine failure resulted in a subsequent fire. Postaccident examination of the airplane's right wing revealed that an HPT stage 2 disk fragment (later identified as disk fragment A) penetrated the lower surface of the right wing beneath the dry bay, resulting in a hole in the dry bay.[106] Disk fragment A also severed the main engine fuel feed line and caused a large breach and multiple small breaches between the dry bay and the fuel tank, which allowed fuel to flow into the dry bay and out of the hole of the wing. Video showed that a fire had already begun on the right side of the airplane as the airplane decelerated to a stop (as a result of the rejected takeoff). Although the quantity of fuel that spilled out of the wing as the airplane decelerated could not be determined, the released amount ignited, resulting in a fire that (1) damaged the right wing and its flight control surfaces, the right main landing gear, the right-side fuselage, and the right stabilizer and (2) caused the cabin to fill with smoke.[107]

Also, the NTSB investigated a September 2000 accident in which an uncontained engine failure on a Boeing 767-200 resulted in a subsequent fire.[108] In that accident, the size of the dry bay in the main fuel tanks and the drip clearance distance were also consistent with the guidance in AC 20-128A. Thus, the accepted design precautions in AC 20-128A to reduce the risk of an uncontrolled fire for fuel tanks located in impact areas did not adequately minimize the hazards to the 767-200 and -300 airplanes from an uncontained engine failure.

The NTSB concludes that future aircraft certification efforts would benefit from guidance on uncontained engine failure debris models and resulting design mitigations that is based on lessons learned from recent in-service events. Therefore, the NTSB recommends that the FAA revise AC 20-128A, based on an analysis of uncontained engine failure data since the time that the AC was issued, to minimize hazards to an airplane and its occupants if an uncontained engine

[106] The hole was triangular shaped and had an area of about 70 square inches.

[107] About 2,040 gallons of fuel was released from the right main fuel tank through the hole in dry bay, but the NTSB could not determine the portion of the fuel that was released before, during, and after the deceleration.

[108] On September 22, 2000, a US Airways Boeing 767-2B7 airplane, N654US, equipped with GE CF6-80C2B2 engines, experienced an uncontained failure of the HPT stage 1 disk in the No. 1 (left) engine at Philadelphia International Airport, Philadelphia, Pennsylvania, during a high-power ground run performed as part of maintenance. For more information about this accident, see the letter transmitting Safety Recommendations A-00-121 through -124 at the NTSB's website.

failure were to occur. The revised AC should include modifications to the accepted design precautions for fuel tanks given the fires that have occurred after uncontained engine failures.

3. Conclusions

3.1 Findings

1. The flight crew was properly certificated and qualified in accordance with federal regulations and company requirements. A review of the flight crew's work and sleep schedules and recent activities showed no evidence of factors that could have adversely affected the performance of either crewmember on the day of the accident.

2. The airplane was properly certificated, equipped, and maintained in accordance with federal regulations. No evidence indicated any structural, engine, or system failures before the uncontained engine failure occurred.

3. The right engine experienced an uncontained high-pressure turbine (HPT) stage 2 disk rupture during the takeoff roll. The HPT stage 2 disk initially separated into two fragments. One fragment penetrated through the inboard section of the right wing, severed the main engine fuel feed line, breached the fuel tank, traveled up and over the fuselage, and landed about 3,000 ft away. The other fragment exited outboard of the right engine, impacting the runway and fracturing into three pieces.

4. The high-pressure turbine stage 2 disk failed because of multiple low-cycle fatigue cracks that initiated from an internal material anomaly, known as a discrete dirty white spot, which formed during the processing of the material from which the disk was manufactured.

5. The discrete dirty white spot was most likely not detectable by the inspection methods used during production of the high-pressure turbine stage 2 disk.

6. Additional Federal Aviation Administration and industry efforts are needed to determine if enhanced ultrasonic inspection methods are a best practice for inspecting nickel parts during manufacturing.

7. The fatigue cracks that initiated from the discrete dirty white spot were not detectable at the time of the high-pressure turbine stage 2 disk's last inspection using the surface-based inspection techniques mandated by the applicable airworthiness directive.

8. If a subsurface inspection technique, such as an ultrasonic inspection, had been required at the time of the high-pressure turbine stage 2 disk's last inspection, the cracks that developed from the discrete dirty white spot should have been detectable because of the size of the cracks at that time and the sensitivity of ultrasonic inspection techniques.

9. Future aircraft certification efforts would benefit from guidance on uncontained engine failure debris models and resulting design mitigations that is based on lessons learned from recent in-service events.

10. The captain made a timely decision to reject the takeoff and performed the maneuver in accordance with company training and procedures.

11. The captain's decision to perform the engine fire checklist was appropriate given his training, the information provided by air traffic control, and the fire warnings in the cockpit.

12. Engine fire checklists that specifically address ground operations would allow a flight crew to secure an engine and command an evacuation, if required, in a timelier manner than engine fire checklists that do not differentiate between ground and in-flight operations.

13. The flight attendants made a good decision to begin the evacuation given the fire on the right side of the airplane and the smoke in the cabin, but the left overwing exit should have been blocked while the left engine was still operating because of the increased risk of injury to passengers who evacuated from that exit.

14. If the flight crew or the flight attendants had communicated after the airplane came to a stop, the flight crew could have become aware of the severity of the fire on the right side of the airplane and the need to expeditiously shut down the engines.

15. American Airlines did not adequately train flight attendants qualified on the Boeing 767 to effectively use the different interphone system models installed on the airplane during an emergency.

16. The Federal Aviation Administration's inadequate actions to improve guidance and training on communication and coordination between flight and cabin crews during emergency situations, including evacuations, could lead to negative consequences for the traveling public if this safety issue continues to be unresolved.

17. The flight crewmembers and flight attendants did not coordinate in an optimal manner once the passengers were evacuated.

18. Evidence of passengers retrieving carry-on baggage during this and other recent emergency evacuations demonstrates that previous Federal Aviation Administration actions to mitigate this potential safety hazard have not been effective.

3.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of this accident was the failure of the high-pressure turbine (HPT) stage 2 disk, which severed the main engine fuel feed line and breached the right main wing fuel tank, releasing fuel that resulted in a fire on the right side of the airplane during the takeoff roll. The HPT stage 2 disk failed because of low-cycle fatigue cracks that initiated from an internal subsurface manufacturing anomaly that was most likely not detectable during production inspections and subsequent in-service inspections using the procedures in place. Contributing to the serious passenger injury was (1) the delay in shutting down the left engine and (2) a flight attendant's deviation from company procedures, which resulted in passengers evacuating from the left overwing exit while the left engine was still operating. Contributing to the delay in shutting down the left engine was (1) the lack of a separate checklist procedure for Boeing 767 airplanes that specifically addressed engine fires on the ground and (2) the lack of communication between the flight and cabin crews after the airplane came to a stop.

4. Recommendations

4.1 New Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following new safety recommendations:

To the Federal Aviation Administration:

> Establish and lead an industry group that evaluates current and enhanced inspection technologies regarding their appropriateness and effectiveness for applications using nickel alloys, and use the results of this evaluation to issue guidance pertaining to the inspection process for nickel alloy rotating engine components. (A-18-3)
>
> Require subsurface in-service inspection techniques, such as ultrasonic inspections, for critical high-energy, life-limited rotating parts for all engines. (A-18-4)
>
> Revise Advisory Circular (AC) 20-128A, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure," based on an analysis of uncontained engine failure data since the time that the AC was issued, to minimize hazards to an airplane and its occupants if an uncontained engine failure were to occur. The revised AC should include modifications to the accepted design precautions for fuel tanks given the fires that have occurred after uncontained engine failures. (A-18-5)
>
> When approving the operating procedures of a 14 *Code of Federal Regulations* Part 121 air carrier, require operators to develop and/or revise emergency checklist procedures for an engine fire on the ground to expeditiously address the fire hazard without unnecessarily delaying an evacuation. (A-18-6)
>
> Develop and issue guidance to all air carriers that conduct passenger-carrying operations under 14 *Code of Federal Regulations* Part 121 regarding (1) discussing this accident during recurrent flight attendant training to emphasize the importance of effectively assessing door and overwing exits during an unusual or emergency situation and (2) providing techniques for identifying conditions that would preclude opening exits, including an operating engine. (A-18-7)
>
> Review the training programs of all 14 *Code of Federal Regulations* Part 121 operators and make changes as necessary to ensure that the programs provide flight attendants and flight crews with training aids and hands-on emergency scenarios that account for the different interphone systems that air carriers operate. (A-18-8)
>
> Conduct research to (1) measure and evaluate the effects of carry-on baggage on passenger deplaning times and safety during an emergency evacuation and

(2) identify effective countermeasures to reduce any determined risks, and implement the countermeasures. (A-18-9)

To Boeing:

Work with operators as required to develop and/or revise emergency checklist procedures for an engine fire on the ground to expeditiously address the fire hazard without unnecessarily delaying an evacuation. (A-18-10)

To American Airlines:

For all airplanes that you operate, review existing engine fire checklists and make changes as necessary to ensure that the procedures would expeditiously address engine fires occurring on the ground without unnecessarily delaying an evacuation. (A-18-11)

4.2 Previously Issued Recommendations Reiterated in This Report

The National Transportation Safety Board reiterates the following recommendations to the Federal Aviation Administration:

Revise Advisory Circular 120-48, "Communication and Coordination Between Flight Crewmembers and Flight Attendants," to update guidance and training provided to flight and cabin crews regarding communications during emergency and unusual situations to reflect current industry knowledge based on research and lessons learned from relevant accidents and incidents over the last 20 years. (A-09-27)

Develop best practices related to evacuation communication, coordination, and decision-making during emergencies through the establishment of an industry working group and then issue guidance for 14 *Code of Federal Regulations* Part 121 air carriers to use to improve flight and cabin crew performance during evacuations. (A-16-26)

4.3 Previously Issued Recommendation Classified in This Report

Safety Recommendation A-16-26 is reclassified "Open—Unacceptable Response" in section 2.3.2.2 of this report.

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

ROBERT L. SUMWALT, III
Chairman

CHRISTOPHER A. HART
Member

T. BELLA DINH-ZARR
Member

Adopted: January 30, 2018

5. Appendixes

Appendix A: Investigation

The National Transportation Safety Board (NTSB) was notified about this accident immediately after it occurred. An NTSB investigator located in the Chicago, Illinois, area responded to the accident about 1500 on October 28, 2016, and, after arriving on scene shortly afterward, began gathering initial information and securing the accident site until investigators from NTSB headquarters in Washington, DC, arrived on scene later in the day. The following investigative groups were formed: airworthiness, operations/human performance, powerplants, and survival factors. Also, specialists were assigned to conduct the readout of the flight data recorder and transcribe the cockpit voice recorder at the NTSB’s laboratory in Washington, DC.

Parties to the investigation were the Federal Aviation Administration, the Boeing Company, American Airlines, the Allied Pilots Association, the Transport Workers Union of America, the Association of Professional Flight Attendants, General Electric, and ATI Specialty Materials.

Appendix B: Cockpit Voice Recorder Transcript

The following is a transcript of the L-3/Fairchild FA2100-1020 cockpit voice recorder, serial number 158589, installed on American Airlines flight 383, a Boeing 767-323, N345AN, which experienced an uncontained engine failure and subsequent fire during the takeoff ground roll at Chicago O'Hare International Airport, Chicago, Illinois, on October 28, 2016:

LEGEND

CAM	Cockpit area microphone voice or sound source
HOT	Flight crew audio panel voice or sound source
TWR	Radio transmission from O'Hare Tower controller
-1	Voice identified as the captain
-2	Voice identified as the first officer
-?	Voice unidentified
#	Expletive
[ ]	Editorial insertion

Note 1: Times are expressed in Central Daylight Time.

Note 2: Generally, only radio transmissions to and from the incident aircraft were transcribed.

Note 3: Words shown with excess vowels, letters, or drawn out syllables are a phonetic representation of the words as spoken.

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:30:29.4 **START OF TRANSCRIPT**			
		14:30:29.4 **TWR**	American three eighty three heavy runway two eight right at november five line up and wait. winds two zero zero at one four.
		14:30:33.5 **RDO-2**	line up and wait American three eighty three heavy.
14:30:35.6 **HOT-1**	okay checklist.		
14:30:36.4 **HOT-2**	map display?		
14:30:37.3 **HOT-1**	and checked at two eight right.		
14:30:40.3 **HOT-2**	takeoff PA?		
14:30:41.2 **HOT-1**	complete.		
14:30:42.3 **HOT-2**	packs?		
14:30:44.0 **HOT-1**	are auto.		
14:30:45.2 **HOT-2**	lights?		
14:30:46.2 **HOT-1**	set.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:30:46.6 **HOT-2**	checklist complete.		
		14:30:57.2 **TWR**	American three eighty three heavy turn left heading two two zero runway two eight right at november five cleared for takeoff.
14:31:00.5 **CAM**	[sound of five clicks, similar to light switches]		
		14:31:02.5 **RDO-2**	left turn to two two zero cleared for takeoff American three eighty three heavy.
14:31:06.5 **HOT-1**	cleared for takeoff two twenty heading.		
14:31:17.1 **HOT-1**	and engage.		
14:31:19.2 **CAM**	[sound similar to engine rpm increase]		
14:31:19.6 **HOT-2**	clock's running.		
14:31:24.8 **HOT-2**	thrust set.		
14:31:32.0 **HOT-2**	eighty knots.		
14:31:32.8 **HOT-1**	checked.		
14:31:43.5 **CAM**	[sound of bang]		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:31:44.4 **HOT-1**	whoa.		
14:31:44.7 **CAM**	[sound of click, similar to throttles contacting idle stops]		
14:31:45.1 **CAM**	[sound similar to engine rpm decrease]		
		14:31:50.0 **RDO-2**	American three eighty three heavy stopping on the runway.
		14:31:52.4 **TWR**	roger roger. fire.
14:31:54.0 **CAM**	[sound of two clicks]		
		14:31:56.2 **RDO-2**	do you see any smoke or fire?
14:31:57.0 **HOT**	[sound similar to master caution]		
		14:31:58.0 **TWR**	yeah fire off the right wing.
		14:31:59.7 **RDO-2**	okay send out the trucks.
14:31:59.9 **CAM**	[sound similar to engine fire warning]		
		14:32:02.1 **TWR**	sending em.
14:32:04.1 **HOT-1**	okay let's run the uh checklist.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:32:04.4 **HOT-2**	alright.		
14:32:06.7 **HOT-2**	checklist.		
14:32:06.9 **HOT-1**	we can shut it—		
14:32:08.3 **HOT-2**	just shut it down and get— pull the handle?		
14:32:09.4 **CAM**	[sound similar to engine fire warning]		
14:32:10.6 **HOT-1**	pull it yeah.		
14:32:11.2 **CAM**	[sound of click, similar to fire handle being pulled]		
14:32:11.8 **CAM**	[sound similar to engine fire warning]		
14:32:12.9 **CAM**	[sound of three clicks]		
14:32:15.6 **HOT-2**	checklist for engine fire.		
		14:32:17.9 **TWR**	American three eighty three can you give us any information right now?
14:32:17.9 **HOT-1**	#.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:32:21.3 **CAM**	[sound similar to engine fire warning]		
		14:32:23.4 **RDO-2**	uh stand by.
14:32:25.9 **CAM**	[sound similar to master caution]		
14:32:26.0 **HOT-2**	just the—		
14:32:28.3 **CAM-2**	engine fire severe damage.		
14:32:30.7 **CAM**	[sound similar to engine fire warning]		
14:32:31.0 **HOT-2**	*.		
14:32:32.5 **HOT-2**	okay.		
14:32:32.9 **HOT-1**	you didn't— you didn't fire the bottle.		
14:32:34.6 **HOT-1**	did ya?		
14:32:34.9 **HOT-2**	I did. I pushed it twice.		
14:32:35.6 **CAM**	[sound of click]		
14:32:35.7 **HOT-1**	which one?		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:32:36.3 **HOT-2**	oh I didn't twist it. there we go.		
14:32:36.5 **CAM**	[sound of click]		
14:32:37.3 **HOT-1**	oh.		
14:32:38.2 **HOT-2**	okay.		
14:32:39.1 **CAM**	[sound of two whooshing sounds]		
14:32:40.2 **CAM**	[sound similar to engine fire warning]		
14:32:40.9 **HOT-2**	alright.		
14:32:40.9 **CAM-1**	oh look at the smoke— check out the smoke.		
14:32:41.7 **HOT-1**	[sound of rustling noise, similar to headset being moved]		
14:32:42.6 **HOT-2**	okay.		
14:32:44.0 **HOT-2**	uhh.		
14:32:45.2 **CAM-1**	do the evacuation checklist.		
14:32:46.6 **HOT-2**	okay evacuation checklist.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:32:49.2 **CAM-1**	#.		
14:32:49.7 **CAM**	[sound similar to engine fire warning]		
14:32:53.4 **HOT-1**	okay I'm going both ways. go.		
14:32:54.8 **HOT-2**	okay.		
14:32:55.1 **HOT-1**	go.		
14:32:55.5 **HOT-2**	parking brake set?		
14:32:56.5 **HOT-1**	set.		
14:32:57.3 **HOT-2**	cabin altitude mode selector manual?		
14:32:59.2 **CAM**	[sound similar to engine fire warning]		
14:33:00.8 **HOT-1**	okay.		
14:33:01.1 **HOT-2**	uh cabin altitude control hold in climb.		
14:33:05.2 **HOT-1**	okay. what about the—		
14:33:06.7 **HOT-2**	fuel control switches both cutoff.		

TIME and SOURCE	INTRA-COCKPIT COMMUNICATION CONTENT	TIME and SOURCE	AIR-GROUND COMMUNICATION CONTENT
14:33:06.9 **CAM**	[sound similar to master caution]		
14:33:08.6 **CAM**	[sound similar to engine fire warning]		
14:33:09.7 **HOT-2**	PA evac this is the captain—		
14:33:11.0 **CAM**	[sound of thunk]		
14:33:11.7 **END OF TRANSCRIPT END OF RECORDING**			

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