National Transportation Safety Board
Aviation Accident Final Report

Location:	Fort Lauderdale, FL	**Accident Number:**	DCA17MA022
Date & Time:	10/28/2016, 1751 EDT	**Registration:**	N370FE
Aircraft:	MCDONNELL DOUGLAS MD 10-10F	**Aircraft Damage:**	Substantial
Defining Event:	Landing gear collapse	**Injuries:**	2 None
Flight Conducted Under:	Part 121: Air Carrier - Non-scheduled		

Analysis

On October 28, 2016, about 1751 eastern daylight time, FedEx Express (FedEx) flight 910, a McDonnell Douglas MD-10-10F, N370FE, experienced a left main landing gear (MLG) collapse after landing on runway 10L at Fort Lauderdale–Hollywood International Airport (KFLL), Fort Lauderdale, Florida, and the left wing subsequently caught fire. The airplane came to rest off the left side of the runway. As the flight crew was preparing to evacuate, the nearly empty left main fuel tank exploded after the exterior surfaces were heated by burning fuel, which flowed from a broken fuel supply tube in the left engine pylon. The two flight crewmembers evacuated the airplane, and the captain sustained minor injuries during the evacuation. The first officer was not injured. The airplane sustained substantial damage.

The first officer, who was the pilot flying the cargo flight, conducted an approach and landing that were stabilized and within specified limits. Although crosswind conditions were present at the time the airplane landed, the weather did not affect the landing. The application of braking by the flight crew did not initiate or contribute to the landing gear fracture. A review of the status of all applicable airworthiness directives and service bulletins for the airplane, powerplants, and appliances found no discrepancies.

Metallurgical examination of a 3-by-3-inch fragment of the left MLG cylinder (see images B and C in figure 1) and the mating fracture region on the largest piece of the fractured left MLG (see figure 2) found indications consistent with overstress fracture having emanated from the air filler valve bore. The overstress features emanated from a small thumbnail crack, located at the radius between the cylinder inner diameter surface and the air filler valve bore surface. This thumbnail crack was observed on both mating fracture surfaces of the MLG and the 3-by-3-inch fragment, and it exhibited features (such as crack arrest marks) consistent with a pre-existing crack that progressed to fracture of the MLG. The observed features in the initiation region of the thumbnail crack were found to be consistent with fatigue cracking, as exhibited by the fatigue striations observed during microscopic examination. Later propagation regions of the thumbnail crack revealed features consistent with mixed mode fatigue, overstress, and intergranular fracture. These findings confirmed that once the crack progressed to a critical length, the left MLG cylinder fractured in overstress due to the loads imposed during landing.

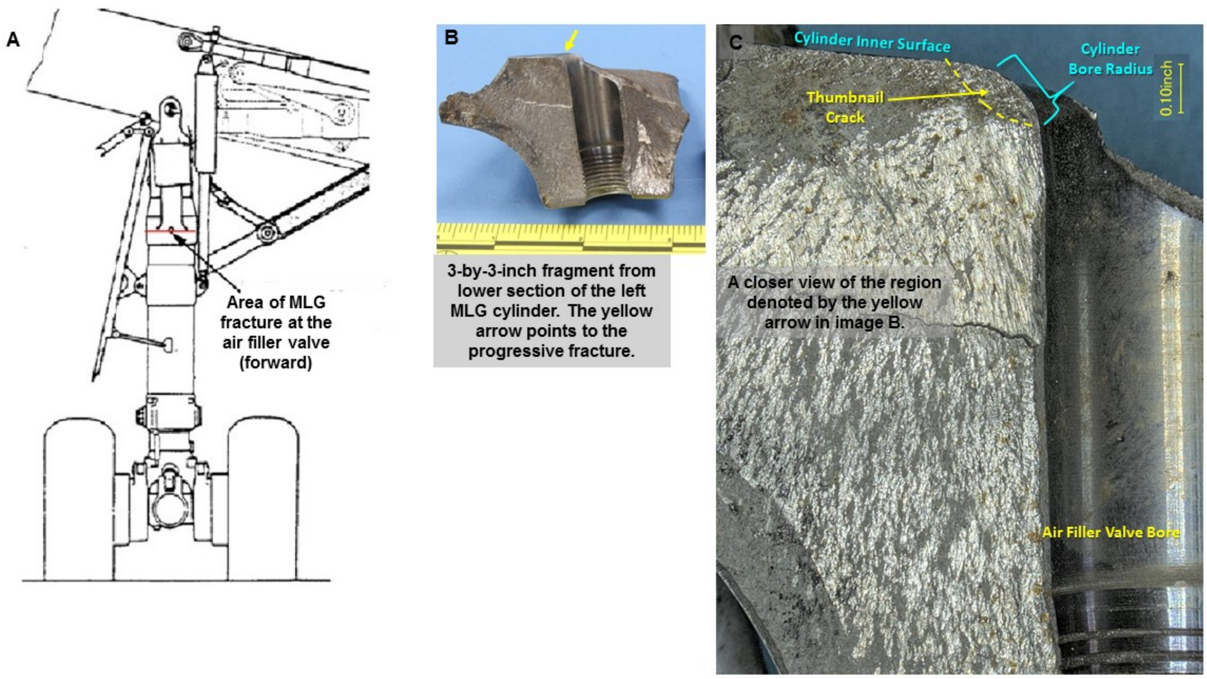

Figure 1. A diagram of an MD-10-10F left MLG (A), photograph of the 3-by-3-inch fragment from the lower section of the accident left MLG cylinder (B), and closer view of the region pointed out in image B (C).

Figure 2. Photographs of largest piece of fractured left MLG pointing to the crack initiation site (top) and a closer view of the crack initiation site, with a yellow dashed line highlighting the mating thumbnail crack (bottom).

The most prominent quality of the crack initiation site was a feature consistent with a corrosion pit. No indications of nickel, chrome, or cadmium plating were found at the radius or along the smooth sections of the air filler valve bore, as stipulated by maintenance instructions. The absence of a protective coating, over time, could lead to corrosion pitting. Any corrosion pitting or mechanical damage to the protective coating incurred during maintenance can lead to fatigue cracking.

Figure 3. Closer view of the primary fatigue crack region (highlighted by the dashed yellow line) and the region of mixed-mode crack propagation (highlighted by the dashed blue line).

The MLG's last overhaul was completed on February 28, 2008, during which the air filler valve bore was inspected per Alert Service Bulletin (ASB) DC10-32A259. This ASB (which was prompted by an MLG collapse on a FedEx MD-10-10F in 2006 and indicated that stray plating, if present, can enhance local corrosion under the edge of the plating in and around the bore) instructed operators to inspect the air filler valve bore for stray nickel or chrome electroplating deposits, corrosion, or cracks to prevent fatigue failure of the cylinder. Although neither stray plating nor cracks were found as part of the ASB inspection, corrosion repair was completed on the accident cylinder, and it underwent brush cadmium plating per maintenance instructions before being returned to service.

It was not possible to determine whether cadmium plating applied during the last overhaul did not properly bond to the bore surface, was removed during later maintenance, or wore off over time because there is no routine procedure to effectively inspect this area during on-wing maintenance activities conducted since the last MLG overhaul. To be effective, it is critical that a protective coating be uniform, adherent, and complete when applied in areas known to be susceptible to pitting corrosion. Finite element analysis of this MLG cylinder (conducted using the same method, tools, and format as those used in the investigation of the 2006 event) concluded that residual stress levels at the corrosion pit were sufficiently high to promote crack propagation leading to full fracture of the cylinder barrel. Since the accident, the maintenance facility that performed the last MLG cylinder overhaul has introduced a tank dip method for plating air filler valve bores, which provides improved uniformity, adherence, and coverage over the brush plating method.

The manufacturer-recommended overhaul limit for the MLG assembly is every 8 years or 7,500 flight cycles, whichever occurs first. At the time of the accident, FedEx's MLG overhaul limit was 9 years or 30,000 flight hours, whichever occurred first, and the left MLG outer cylinder on the accident airplane was 152 days away from its next required overhaul. FedEx reportedly adopted the 9-year overhaul interval used by the previous owner/operator of the first DC10s it purchased. The company produced no documentation or data analysis supporting the longer overhaul interval.

Following this accident, FedEx inspected all MLGs in its MD-10-10F fleet (27 in-service airplanes and 54 MLG). Sixteen cylinders were identified as "concerns" and were permanently removed from service. After reviewing its maintenance program, FedEx reverted to an 8-year overhaul limit for MLG cylinders, as recommended by the manufacturer. The NTSB notes that if FedEx had not adopted an overhaul limit that exceeded the manufacturer's recommendation, the fatigue crack in the accident MLG cylinder, which was last overhauled 8.5 years before the accident, likely would have been detected and addressed before it could progress to failure.

Probable Cause and Findings

The National Transportation Safety Board determines the probable cause(s) of this accident to be:

The failure of the left main landing gear (MLG) due to fatigue cracking that initiated at a corrosion pit. The pit formed in the absence of a required protective cadmium coating the cause of which could not be determined from available evidence. Contributing to the failure of the left MLG was the operator's overhaul limit, which exceeded that recommended by the airplane manufacturer without sufficient data and analysis to ensure crack detection before it progressed to failure.

Findings

Aircraft	Main landing gear - Fatigue/wear/corrosion (Cause) Main landing gear - Inadequate inspection (Factor)
Organizational issues	Adequacy of policy/proc - Operator (Factor)

Factual Information

History of Flight

Prior to flight	Miscellaneous/other
Landing-landing roll	Landing gear collapse (Defining event) Runway excursion
Post-impact	Fire/smoke (post-impact) Explosion (post-impact)

On October 28, 2016, about 1751 eastern daylight time, FedEx Express (FedEx) flight 910, a McDonnell Douglas MD-10-10F, N370FE, experienced a left main landing gear (MLG) collapse after landing on runway 10L at Fort Lauderdale–Hollywood International Airport (KFLL), Fort Lauderdale, Florida, and the left wing subsequently caught fire. The airplane came to rest off the left side of the runway. The two flight crewmembers evacuated the airplane. The captain reported a minor cut and abrasions from the evacuation, and the first officer was not injured. The airplane sustained substantial damage. The cargo flight was operating on an instrument flight plan under the provisions of Title 14 *Code of Federal Regulation* (*CFR*) Part 121 and originated at Memphis International Airport (KMEM), Memphis, Tennessee.

The first officer was the pilot flying, and the captain was the pilot monitoring. Both flight crewmembers stated in postaccident interviews that the departure from MEM and the en route portion of the flight were normal. About 1745, air traffic control (ATC) cleared the flight for final approach to the instrument landing system (ILS) approach to runway 10L at KFLL. Recorder data indicate that the first officer set the flaps at 35° about 1746 when the airplane was 3,000 ft above ground level (agl). The first officer disconnected the autopilot about 1749 when the airplane was 1,000 ft agl. Both flight crewmembers reported that the approach was stable at 500 ft agl. At 200 ft agl, the first officer began making airspeed corrections to compensate for the crosswind. About 1750, the first officer disconnected the autothrottles, as briefed, when the airplane was at 100 ft agl.

At 50 ft agl, the first officer initiated the flare. The left MLG touched down about 1750:31 in the touchdown zone and left of the runway centerline. The first officer deployed the spoilers at 1750:34, and the nose gear touched down 3 seconds later. The thrust reversers were deployed at 1750:40. According to cockpit voice recorder (CVR) data, the captain instructed the first officer to begin braking about 1750:39 (the airplane was not equipped with autobrakes). FDR data indicate an increase in brake pedal position angle and increase in longitudinal deceleration (indicating braking) about 1750:41. In postaccident interviews, the flight crewmembers reported hearing a "bang" as the first officer applied the brakes, and the airplane yawed to the left. About this time, the CVR recorded the sound of multiple thuds, consistent with the sound of a gear collapse.

About 1750:48, the captain stated, "I have the airplane," and the first officer replied, "you got the airplane." The captain applied full right rudder without effect while the first officer continued braking. About 1750:53, the captain instructed the first officer to call and inform the tower about the emergency.

An airport video of the landing showed that the No. 1 engine was initially supporting the airplane after the left MLG collapse when a fire began near the left-wing tip. The airplane eventually stopped off the left side of runway 10L, about 30° to 40° off the runway heading. About 1751, the flight crew began executing the evacuation checklist. The pilots reported that, as they were about to evacuate, they heard an explosion. The airport video showed a fireball erupted at the No. 1 engine. The captain attempted to discharge a fire bottle in the No. 1 engine, but it didn't discharge. They evacuated the airplane through the right cockpit window.

Pilot Information

Certificate:	Airline Transport	**Age:**	55, Male
Airplane Rating(s):	Multi-engine Land; Single-engine Land	**Seat Occupied:**	Left
Other Aircraft Rating(s):	None	**Restraint Used:**	5-point
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	Airplane Multi-engine; Airplane Single-engine	**Toxicology Performed:**	
Medical Certification:	Class 1 Without Waivers/Limitations	**Last FAA Medical Exam:**	06/16/2016
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	10/09/2016
Flight Time:	(Estimated) 10000 hours (Total, all aircraft), 1443 hours (Total, this make and model)		

Co-Pilot Information

Certificate:	Airline Transport	**Age:**	47, Male
Airplane Rating(s):	Single-engine Land	**Seat Occupied:**	Right
Other Aircraft Rating(s):	None	**Restraint Used:**	5-point
Instrument Rating(s):	Airplane	**Second Pilot Present:**	Yes
Instructor Rating(s):	None	**Toxicology Performed:**	
Medical Certification:	Class 1 Without Waivers/Limitations	**Last FAA Medical Exam:**	09/06/2016
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	07/20/2016
Flight Time:	(Estimated) 6300 hours (Total, all aircraft), 1244 hours (Total, this make and model)		

The two crewmembers had flown together previously and reported having a good rapport. The departure from MEM was the first leg of the most recent flight pairing.

The Captain

The captain, age 55, was hired as a flight engineer by FedEx in 2000. At the company, he worked in the Boeing 727 as a flight engineer, a first officer, and a captain, as well as a captain on the MD-11. He had a total flight time of about 10,000 hours (he was uncertain about his time as pilot-in-command) and estimated about 1,500 hours in the MD-11. The captain held a multiengine airline transport pilot certificate, with type ratings in the LR-Jet, Boeing 727, and MD-11. The captain held a Federal Aviation Administration (FAA) first-class airman medical certificate dated June 6, 2016, with a limitation that he "must have glasses available for near vision."

The First Officer

The first officer, age 47, was hired as a flight instructor by FedEx in 2004. In 2007, he became a flight engineer in the Boeing 727 and became a first officer in the MD-11 in 2012. He estimated a total flight time of 6,000 to 6,300 hours, with about 4,000 hours as pilot-in-command. He estimated a total time of about 400 to 500 hours in the MD-11, with no time as pilot-in-command. The first officer held a multiengine airline transport pilot certificate, with a type rating in the MD-11. The first officer held an FAA first-class airman medical certificate dated September 6, 2016, with no limitations.

Aircraft and Owner/Operator Information

Aircraft Make:	MCDONNELL DOUGLAS	**Registration:**	N370FE
Model/Series:	MD 10-10F 10F	**Aircraft Category:**	Airplane
Year of Manufacture:		**Amateur Built:**	No
Airworthiness Certificate:	Transport	**Serial Number:**	46608
Landing Gear Type:	Retractable - Tricycle	**Seats:**	6
Date/Type of Last Inspection:	09/21/2016, Continuous Airworthiness	**Certified Max Gross Wt.:**	440000 lbs
Time Since Last Inspection:		**Engines:**	3 Turbo Fan
Airframe Total Time:	84589 Hours at time of accident	**Engine Manufacturer:**	General Electric
ELT:	Installed, not activated	**Engine Model/Series:**	CF6-6D
Registered Owner:	FEDEX CORPORATION	**Rated Power:**	41500
Operator:	FedEx Express	**Operating Certificate(s) Held:**	Flag carrier (121); Supplemental

The airplane, a McDonnell Douglas MD-10-10F, serial number 46608, registration N370FE, was manufactured in 1972 and had an airframe total time of 84,589 total flight hours with 35,606 total flight cycles at the time of the accident. FedEx purchased the airplane on August 21, 1997. The airplane was converted from a DC10-10 to a DC10-10F on July 3, 1999; it was converted to an MD-10-10F on November 2, 2003, when a transport-category standard airworthiness certificate was also issued. It was powered by three General Electric model CF6-6D turbo-fan engines. The airplane's last "C" check was on September 21, 2016. It's last inspection as October 25, 2016, when a service check, an "A" check, and a "B check" were completed.

Left Main Landing Gear

The most recent overhaul of the left MLG occurred February 28, 2008, by Hawker Pacific Aerospace (HPA) Repair Station No. RJ3R817L in Sun Valley, California. It was installed on the accident airplane March 31, 2008. Aircraft time at installation was 74,340.02 total flight hours and 29,953 total cycles. Time since installation was 10,249.03 flight hours, 5,653 cycles, and 3,133 days (8.58 years). At the time of the accident, the MLG overhaul limit at FedEx was 9 years or 30,000 flight hours, whichever occurs first; the left MLG's time remaining until the next overhaul was 152 days (most restrictive). The Boeing maintenance planning document recommends the restoration (overhaul) of the MLG assembly every 8 years or 7,500 flight cycles, whichever occurs first. A FedEx representative indicated that the company adopted the 9-year MLG overhaul limit used by the previous owner/operator of the first DC10s purchased by FedEx.

The most recent service of the MLG full shock strut was performed at the airplane's last "C" check in September 2016, in Mobile, Alabama (this work included draining and replacing the strut fluid and nitrogen charge; it does not include a requirement to do a borescope inspection of the air fill valve bore).

In addition, aircraft log writeups revealed a pilot report dated February 6, 2014, indicated a hard landing that occurred at Newark Liberty International Airport, Newark, New Jersey. Maintenance personnel downloaded and reviewed FDR data and performed structural inspections in accordance with manufacturer specifications. No defects were noted during the inspections, and no additional work was required.

Maintenance History of the Left MLG Outer Cylinder

Of the 3 airworthiness directives and 14 service bulletins (SB) accomplished during the left MLG's last overhaul, the work associated with Alert Service Bulletin DC10-32A259 was identified for further examination based on findings in the NTSB's investigation. Maintenance records indicate that no stray nickel or chrome was found during the initial inspection of the air filler valve bore, but corrosion was found and removed per ASB instructions. The MLG cylinder was then brush cadmium plated per the CMM (see Additional Information). The overhaul was completed on February 28, 2008.

All dimensions related to the fill valve bore rework were documented in HPA work cards indicating the air filler valve bore was oversized within manufacturer limits, and all recorded dimensions were within manufacturer limits with one exception. The ASB and CMM state that the radius of the air fill valve bore at both the inner diameter wall and thread junction should be maintained at 0.015 to 0.030 inch during rework and that findings be recorded. After rework, the thread junction radius was recorded as 0.030 inch and the inner diameter wall was recorded as 0.090 inch. No additional records were found that addressed the exception. When asked about this exception, a Boeing representative indicated that this type of discrepancy had been brought to the manufacturer's attention previously and that larger radius findings had been approved for continued service.

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual Conditions	**Condition of Light:**	Day
Observation Facility, Elevation:	KFLL	**Distance from Accident Site:**	
Observation Time:	2153 UTC	**Direction from Accident Site:**	
Lowest Cloud Condition:	Few / 2100 ft agl	**Visibility**	10 Miles
Lowest Ceiling:	Broken / 4100 ft agl	**Visibility (RVR):**	
Wind Speed/Gusts:	15 knots / 24 knots	**Turbulence Type Forecast/Actual:**	/ None
Wind Direction:	50°	**Turbulence Severity Forecast/Actual:**	/
Altimeter Setting:	29.99 inches Hg	**Temperature/Dew Point:**	26°C / 21°C
Precipitation and Obscuration:			
Departure Point:	Memphis, TN (KMEM)	**Type of Flight Plan Filed:**	IFR
Destination:	Fort Lauderdale, FL (FLL)	**Type of Clearance:**	IFR
Departure Time:	1500 CDT	**Type of Airspace:**	Class B

About an hour before the accident, at 1653, the KFLL METAR reported wind from 50° at 15 knots gusting to 25 knots, 10 miles visibility, few clouds at 2,400 ft agl, scattered clouds at 3,300 ft agl, broken ceiling at 4,100 ft agl, overcast clouds at 25,000 ft agl, temperature 26°C, dewpoint 20C, and an altimeter setting of 29.99 inches of mercury.

At 1753, about 2 minutes after the accident, the KFLL METAR reported wind from 050° at 15 knots gusting to 24 knots, 10 miles visibility, few clouds at 2,600 ft agl, broken ceiling at 5,000 ft agl, overcast clouds at 25,000 ft agl, temperature 26°C, dewpoint 21°C, and an altimeter setting of 29.98 inches of mercury. A peak wind speed had been recorded at 1732 of 060 degrees at 26 knots.

Airport Information

Airport:	FORT LAUDERDALE/HOLLYWOOD INTL (FLL)	**Runway Surface Type:**	Asphalt
Airport Elevation:	64 ft	**Runway Surface Condition:**	Dry
Runway Used:	10L	**IFR Approach:**	Unknown
Runway Length/Width:	9000 ft / 150 ft	**VFR Approach/Landing:**	Unknown

KFLL is located about 3 miles southwest of downtown Fort Lauderdale. The airport has two parallel east/west runways (10L/28R and 10R/28L). The airport elevation is 9 ft above mean sea level. Runway 10L/28R is 9,000 ft long and 150 ft wide and is constructed of grooved asphalt. It is equipped with an instrument landing system approach and a medium intensity approach lighting system with runway alignment indicator (MALSR).

Wreckage and Impact Information

Crew Injuries:	2 None	**Aircraft Damage:**	Substantial
Passenger Injuries:	N/A	**Aircraft Fire:**	On-Ground
Ground Injuries:	N/A	**Aircraft Explosion:**	On-Ground
Total Injuries:	2 None	**Latitude, Longitude:**	26.077500, -80.144444

The airplane came to rest off the left side of runway 10L near the A4 taxiway. The outer cylinder of the left MLG was fractured midway through the air filler valve bore on the aft side. The outer cylinder of the left MLG shock strut fractured around its entire circumference; the upper portion of the cylinder remained intact and attached to the airplane at the forward and aft trunnion lugs (figure 1 shows a diagram of an MD-10-10F MLG and figure 2 shows the upper portion of the accident MLG). No anomalies were noted with the trunnion lugs or trunnion bolt attachment points.

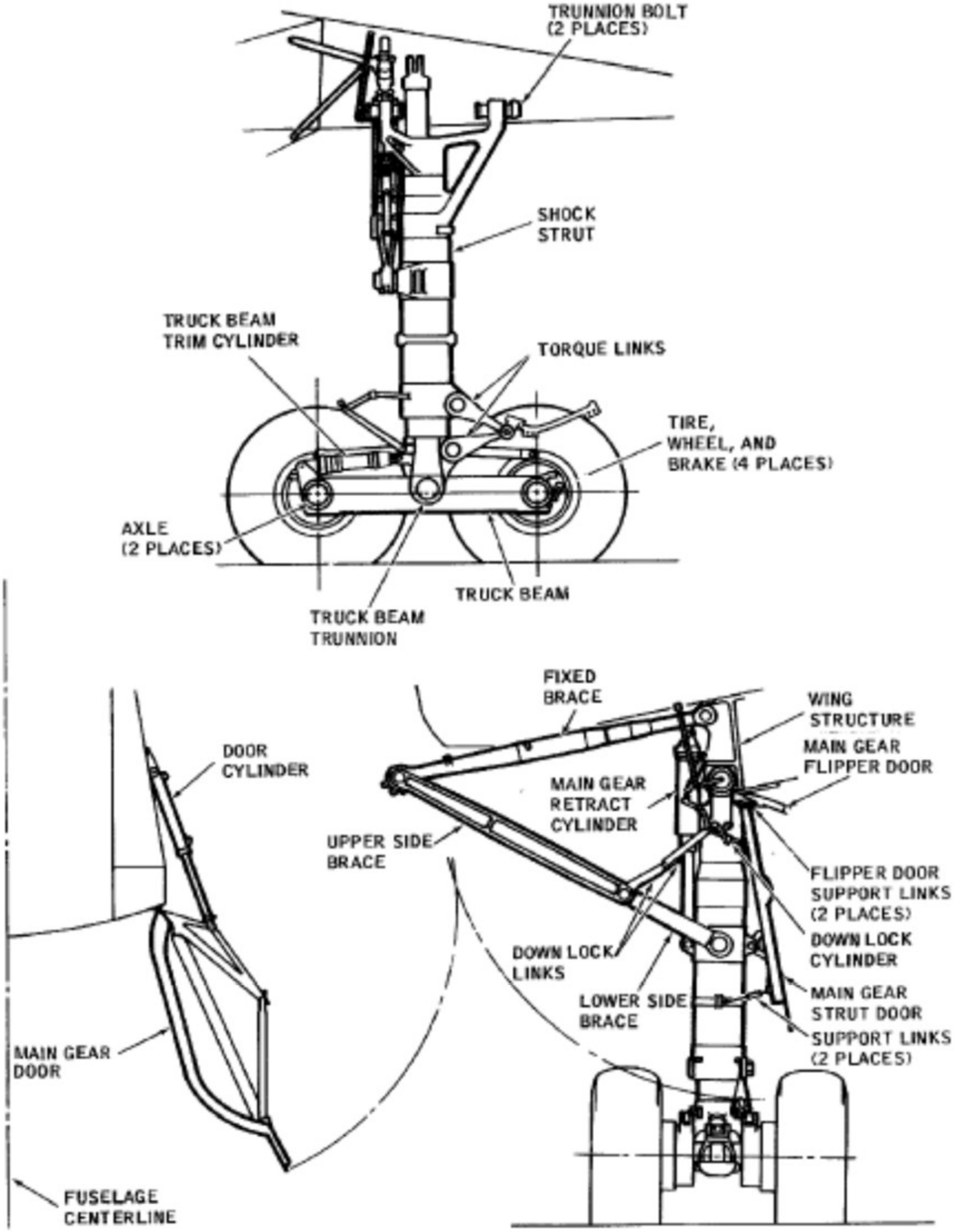

Figure 1. Diagram of MD-10-10F MLG (right shown)

Figure 2. Upper portion of the left MLG attached to the airplane.

The inboard side lugs and bolt and nut for the retract actuator attach points and the fixed door attach points remained intact. On the aft side of the lower section of the fractured gear, about half of the upper charging bore was visible (see figure 3). On-scene examination identified features consistent with fatigue on the fracture surface of the outer cylinder in the area of the air filler valve bore (see Tests and Research for more information).

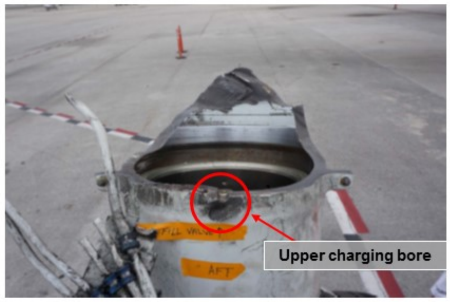

Figure 3. Aft side of the lower section of the left MLG cylinder and fill valve.

The lower segment of the landing gear was folded aft into the left side inboard flap. The lower portion of the gear remained attached to the MLG side brace assembly. The left MLG truck beam remained attached to the lower portion of the cylinder and shock strut at the pivot pin. The truck beam exhibited a crack running aft from the No. 1 wheel position axle to a 3-inch-long by 2-inch-wide hole on the top side near the pivot area (see MLG diagram in figure 3).

Three pieces of the left MLG outer cylinder were found on the runway. One piece measured about 12 to 14 inches long by about 30 inches in circumference. Two smaller portions, about 2 by 2 inches and 3 by 3 inches, from the upper charging bore and boss were also found on the runway. The upper charging bore fill valve was not found. These pieces, along with the remainder of the left MLG cylinder were sent to the NTSB Materials Laboratory for examination. The fracture surface of the 3-by-3-inch section had features consistent with fatigue in the area of the upper charging bore (see Tests and Research for more information).

Several of the internal components of the left MLG shock strut were recovered from the runway, including the upper chamber, the orifice assembly, the upper bearing, the metering pin (fractured), and the upper bearing carrier (2 halves).

The left wing sustained fire damage that extended from inboard of the No. 1 engine pylon outboard to the left wingtip and chordwise from the leading-edge wing spars to the aft trailing edge wing spars. The left wing trailing edge upper and lower closeout panels, inboard and outboard flaps, and ailerons sustained damage from the impact and fire. Slats 2 and 3 surrounding the No. 1 engine and pylon sustained fire damage. Slats 4 through 8 had impact damage. The bottom of the left-wing fuel tank sustained structural damage during the accident sequence.

The bottom of the No. 1 engine had two large scraped areas. The forward scrape was along the bottom of the cowling doors, and the second scrape extended aft from the aft edge of the thrust reverser blocker vanes. The No. 1 pylon fuel tube was found torn and partially consumed by fire, and the firewall shutoff valve was found in the closed position. The No. 1 pylon sustained both fire damage and structural damage due to impact.

The pilots reported hearing an explosion as they were preparing to evacuate and a fireball was captured by an airport surveillance camera after the airplane came to a stop. The recording shows a large portion of debris above the fireball and at more than twice the height of the 75-ft-tall airplane tail. A large portion of the heavy structure of the left main fuel tank upper skin was found near the left-wing tip, 25 ft in span by 8 ft in cord, as well as smaller fragments. Burns and melting damage to the forward and lower exterior surfaces of the left main fuel tank were found near where the fuel supply tube had broken in the engine pylon.

Flight Recorders

The accident airplane was equipped with a Honeywell model 980-4700-042, 256-word solid-state FDR, serial number 10591. The recorder was in good condition and the data were extracted normally. The FDR recording contained about 27.2 hours of data. The event flight was the last flight of the recording and its duration was about 2 hours.

The accident airplane was equipped with a General Electric (GE) combination cockpit voice flight data recorder (CVFDR), model number 175497-01-01, serial number 0000061. Four channels are recorded: one channel for each flight crew, one channel for a cockpit observer, and one channel for the cockpit area microphone. Good-to-excellent quality audio information was extracted from the recorder normally (the observer channel, number 2, didn't contain any audio information and wasn't expected to since there wasn't an observer pilot on the flight). A cockpit voice recorder group was convened at the NTSB audio laboratory and a partial transcript for the 2-hour digital recording was produced.

Tests And Research

Materials Laboratory

The left MLG cylinder and fragments found on the runway were examined at the NTSB Materials Laboratory. A small thumbnail crack was observed on the 3-by-3-inch fragment at the radius between the cylinder inner diameter surface and the valve bore surface that was consistent with a pre-existing crack before the complete fracture of the MLG. Most of the fracture surface area had been damaged by smearing, consistent with post-fracture impact damage. Surface contamination, such as rust and dirt, were also present. A small area next to the radius exhibited features (such as crack arrest marks) consistent with progressive crack growth. The progressive crack growth was found to be fatigue cracking, as exhibited by the fatigue striations found on microscopic examination of the thumbnail crack.

Metallurgical examination of the main fracture region of the left MLG cylinder found almost all of the fracture surfaces exhibited a dull luster with a rough surface, with radial lines and chevron marks. These features were consistent with overstress fracture in low ductility (hardened) metal alloys and having emanated from the air filler valve bore on the MLG. A flat, thumbnail-shaped crack observed at the bore location corresponded with the mating crack face on the 3-by-3-inch fragment.

The inner diameter of the cylinder at the valve bore was measured using a tape measure, accurate to the 1/16-inch scale. The maximum recorded cylinder diameter was 12.531 inches. The drawing requirement for the diameter was 12.540 inches.

The inside bore of the air filler valve was measured from a replicating rubber negative using an optical comparometer. The smooth portion of the bore had a diameter between 0.492 and 0.523 inch, with an average of 0.514 inch. The stated requirement for the bore diameter was 0.494 to 0.524 inch, up to a maximum of 0.550 inch after rework.

The radius of the curved portion of the air filler valve bore at the location of the thumbnail crack initiation site was measured between 0.105 and 0.154 inch, with an average of 0.128 inch. (As stated previously, the ASB and Component Maintenance Manual (CMM) requirement for the radius diameter was 0.015 to 0.030 inch, and the radius recorded on the HPA work card from the MLG assembly's last overhaul was 0.090 inch; however, the manufacturer had a history of approving larger radius findings for continued service.)

Examination of the thumbnail crack using a scanning electron microscope (SEM) found the initiation of the crack inside the machined portion of the bore, which exhibited radial machine marks. Fatigue striations were present in the initial portion of the crack and the subsequent fatigue bands. Outside of the fatigue bands, dimple rupture consistent with overstress was observed. The fatigue features extended to a minimum of about 0.110 inch along the inner diameter and a maximum of 0.192 inch along the air valve bore.

The examination also found that the thumbnail crack was not exclusively consistent with fatigue crack propagation, but rather contained bands of other failure modes. After the initial fatigue cracking from the crack initiation site, an intergranular fracture band surrounded the first 0.02 inch of fatigue, followed by a band of fatigue striations. After this, three overstress bands (exhibiting dimple rupture features) alternating with fatigue were observed, followed by a final mixed fatigue and overstress band (see Fatigue Analysis later in this section for more information). The distance from the fatigue crack to the intergranular region measured 0.019 inch. The measured width of the intergranular band was 0.013 inch.

Inspected using energy dispersive x-ray spectroscopy (EDS), there were no impurities or elements unique to the intergranular fracture band or on the fractured facets that were not present on other regions of the fracture surface. The most prominent quality of the initiation site was a feature consistent with a corrosion pit. The corrosion pit measured 0.004 inch wide with a depth of 0.002 inch. EDS probes found detectable levels of oxygen, sodium, calcium, and phosphorus in the pit.

SEM examination found that the area consistent with the valve bore surface exhibited corrosion pitting. EDS spectra of this corrosion pitting were consistent with that of probes taken at the corrosion pit at the fatigue crack initiation site. Measurement of these pits averaged 0.0012 inch in diameter.

The chemical composition of the cylinder was inspected using EDS and x-ray fluorescence. The composition was consistent with 300M, the prescribed material for the part. No indications of cadmium or cadmium compounds were found in the bore radius near the thumbnail crack. Likewise, inspection of the fracture surface and bore using backscattered electron imaging found no evidence of any particles consistent with previous nickel, chrome, or cadmium plating.

Hardness tests were performed in accordance with ASTM Standard E18. The hardness adjacent to the plasma torch section measured 54 on the Rockwell C Hardness scale (HRC), then dropped to a minimum of 45 HRC. The hardness measurements increased farther away from the cut surface, and, at a depth of 0.565 inch, the hardness measurements stabilized and averaged 54 HRC. According to published data, this hardness was consistent with a 300M that has a tensile strength of 297 ksi (thousand pounds per square inch), which typically requires a tempering temperature of 500 °F (260 °C). The part drawing required a heat treatment to a tensile strength of 275 to 305 ksi. According to literature, the measured hardness values were consistent with the prescribed heat treatment requirements.

One of the fragments of the landing gear about the air filler valve bore was sectioned, mounted, polished and etched with a 2% Nital solution to reveal the bore's microstructure. The threads in the bore exhibited no indication of a metallic coating. In addition, the grain structure inside the thread was consistent with that of the bulk, indicative of machined (cut) threads. A closer view of the bulk microstructure showed a tempered martensite microstructure, consistent with those typically observed for this alloy and heat treatment. No microstructural deformation or grain flow was present in the threaded portions, indicating they were machine cut rather than rolled.

A cross-section through the valve bore near the fracture surface was mounted and polished to inspect the local hardness properties using microindentation hardness testing per ASTM Standard E384. The regions of highest hardness were located along and near the threads, consistent with strain hardening imparted by the cutting process. There were no indications of lower hardness regions near the bore.

Fatigue Analysis

A fatigue analysis of the thumbnail crack was performed. Fatigue striations were counted at more than 35 random, unique, and nonduplicated sites on the fracture surface, along with their distances from the initiation site. The analysis assumed that each counted striation (a feature consistent with crack growth) correlated directly to a landing cycle with no other comparable stresses (such as from braking). The analysis also assumed that sampled regions were representative regions of fatigue crack growth at each crack depth, the fracture surface was flat, and that the fatigue striation spacing increased with crack depth.

The estimated total number of cycles for each band are summarized below (figure 4 shows a closeup view of the fatigue striation region); the number in parentheses represents the total striation quantity summation to that point:

- Striation count in 1st fatigue thumbnail (origin to intergranular band): 526
- Striation count in 1st fatigue thumbnail (intergranular band to overstress band 1): 165 (691 total to this point)
- Striation count before overstress band 1: 691
- Striation count in 2nd band: 253 (944)
- Striation count in 3nd band: 242 (1186)
- Striation count in 4th band: 218 (1404)

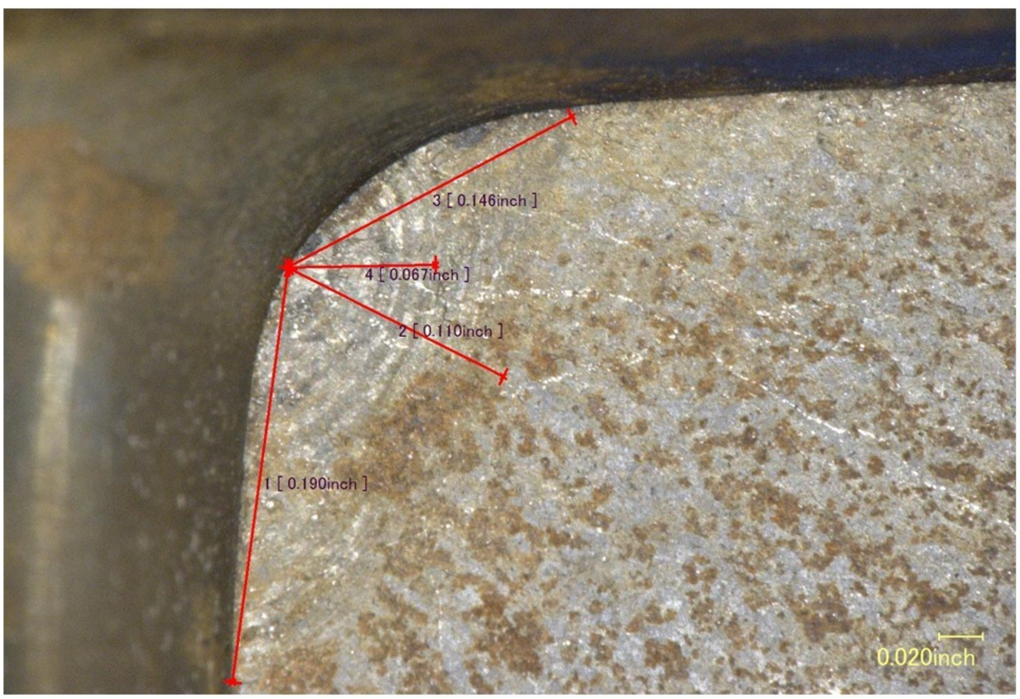

Figure 4. A closeup view of the fatigue striation region.

Boeing Finite Element and Fatigue Analysis

Boeing performed a finite element analysis (FEA) and fatigue (crack initiation) analysis of the MLG cylinder failure based on the same method, tools and format that were used in the investigation of the 2006 event. For this event, the previous finite element model was modified to represent the characteristics and conditions of the air filler valve bore of the accident MLG cylinder. The FEA results concluded that the residual stress at the corrosion pit was very high during the braking conditions. A residual stress—137,169 psi—from a braking condition was assumed in the fatigue analysis. The MD-10-10F fatigue spectrum from the certification data and the previous in-service evaluation (ISE) from 2006 were used to calculate fatigue damage. The fatigue analysis results show that, with a corrosion pit on the large transition radius on the critical 3-o'clock-to-9-o'clock plane, crack initiation was most likely to occur within either the certification spectrum or the ISE spectrum.

FedEx Postaccident Actions

FedEx performed a safety risk assessment of all the MLGs in its MD-10-10F fleet (27 in-service airplanes with 54 MLG subjected to borescope inspection). Of those inspected, 16 cylinders (26%) were identified as "concerns." Fourteen of those exhibited adverse features in the bore, such as tooling marks and corrosion pitting.

FedEx reviewed its maintenance program and has reverted to an 8-year overhaul limit for MLG cylinders as recommended by the manufacturer (FedEx had previously been granted an extension of 9 years for cylinder service life). Any cylinders with pitting have been permanently removed from service. FedEx is also reassessing the service life of the MD-10-10F fleet. In addition, FedEx intends to remove all of the MD-10-10F aircraft from service by January 1, 2020, through attrition.

Organizational And Management Information

FedEx was incorporated in June 1971 and, in April 1973, began operating 14 corporate-type jet airplanes from the airline's hub at KMEM. After the deregulation of the air cargo industry in 1977, FedEx began to expand, acquiring more and larger airplanes (including Boeing 727s and McDonnell Douglas DC-10s) and using multiple airports for its operations. In recent years, FedEx has started to phase out older aircraft models, including Boeing/McDonnell Douglas MD-11s/-10s and Airbus A300s and A310s, to be replaced with Boeing 767s. At the time of the accident, FedEx operated a fleet of 422 airplanes with about 4,300 pilots.

Maintenance and Inspection Programs

FedEx aircraft, including engines, systems and appliances, are maintained in a continuous state of airworthiness by a program of preventive and corrective maintenance. Air Operations is responsible for the airworthiness, maintenance, servicing, alteration, and inspection of FedEx aircraft. Air Operations is also responsible for maintenance or alterations performed on FedEx aircraft by other organizations (section D091 of the company's operations specifications authorized FedEx to make arrangements with other maintenance providers to accomplish maintenance, preventive maintenance, or alterations for the certificate holder).

FedEx conducted audits of its essential maintenance providers and critical vendors on an annual basis or on a more frequent schedule based on findings (all other vendors are audited on a risk-based assessment frequency with a maximum 84-month period). All essential maintenance and component vendors were listed in the operator's approved maintenance provider list. No discrepancies in the listing were noted during the investigation. The results of the last two audits of the Sun Valley HPA facility, conducted in 2014 and 2015 were also reviewed. The 2014 audit score did not meet FedEx's desired compliance requirements, and corrective action was documented and taken. The 2015 audit score met FedEx's desired requirements.

Continuing Analysis and Surveillance System (CASS) and Reliability Program

To comply with requirements of 14 *CFR* 121.373, FedEx has an approved CASS program, which is a systems approach to assess the performance and effectiveness of the FedEx Continuous Airworthiness Maintenance Program. Several CASS meeting minutes and monthly reliability reports were reviewed for 2016 with no issues noted with the accident landing gear structure; however, they validated the existence of an actively managed program.

HPA Repair Station

The FAA Van Nuys flight standards district office issued an approved Repair Station Certificate (Certificate Number RJ3R817L), original date April 24, 1987, to Hawker Pacific Aerospace, Sun Valley, California, with the following ratings: Accessories, Limited Accessories (August 5, 2015), Limited Landing Gear.

Additional Information

Revised Maintenance Instructions for MLG Shock Strut Cylinders

In 2007, Boeing revised maintenance instructions for the repetitive inspection and repair of the air filler valve bore of MLG shock strut cylinders on DC-10-10, DC-10-10F, DC-10-15, and MD-10-10F airplanes. Boeing's actions were prompted by preliminary findings in the NTSB's investigation of a July 28, 2006, accident involving FedEx flight 630, a Boeing MD-10-10F, which experienced a left MLG failure immediately after landing at KMEM (see the Previous Gear Collapse Events later in this section for more information about this accident, NTSB case number DCA06FA058).

On September 15, 2007, Boeing issued a revision to CMM 32-11-04, which added instructions for a video probe inspection of the air filler valve bore for corrosion, sulfamate nickel or chrome electroplating splatter, tool marks, or other defects followed by an eddy current inspection of the bore for cracks. Instructions for repair of allowable damage were also included.

Issued on October 30, 2007, ASB DC10-32A259 terminated SB DC10-32A259 and instructed operators to perform an inspection of the MLG cylinder air filler valve bore for stray nickel or chrome electroplating deposits, corrosion, or cracks. The ASB provided instructions for repair or replacement of the MLG shock strut cylinder assembly if any of the noted conditions were found.

AD 2008-09-17 (issued on May 2, 2008, and effective June 6, 2008) required operators to perform a video scope inspection of the air filler valve bore for the presence of stray nickel or chrome plating deposits and to perform the investigative and corrective actions per the ASB.

Eddy Current Inspection Process for Air Filler Valve Bore

The eddy current inspection process for the air filler bore was demonstrated for NTSB investigators. For the demonstration, the equipment used a rotating probe with a specific probe thickness designed to have an interference fit with the fill valve bore, which was cleaned before inspection. The probe was calibrated using a reference standard with a 0.001 inch surface flaw. The instrument was operated at a frequency of 500 kHz (which exhibits higher precision for surface defects but has lower penetration depth) and calibrated to a 60% full-scale deflection.

During the demonstration of the process, the technician noted that surface roughness will indicate interference and would usually require additional polishing. With the filler valve bore configuration, the eddy current deflection would become inconsistent and inconclusive at the inner diameter radius of the valve bore due to edge effect. The technician demonstrated that at the inner diameter radius, the probe exhibited poor contact, which produced a false positive indication of a crack. The technician stated that although magnetic particle inspection would be the most effective detection method at the inner diameter radius, the MLG would still need to be completely disassembled to inspect for the type of crack in this accident using this technique. Other nondestructive techniques, such as fluorescent penetrant, would also likely be ineffective.

Brush Cadmium Plating Process

The brush cadmium plating process used on the left MLG cylinder during the 2008 overhaul was performed as follows:

1. Chrome plate followed by initial bake
2. Electroless nickel plate followed by 2nd bake
3. Bushing installation
4. Cadmium plate (tank) followed by 3rd bake
5. Stylus cadmium plate valve bores
6. Borescope check valve bores
7. Magnetic particle inspect

In July 2015, HPA introduced an electronic work card system that changed the work flow for this process. The revised procedure moved the step for stylus cadmium plating earlier in the process, before the MLG cylinder has been tank-plated and baked for a second (and final) time.

HPA has since introduced a tank dip method for plating air filler valve bores, which is an improvement over the brush plating method.

Previous Gear Collapse Events

On July 28, 2006, the left MLG of a FedEx Boeing MD-10-10F collapsed immediately after landing on runway 18R at KMEM, and the airplane came to rest on the left side of the runway. After the gear collapsed, a fire developed on the left side of the airplane. The investigation found that corrosion pitting (with a measured depth of about 0.002 inch) led to fatigue cracking that also originated inside the air filler valve bore. However, the cause of the pitting in the 2006 accident was from stray nickel plating present inside the smooth portion of the valve bore (the fatigue crack had propagated from inside the bore, not the radius). This stray nickel plating allowed localized corrodents to attack underneath the plating, leading to localized corrosion that manifested into a small pit. A crack grew out of this corrosion pit, propagating by mixed mode fatigue and stress corrosion cracking.

On December 18, 2003, the right MLG of a FedEx MD-10-10F collapsed after touchdown on runway 36R at KMEM, and the airplane veered off the right side of the runway (NTSB case number DCA04MA011; NTSB report number AAR/05/01). After the gear collapsed, a fire developed on the right side of the airplane. The fracture of the right MLG of this airplane initiated from the same air filler valve bore hole location as that involved in the 2006 event; however, the investigation of the 2003 event concluded that the "excessive vertical and lateral forces on the right main landing gear during the landing exceeded those that the gear was designed to withstand and resulted in the fracture of the outer cylinder and the collapse of the right main landing gear."

Administrative Information

Investigator In Charge (IIC):	Daniel R Bower	**Adopted Date:**	08/23/2018
Additional Participating Persons:			
Publish Date:	08/23/2018		
Note:	The NTSB traveled to the scene of this accident.		
Investigation Docket:	http://dms.ntsb.gov/pubdms/search/dockList.cfm?mKey=94310		

The National Transportation Safety Board (NTSB), established in 1967, is an independent federal agency mandated by Congress through the Independent Safety Board Act of 1974 to investigate transportation accidents, determine the probable causes of the accidents, issue safety recommendations, study transportation safety issues, and evaluate the safety effectiveness of government agencies involved in transportation. The NTSB makes public its actions and decisions through accident reports, safety studies, special investigation reports, safety recommendations, and statistical reviews.

The Independent Safety Board Act, as codified at 49 U.S.C. Section 1154(b), precludes the admission into evidence or use of any part of an NTSB report related to an incident or accident in a civil action for damages resulting from a matter mentioned in the report.