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2 January 2009
66-ZB-H200-ASI-18407

Ms. Lorenda Ward
Investigator In Charge
National Transportation Safety Board
490 L'Enfant Plaza, SW
Washington DC 20594-003

BOEING

Subject: Boeing Submission for American Airlines MD-82 N454AA Engine Fire Accident, St. Louis, MO – 28 September 2007

Reference: NTSB Tech Review Telecon Meeting, 19 November 2008

Dear Ms. Ward:

As requested during the reference technical review, please find enclosed a copy of The Boeing Company's submission on the subject landing accident. Please note that we are also sending electronic copies of this submission to the party coordinators during the week of January 5, 2009.

We would like to thank the NTSB for giving us the opportunity to make this submission. If you have any questions, please contact William Steelhammer at 562-593-2394, or via e-mail at william.c.steelhammer@boeing.com.

Best regards,

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Enclosure: Boeing Submission to the NTSB for the subject accident

cc: Mr. David Keenan, FAA
Mr. Billy Nolen, American Airlines
Mr. Brian Beach, Allied Pilots' Association
Mr. Bill Korte, Lambert St. Louis International Airport
Mr. Martin Kruse, Honeywell Aerospace
Mr. Rowland Ellis, PTI Technologies, Inc.
Mr. Brad Brugger, Transport Workers Union of America

BOEING®

Submission to the

National Transportation Safety Board

for the

American Airlines MD-82 N454AA
Accident at Saint Louis, Mo.
28 September 2007

The Boeing Company
2 January 2009

INTRODUCTION

On September 28, 2007, at approximately 1316 central daylight time, a McDonnell Douglas DC-9-82 (MD-82), N454AA, operated by American Airlines as flight 1400, executed an emergency landing at Lambert-St Louis International Airport (STL), St. Louis, Missouri, after the flight crew received a left start valve open light followed by a left engine fire warning during departure climb from the airport. The airplane sustained substantial damage. Visual meteorological conditions prevailed and an instrument flight rules flight plan was filed for the 14 CFR Part 121 scheduled domestic flight.

Upon receiving the left engine fire warning during climb, the flight crew discharged the aircraft engine fire bottles into the affected engine. During the visual return and single-engine approach to the airport, the nose landing gear did not extend. A single-engine go-around was performed and the flight crew subsequently extended the nose landing gear using the emergency landing gear extension procedure. The airplane returned for landing on runway 30L and was met by STL Airport Rescue and Fire Fighting Vehicles. Ground fire fighting personnel confirmed that the fire was extinguished.

Approximately 39 minutes after landing, the 2 flight crew, 3 flight attendants, and 138 passengers deplaned via airstairs and no occupant injuries were reported. The intended destination of the flight was Chicago O'Hare International Airport (ORD), Chicago, Illinois.

Post-landing inspection revealed damage to the left engine and structure related to the failure of the left engine starter motor. Also damaged were engine-driven hydraulic and electrical system components.

Submission Abstract

- The Boeing Company, as the airplane's manufacturer, is acting as a technical and operational advisor to the National Transportation Safety Board (NTSB) in this investigation.
- The conclusions presented in this submission are based on factual information, Boeing expertise, the use of analytical tools, and a methodical investigation process.
- Boeing believes the probable causes of this accident are:
- The failure of the left engine start valve; and
- The left engine thrust remaining at high power for approximately one minute after the left engine fire warning aural and red light annunciations (an emergency procedure requiring immediate action) and two minutes after the amber left start valve open annunciation (an abnormal procedure requiring corrective action).
- Contributing to the severity of the event was the cockpit crew's failure to complete appropriate checklists associated with the subsequent (to the start valve open) warnings and indications, which could or would have interrupted the cascading events that occurred during the flight.
- Contributing to the duration of the event and flight crew distraction was the continued operation of the PTU after left system hydraulic fluid was lost.

BOEING ASSISTANCE WITH THIS INVESTIGATION

The National Transportation Safety Board (NTSB) is leading the investigation into this American Airlines MD-82 accident. Assisting the NTSB in their investigation are the Federal Aviation Administration (FAA), American Airlines, Honeywell, the Allied Pilots Association, Boeing, and other designated parties.

As the manufacturer of the MD-82 airplane, Boeing's specific role in this investigation has been to provide technical information regarding the airplane design and operation to assist the NTSB.

Furthermore, the NTSB requested that all parties submit proposed findings to be drawn from the evidence revealed during the course of the investigation. Boeing has responded to the NTSB request with this document, which:

- Provides an assessment of the evidence and other pertinent data.
- Identifies knowledge gained from the investigation.
- Identifies conclusions and recommendation supported by the knowledge gained from the investigation.

EVIDENCE ASSESSMENT

The Boeing assessment of the evidence is based upon post-accident examination of airplane systems and components, flight data recorder (FDR) data, the cockpit voice recorder (CVR) transcript, maintenance documents, and flight and maintenance crew interview data.

Due to repeated faults in the left engine starter system,[1] the left engine start at St. Louis was accomplished by the manual start process.[2] The manual process requires that the ground crew manipulate the start valve open and closed during the engine start sequence.

Approximately 35 seconds after takeoff the cockpit crew noted a left engine start valve open light.[3] No checklist action was taken by the flight crew.[4] Approximately 53 seconds later the left engine fire warning activated and, except for the warning bell, remained on throughout the flight.[5] Approximately 45 seconds later, the crew initiated the ENGINE FIRE OR SEVERE DAMAGE OR SEPARATION checklist.[6] Approximately 20 to 25 seconds later the left throttle was pulled to idle.[7] The left engine fire handle was pulled[8] approximately 2 minutes

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[1] Maintenance Records Factual Report, pp. 10-12

[2] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-9

[3] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-29 through 12-31

[4] Both Boeing's and the operator's start valve open annunciation checklists require the crew to reduce the affected engine throttle to idle. It is the first step in the Boeing checklist (in flight), ref. TBC MD-80 FCOM Vol. II p. Eng.30.21. It is the second step in the operator's checklist, ref. Operational / Human Factors Group Report Attachment 9.

[5] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-31 through 12-32

[6] Boeing's and the operator's engine fire / damage / separation checklists require the crew to reduce the throttle on the affected engine to idle. It is the first step in the Boeing checklist and the second step in the operator's checklist. Ref. TBC MD-80 FCOM Vol. II p. Emer.10.13-14 and Operational / Human Factors Group Report Attachment 2.

[7] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-33 through 12-34

and 36 seconds later,[9] and both engine fire bottles were discharged into the left engine.[10] The crew reported difficulty in operating the fire handle and discharging the fire bottles,[11] but subsequent ground checks could not duplicate the reported difficulty.[12] The crew did not initiate or complete the START VALVE OPEN ANNUNCIATION procedure, nor did they complete the engine fire checklist procedure.

The cockpit crew also noted multiple electrical and hydraulic systems indications, and apparently experienced an AC CROSSTIE LOCKOUT annunciation.[13] The crew also noted an intermittent start valve open light. During the initial visual return and approach to the airport, the nose landing gear did not extend.[14]

The crew executed a single-engine go-around with main landing gear extended.[15] The captain of the inbound flight, a passenger on the accident flight, was asked to join the cockpit crew, and occupied the jumpseat. The crew noted loss of hydraulic power to the right system and subsequently extended the nose landing gear on right downwind leg using the emergency landing gear extension procedure.[16] After the nose gear was extended the cockpit crew also noted abnormal hydraulic pressure and/or quantity on the left hydraulic system.[17] Abnormal hydraulic system checklists were not attempted.[18] During the return for landing the APU was started and power was restored to the left AC bus about 2 minutes 45 seconds prior to landing.[19,20] The airplane made a slats-extended, partial flap landing on runway 30L (11,019 feet by 200 feet).

The airplane was met by STL Airport Rescue and Fire Fighting vehicles. The ground vehicles reported to the cockpit crew that the left engine still had "a little bit of fire in there" and proceeded to extinguishing the remaining fire.[21] The airplane remained on the runway with the #2 engine and APU running. The passengers and crew remained on board, as there was no smoke or fire indication in the cabin, the fire trucks were spraying foam, and there was vehicular traffic nearby.[22] The flight crew decided to operate the left air conditioning pack to provide additional air to the cockpit and cabin, and opened the left pneumatic crossfeed lever. Opening the left crossfeed valve reset the left fire handle, which re-opened the left fuel and hydraulic systems fire shutoff valves, resulting in a fuel discharge from the left engine area. Ground firefighters advised the cockpit crew of the fuel discharge, and the fire handle was pulled once again to shut off the fuel.[23] Subsequently, a successful deplaning of passengers and crew was performed.

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[8] "He extended the fire handle about half way out and tried to fire the bottles but then had to pull the handle again." Operational Factors/Human Performance Group Chairmans' Report Attachment I, p. 5
[9] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-33 through 12-41
[10] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-41
[11] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-96; Operational Factors/Human Performance Group Chairmans' Report Attachment I, p. 5
[12] Systems Group Chairman's Factual Report p. 3
[13] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-37 through 12-55
[14] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-47 through 12-51
[15] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-51
[16] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-63 through 12-64
[17] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-66
[18] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-66 through 12-75
[19] Flight Data Recorder Specialist's Factual Report p. 10-3
[20] Operational Factors/Human Performance Group Chairmans' Report Attachment I, p. 3 "He selected the auxiliary power unit switch to start on downwind. The APU did not take over the left bus until the first officer reset the APU generator."
[21] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-78 through 12-89
[22] Operational Factors/Human Performance Group Chairmans' Report Attachment I, p. 3
[23] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-130 through 12-133

ENGINE START VALVE

Examination of the start valve solenoid filter from this accident (PTI P/N 11-10579, DAC P/N 7958540-1) and one subsequent start valve opening incident reported by this same operator indicates that the solenoid filters may be experiencing fatigue or other damage leading to the disintegration of the filter or filter material, in turn leading to contamination of and/or damage to the start valve solenoid.[24] Such contamination could lead to an intermittent or inadvertent start valve open condition.

Boeing was not aware of any previous similar filter degradation reports prior to this event.

Other "start valve open light" events reported by this operator to the NTSB and Boeing appear to be the result of other, unrelated indication issues.

The start valve and starter motor data from this accident is under evaluation by both Boeing and the FAA via the Continued Operational Safety agreement between Boeing and the Long Beach FAA Aircraft Certification Office. The evaluation has not been completed and corrective action has not yet been identified.

HYDRAULIC SYSTEMS

Before takeoff, the TRANS HYD (PTU) and AUX (auxiliary) hydraulic pumps are turned on, primarily to assure the ability to retract the landing gear in the event the right engine or the right engine-driven hydraulic pump fails after V1 speed (the landing gear is powered by the right hydraulic system).

If the PTU is ON and a hydraulic power failure occurs in one system without a corresponding loss of hydraulic fluid, pressure in the operating system will power the PTU and provide hydraulic pressure and flow to the opposite hydraulic system.

In the event of a hydraulic fluid loss in one system, an automatic PTU shutoff system will close the motor-operated shutoff valve when the hydraulic reservoir diaphragm assembly decreases below a preset value. A mechanism driven by the diaphragm actuates an electrical switch to command the shutoff valve. If the PTU is not shutoff by the flight crew or by the automatic system, and there is a hydraulic fluid loss in one system, the hydraulic fluid flow into the PTU can result in low hydraulic system pressure in the operating hydraulic system. The likely result is the loss of power in both hydraulic systems.

Apparently, during the accident flight, depletion of the fluid in the left hydraulic system[25] and the continued operation of the PTU resulted in the loss of right system hydraulic power to the flaps, rudder, landing gear extension/retraction system, nosewheel steering, and other systems.[26] The flight crew recognized the loss of right hydraulic system pressure.[27]

Post accident testing of the airplane with the AUX hydraulic pump ON and the PTU selected OFF revealed that the right hydraulic system (which powers the landing gear and rudder

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[24] Powerplant Group Chairman's Factual Report -- Addendum 1 Engine Starting System pp. 10-14
[25] Systems Group Chairman's Factual Report p. 3
[26] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation pp. 12-49 through 51; 12-61 (CAM-1 and I can't hardly turn (us)); 12-76
[27] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-68

power) would pressurize to 2200-2750 psi,[28] which is sufficient for normal landing gear and rudder actuation. This evidence would indicate that the right system was capable of normal operation during the event, but the PTU was absorbing the right system's power such that insufficient power remained to actuate other aircraft systems.

There was no evidence of a hydraulic fluid leak near the PTU or hydraulic reservoir,[29] but there was evidence of hydraulic fluid leaks at the engine.[30]

Based on the detail information provided by the operator after the event, the hydraulic reservoir diaphragm assembly in the left hydraulic system was not in the automatic PTU shutoff position.[31] Although the cockpit crew discussed abnormal left hydraulic system indication(s), it could not be confirmed if a hydraulic low fluid level indication was generated. Numerous hydraulic components including the reservoir were functionally checked by the airline after the event and all were operating within their operational requirements.[32] The review of this information suggests that the hydraulic fluid loss in the left hydraulic system occurred with such rapidity that the hydraulic pressure to the left system reservoir was not available to move the reservoir diaphragm assembly to the automatic PTU shutoff position. It appears likely that friction in the diaphragm assembly hydraulic seal was holding the diaphragm in place.

Since the PTU did not shut off automatically in this accident, the PTU automatic shutoff system is under evaluation by Boeing and the FAA via the Continued Operational Safety process. The evaluation has not been completed and corrective action has not yet been identified.

Boeing's checklists (ENGINE FIRE OR SEVERE DAMAGE OR SEPARATION; QUANTITY LOW OR DROPPING; and (L/R) HYD PRESS LOW ANNUNCIATION) require the PTU cockpit control switch to be set early in the checklist sequence to maintain available hydraulic power in the operating hydraulic system.[33]

PNEUMATIC CROSSFEED LEVER

From Vol. II Section 4 page 15-10-0 of the MD-80 Flight Crew Operating Manual (FCOM):

> "If ENG FIRE handle is pulled, placing respective (sic) PNEU X-FEED VALVE lever to OPEN will retract ENG FIRE handle."

If the ENG FIRE handle is retracted or reset, the fuel and hydraulic fire shutoff valves are reopened, along with the generator fire shutoff switch.[34] If closed, the PNEU X-FEED VALVE lever will remain closed.

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[28] Systems Group Chairman's Factual Report p. 2
[29] Systems Group Chairman's Factual Report p. 3
[30] Powerplant Group Chairman's Engine Factual Report pp. 15-16
[31] Systems Group Chairman's Factual Report p. 10
[32] Systems Group Chairman's Factual Report pp. 2-3; 9-12
[33] Setting the TRANS HYD PUMPS Switch to OFF is the first step in both the (L/R) HYD PRESS LOW ANNUNCIATION and the QUANTITY LOW AND DROPPING PROCEDURES, ref. TBC MD-80 FCOM Vol. II, p. Hyd.30.2 and Hyd.30.6, respectively. TRANS HYD PUMPS Switches 'as required' is the 7th step in the ENGINE FIRE OR SEVERE DAMAGE OR SEPARATION checklist, ref. TBC MD-80 FCOM p. Emer.10.13.
[34] Systems Group Chairman's Factual Report p. 4

The FAA issued Safety Alert for Operators (SAFO) No. 08018 on 8/5/08 following this event. The SAFO provides further discussion of the MD-80 fire handle and its interrelationship with the pneumatic crossfeed lever, and is available at the following web site:

http://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/safo/all_safos/media/2008/SAFO08018.pdf

Additionally, Boeing has revised the MD-80 and MD-90 FCOM Volumes I and II procedures ENGINE FIRE OR SEVERE DAMAGE OR SEPARATION to include the following Caution:

> CAUTION
> Do not open affected PNEU X-FEED VALVE lever as this will reset ENG FIRE handle causing fuel and hydraulic shutoff valves to open and fire extinguishing agent to disarm.

ELECTRICAL SYSTEMS

The AC and DC electrical power systems used on the airplane are similar in design. Referred to as a split-bus system, both the AC and DC electrical power systems are divided into two independent systems, the left side and the right side. Normally, each side operates independently from the other, each having a power source and bus system supplying power to the various load demands throughout the airplane. In the event of a power loss on the load buses of either side, a crosstie relay is provided so that the unpowered buses can be connected to the power source energizing the buses of the opposite side.

Auxiliary AC electrical power is provided by an Auxiliary Power Unit (APU) generator. Through the use of control switches and relays, auxiliary power can be supplied to all AC load buses simultaneously, or to only the left or right AC bus (provided the bus selected is not receiving power from an engine driven generator).

The function of the AC crosstie relay (ACTR) is to connect the left and right AC generator buses together under certain conditions, thereby permitting both buses to be energized by a single generator. Normally, the ACTR is prevented from closing by the presence of voltage on both buses.

If power is lost on one bus, the ACTR is designed to automatically close when the associated dead bus sensing circuit senses a loss of power on the bus. Once the ACTR is closed, it can be tripped open by several means, including power returning to the dead bus or if various signals from the airplane's generator control units are received.[35]

The FDR on the MD-80 is powered by the left AC bus, which generally is powered by the left engine-driven generator. Gaps in the FDR data indicate that electrical power to the FDR was interrupted intermittently on the accident flight. The data recording stopped for 22 seconds, then ran briefly for 3.5 seconds, then stopped again for 12 minutes and 12.5 seconds before returning and staying ON when the APU power came on the bus.[36]

[35] Systems Group Chairman's Factual Report – Addendum 1 pp. 2 – 4
[36] Flight Data Recorder Specialist's Factual Report

The following operating parameters of the MD-80 power generating system must be recognized in order to understand what may have occurred in this incident.

1) The MD-80 AC Bus Control Unit controls the power applied to the AC bus. It will remove power from a bus for under-frequency and under-voltage conditions.

2) The AC Bus Control Unit will apply power to a dead bus (cross tie) after a time delay of 200 ms at zero voltage.

3) The under-frequency duration must be for 0.75 to 1.25 seconds and/or the under-voltage duration must be for 5 to 7 seconds to cause a generator to be removed from a bus.

4) Tripping off due to under-frequency or under-voltage does not automatically reset if the frequency or voltage returns to an acceptable value.

5) When a generator is removed from a bus due to under-voltage or under-frequency the other generator may not crosstie, depending on other conditions present at the time.

Boeing believes it is unlikely that the engine may have been running just enough to keep marginal power on the bus, causing intermittent power on the left bus. It appears more likely that for a short period of time the power quality was deteriorating, but in the early stages it did not stay outside acceptable AC Bus Control Unit parameters for a sufficient length of time to trigger the generator shutoff. It appears that the FDR data recording became erratic concurrently with the fire warning. The FDR may have been unable to continue recording with the marginal power quality, except for the short 3.5 second period, then at some point either an under-voltage or under-frequency condition triggered the shutoff. Power was not subsequently restored to the bus until the APU generator became available.[37]

COCKPIT DOOR

The cockpit security door assembly and associated mechanisms were installed on the airplane by the operator via a C&D Zodiac Supplemental Type Certificate. The latching mechanism is powered by the left Miscellaneous DC bus. The crew reported difficulties with the cockpit door being unlatched at times that were concurrent with the FDR being unpowered.[38]

FLIGHT CREW ITEMS

The flight crew had multiple opportunities to manage the event in a more effective manner. These opportunities were lost each time the crew failed to initiate and complete an appropriate checklist.

The first solid opportunity was when the start valve open indication was initially observed. The second item on the operator's L or R START VALVE OPEN light abnormal[39] checklist

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[37] Flight Data Recorder Specialist's Factual Report

[38] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation; Operational / Human Factors Group Report Attachment I, INTERVIEW SUMMARIES and CREW STATEMENTS

[39] Per Boeing's MD-80 FCOM, an Abnormal Procedure associated with an amber light "Indicates a condition that requires corrective action." MD-80 FCOM Vol. II, Section 4, 1-40-10, p. 1

procedure[40] is to bring the affected engine throttle to idle, thus greatly reducing the flow of pressurized, heated bleed air through the starter motor and into the engine nacelle. Prompt reduction of the bleed air flow could have prevented the failure of the starter and subsequent fire, thus making it less likely that there would have been a need for any subsequent emergency or abnormal checklists relating to engine fire, abnormal hydraulic, or AC crosstie systems. As previously described, 53 seconds elapsed between the moment the crew noted the start valve open indication and the fire warning actuated, with left engine power remaining at a high power setting (takeoff then climb thrust).

The second opportunity was when the fire warning actuated. Again, the second step of the Engine Fire / Damage / Separation emergency[41] checklist procedure[42] calls for the affected engine throttle to be pulled to idle. A prompt reduction in high-pressure, high-temperature air could have prevented an actual fire,[43] and certainly would have slowed the progress of the fire (if not extinguished) to give the fuel shutoff, fire shutoff, and fire extinguisher systems an improved opportunity to extinguish the fire. The throttle was moved to idle approximately 1 minute after the fire warning actuated (2 minutes after the start valve open light); the crew initiated discussion of closing the fuel lever approximately 3 minutes after the fire warning, and initiated discussion of pulling the fire handle approximately 3 minutes and 35 seconds after the fire warning.

Quoting from the Operational / Human Factors Group Report, page 16, paragraph 6.11:

"To sum up the information provided in the accident report, this section identifies the checklists applicable during the flight after the start valve light open indication illuminated. The crew stated that they performed all required checklists prior to that time.

- L or R START VALVE OPEN light – this checklist was not performed.
- Engine Fire / Damage / Separation – this checklist was performed in part but was also interrupted at one point.
- One Engine Landing – this checklist was not performed.
- Emergency Landing – this checklist was not performed.
- L or R HYD PRESS LOW light – this checklist was not performed.
- L or R Hydraulic Quantity Low or Decreasing – this checklist was not performed.
- Before Landing – this was a mechanical checklist. This checklist was performed.
- After Landing – this checklist was not performed.
- Parking – unknown if this was performed.
- Ground Evacuation – this checklist was not performed."

An additional checklist that was available to the crew but apparently was not attempted was the AC CROSSTIE LOCKOUT ANNUNCIATION (TBC MD-80 FCOM Vol. II, pp. Elec.30.1-4.)

The flight crew stated they were distracted by the cockpit door opening and closing during the flight. They also stated they were distracted and confused by the loss of power to the left AC bus and the associated cockpit indications.[44] These indications along with the crosstie lockout

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[40] Operational / Human Factors Group Report Attachment 9

[41] Per Boeing's MD-80 FCOM, an Emergency Procedure associated with a red light "Indicates a condition that requires immediate action." MD-80 FCOM Vol. II, Section 4, 1-40-10, p. 1

[42] Operational / Human Factors Group Report Attachment 2

[43] The third step of the checklist has the crew check to see if the fire warning light goes out. If it does not, the crew then proceeds to shut the fuel off (fuel on-off lever) then pull the fire handle (shuts off fuel and hydraulic flow at the wing rear spar, closes the pneumatic crossfeed, and shuts off the engine-driven generator power flow), check the fire warning light again, and if still on, actuate the fire extinguisher(s).

[44] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation; Operational / Human Factors Group Report Attachment I, INTERVIEW SUMMARIES and CREW STATEMENTS.

annunciation noted by the crew[45] would typically lead a crew to perform the AC CROSSTIE LOCKOUT ANNUNCIATION procedure.

As noted previously, the crew report of difficulty with the emergency fire handle could not be duplicated after the flight. The handle was fully extended by the first officer; otherwise the handle could not have been rotated to actuate the engine fire extinguisher bottles. The actuation of the handle and extinguishing bottles, though delayed, eventually put out the engine fire.

[45] Cockpit Voice Recorder Group Chairman's Factual Report of Investigation p. 12-55

KNOWLEDGE GAINED DURING THE INVESTIGATION (Findings)

The following summarizes knowledge gained that is pertinent to drawing conclusions:

- The left engine start valve failed in the open position during takeoff or initial climb.
- This was the first report (to Boeing) of a failed start valve due to a start valve solenoid filter disintegration.
- The crew did not, at any time, initiate or complete the start valve open abnormal checklist, the second step of which is to reduce the affected engine's throttle to idle.
- The start valve open condition at high engine thrust resulted in the failure of the starter.
- The failure of the starter resulted in a fire in the left engine and the fire indication in the cockpit.
- Had the crew reduced left engine thrust to idle in a timely manner the severity and the duration of the accident event would have been greatly reduced; and more importantly, a fire most likely would have been avoided.
- The left engine fire warning cockpit annunciation appeared approximately 53 seconds after the cockpit crew noticed the start valve open annunciation. The left engine remained at climb power, which resulted in the supply of pressurized, high-temperature air into the starter area and engine nacelle.
- The cockpit crew initiated the engine fire checklist roughly 40 seconds after the engine fire indication. The left engine was pulled to idle approximately 20 to 25 seconds later.
- The left engine fire handle was initially pulled approximately 3 minutes 35 seconds after the initial fire warning and both extinguishing bottles were discharged into the left engine (the handle has to be fully extended and rotated to discharge the fire extinguisher bottles).
- Prior to the fire handle being pulled to full extension, fuel and hydraulic fluid was still being fed to left engine components, some of which were damaged.
- By the time the fire handle was pulled, extensive damage had occurred to the engine, accessories, and cowling.
- The reported difficulty with pulling the left engine fire handle could not be duplicated on the ground.
- The damaged left engine fuel system introduced fuel to the left engine fire until the left fire shutoff handle was fully activated.
- The left hydraulic system was depleted of fluid due to fire damage, with the fluid apparently feeding the fire at the left engine until the fire handle was pulled.
- Once actuated, the fire handle and components operated per design and extinguished the fire.
- The automatic PTU shutoff mechanism did not shut off the PTU, thus preventing the intact right hydraulic system from powering the landing gear, rudder, steering, flaps, etc.
- The cockpit crew did not accomplish any of the 3 checklists that would have configured the PTU switch to the OFF position. Had the PTU been turned off, power

would have been restored to the right hydraulic system.

- The right hydraulic system was capable of powering the landing gear normally.
- A powered right hydraulic system would have allowed the crew to land on the first attempt, as well as power the flaps to the selected positions and power the rudder hydraulically to assist with engine-out controllability.
- Once on the ground and after the fire was confirmed to be extinguished, the crew opted to continue operation of the right engine. The cockpit crew opened the left pneumatic crossfeed valve to provide additional air conditioning to passengers and crew.
- When the crew opened the pneumatic crossfeed lever the left fire handle was reset, the left fuel and hydraulic shutoff systems reopened, as evidenced by the airport fire crew noting fuel coming from the left engine area. The cockpit crew re-pulled the engine fire handle, again successfully shutting off the flow of fuel to the left engine.
- The passengers and crew deplaned approximately 39 minutes after landing.

CONCLUSIONS

Boeing believes the probable causes of this accident are:

- The failure of the left engine start valve; and
- The left engine thrust remaining at high power for approximately one minute after the left engine fire warning aural and red light annunciations (an emergency procedure requiring immediate action) and two minutes after the crew noticed the amber left start valve open annunciation (an abnormal procedure requiring corrective action).

The cockpit crew appeared to be overwhelmed by the events of this accident, leading to either inaction or untimely actions, which in turn allowed the initial event to escalate from minor to severe. The crew's prioritization and resource management skills were not fully utilized. Consequently, Boeing believes that:

- Contributing to the severity of the event was the cockpit crew's failure to complete appropriate checklists associated with the subsequent (to the start valve open) warnings and indications, which could or would have interrupted the cascading events that occurred during the flight.

The PTU remained in operation during the event. Although several of the checklists mentioned above have steps to turn off the PTU, the automatic shutoff feature (if actuated) could have been helpful to the flight crew. Thus, Boeing believes that:

- Contributing to the duration of the event and flight crew distraction was the continued operation of the PTU after left system hydraulic fluid was lost.

RECOMMENDATIONS

Boeing makes the following recommendations based on the knowledge gained:

- Operators' training should emphasize timely accomplishment of checklists to cockpit crews, to minimize the likelihood of minor abnormal events becoming full-blown emergencies.
- Boeing to continue evaluation of the start valve failure mode evidenced in this investigation.
- Boeing to continue investigation of the PTU automatic shutoff system function and design.

BOEING ACTIONS

As a result of this investigation, Boeing:

- Has revised the MD-80 and MD-90 FCOM Volumes I and II procedures ENGINE FIRE OR SEVERE DAMAGE OR SEPARATION to include a caution note to leave the pneumatic crossfeed valves closed.
- Is evaluating PTU Shutoff System design and function via the formalized Boeing/FAA Continued Operational Safety process.
- Is evaluating appropriate corrective action(s) for the starter motor failure via the formalized Boeing/FAA Continued Operational Safety process.
- Will provide recommended actions to operators, once determined.