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BOEING

31 October 2000
B-H200-17090 -ASI

Mr. Greg Phillips, AS-10
National Transportation Safety Board
490 L'Enfant Plaza East, SW
Washington DC 20594

Subject: Boeing Submission - Egyptair 767-300ER SU-GAP, Accident off Nantucket, Massachusetts - 31 October 1999

Reference: Your letter to Rick Howes, 19 September 2000

Dear ~~Mr. Phillips~~ GREG:

As requested in the reference letter, please find enclosed fifteen (15) copies of The Boeing Company's Submission on the Egyptair 990 accident. As noted, we are also sending copies of this Submission to each of the parties to the investigation.

We would like to thank the NTSB for giving us the opportunity to make this submission beyond the requested date of 07 October 2000. If you have any questions or would like to discuss any of the information contained in the enclosed document, please feel free to call at any time.

Very truly yours,

Ronald J. Hinderberger

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Encl: Boeing Submission to the National Transportation Safety Board on the Egyptair 990 Investigation

cc: Captain M. El Missiry, Head of Egyptian Delegation - ECAA, 5 copies
Captain S. Kelada, Coordinator - Egyptair, 5 copies
Mr. Tony James, Coordinator - FAA, 5 copies
Mr. A. Bahrami, FAA - SACO, 3 copies
Mr. Micheal Bartron, Coordinator, Pratt and Whitney

Submission to the

National Transportation Safety Board

for the

Egyptair 990 Investigation

from The Boeing Company

October 31, 2000

http://www.boeing.com/news/techissues/

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OVERVIEW

INTRODUCTION

On October 31, 1999, at about 0150 eastern standard time (EST) a Boeing 767-366ER, SU-GAP, operated by Egyptair as Flight 990, crashed into the Atlantic Ocean about 60 miles south of Nantucket, Massachusetts. Egyptair 990 was being operated as a scheduled international flight from John F. Kennedy Airport (JFK), New York, New York, to Cairo International Airport in Cairo, Egypt. The flight departed JFK about 0122 EST with 4 flight crew members, 10 flight attendants, and 203 passengers on board. The accident was fatal to all onboard and the airplane was destroyed. Floating debris from the aircraft was recovered on the morning of October 31, 1999.

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) Investigation.
- Our conclusions in this submission are based on factual information, the expertise of our staff, information using analytical tools, and a methodical investigative process. We devoted approximately 13,000 recorded man-hours to this investigation, as well as the use of a simulator, two 767 test airplanes, and other sophisticated equipment.
- Flight control surface movements recorded on the digital flight data recorder (DFDR) are capable of generating the airplane flight path recorded by the DFDR and radar.
- Based on the examination of the recovered wreckage, Boeing did not find any evidence of a failure condition within the airplane flight control system that could have caused or contributed to the initial pitchover, or prevented recovery from the dive.
- Boeing participated in examining all potential failure conditions developed during the investigation and could not find a failure condition that: (1) matched the data recorded on the DFDR or (2) resulted in a condition that was not recoverable by the pilot.
- Therefore, Boeing does not believe that the loss of Egyptair 990 was the result of a mechanical failure of the aircraft or aircraft systems.

INVESTIGATION—BOEING SUPPORT

The NTSB led this investigation with the support of several parties. Investigation activities included identifying, recovering, and sorting wreckage; collecting factual information; and analyzing data using simulations and tests. The NTSB asked all parties to the Egyptair 990 investigation to:

- Submit proposed findings, based on evidence revealed during the course of the investigation.
- Identify, if possible, a probable cause.
- Propose safety recommendations designed to prevent future accidents.

Boeing responded to the NTSB's request with this document, which:

- Provides an assessment of the evidence and other pertinent data.
- Identifies knowledge gained from the investigation and related activities.

Boeing Participation

As an airplane manufacturer, Boeing typically participates as a technical and operational advisor to the accident investigation authorities, in this case led by the NTSB. From the start of the Egyptair 990 accident investigation, Boeing devoted approximately 13,000 recorded man-hours (6.5 man-years)—as well as resources, effort, and expertise—to providing technical support and implementing simulations and ground tests. As the manufacturer of the 767 airplane, our specific role in this investigation was to:

- Provide technical information regarding the airplane design and operation to assist the NTSB's Performance, Systems, and Operations groups in the investigation.
- Host the NTSB and other parties in wreckage examinations, airplane simulations, and ground tests to validate our engineering analysis, and to compare test data to data collected in the NTSB investigation.

Evidence Assessment

The Boeing assessment of the evidence is based on observations and examination of the collected wreckage, the flight and radar data, and the cockpit voice recording. As a party to the NTSB investigation, we analyzed possible failure modes and data from airplane simulations and ground tests, and reviewed other pertinent data gathered during the investigation. Boeing also examined all the DFDR data, which included the last five flights and takeoffs, and there were no anomalies identified that could have caused or contributed to the initial pitchover during the last flight, or prevented recovery from the dive.

Wreckage Examination

Boeing co-examined all of the wreckage that was recovered. This included detailed examination of components selected by the Systems Group. Based on examination of the wreckage that was recovered, Boeing did not find any evidence of a failure condition within the flight control system or any other part of the airplane that could have caused or contributed to the initial pitchover, or prevented recovery from the dive.

(See Appendix A: *Evidence Assessment*, for details of the Boeing evidence assessment of data and other information.)

Simulation Activities

Background

The NTSB Performance Group requested the use of the Boeing 767-300ER engineering simulator to support the Egyptair 990 accident investigation. Three types of simulation analyses were desired: "background" simulations, "backdrive" simulations, and "pilot-in-the-loop" simulations. These simulations are described in Appendix A: Evidence Assessment, *NTSB Simulation Plan*. The NTSB, the FAA, the Egyptian Delegation, and Boeing agreed to a phased simulator plan, which allowed the groups to evaluate incremental improvements to the simulation.

The simulation plan's first phase concentrated on matching the digital flight data recorder (DFDR) and radar data with the standard, 767 symmetric elevator simulator model. Simulation modifications were made to lift, drag, and pitching moment parameters at speeds beyond the dive Mach number 0.91. These results were reviewed with all the parties during a simulator demonstration on December 8 and 9, 1999, in Seattle, Washington. The Boeing 767 engineering simulator cab (E-Cab) was used to observe the backdrive of the simulator match of the DFDR and radar data. The NTSB Operations Group also had the opportunity to reproduce the flight profile with pilot-in-the-loop simulator demonstrations.

After the December 1999 demonstration, the group defined the goals for the next phase to include the ability to account for the left and right elevator movements independently, and to continue to improve the aerodynamics model for Mach numbers beyond 0.91. The Systems Group also requested the ability to model the effects of specific hypothetical elevator power control actuator (PCA) failures and/or jam scenarios. The results of this phase were reviewed during the E-Cab demonstrations conducted on March 30 and 31, 2000. During this demonstration, the cockpit voice recorder (CVR) recording was synchronized with the backdrive simulation data. Specific hypothetical elevator control system failures were also demonstrated during the March 2000 simulation sessions. These simulations were conducted for the NTSB Systems Group and are described in Appendix A: Evidence Assessment, *Analysis and Simulations of Hypothetical Flight Control Failures*.

Digital Flight Data Recorder Validation

The Boeing 767-300ER engineering simulator was used to validate the DFDR data for the Egyptair 990 accident. A description of this validation is presented in Appendix A: Evidence Assessment, *Simulator Validation of DFDR and Radar Data*. It used a mathematical pilot to modulate the simulator control column, control wheel, and rudder pedals to achieve a match with the pitch, roll, and heading angles recorded on the DFDR. The left and right elevators were modeled individually to duplicate split elevators recorded on the DFDR. To accommodate the Mach numbers achieved during the recorded dive, the aerodynamic data within the simulation were enhanced with extrapolations beyond the dive Mach number of 0.91. This extrapolation was based on the best aerodynamic data available to the Performance Group and Boeing.

This enhanced simulation provides a good match of the airplane flight profile and the flight control surface angles recorded by the DFDR. In the pitch axis, this validation indicates that the dive from 33,000 feet and the airplane's initial recovery are consistent with the motion of the elevators recorded on the DFDR, and the airplane initiates recovery from this dive when the elevators are moved toward neutral.

Elevator Blowdown

Elevator blowdown angle is the maximum elevator deflection that can be achieved when the aerodynamic forces are counteracting the elevator power control actuators (PCA). The elevator blowdown angles Boeing provided to the NTSB were a function of elevator deflection, stabilizer position, and Mach number. These angles were used in the March 2000 simulator evaluations of hypothetical elevator PCA failures. Questions were raised within the Performance Group as to why these blowdown angles were not also a function of angle of attack. In response to this question, Addendum #1 to the NTSB Aircraft Performance Study[1] contains an estimate of the effects of angle of attack. This study employed theoretical aerodynamics and assumed angle-of-attack relationships to define the elevator blowdown angles that existed during the dive and initial recovery of Egyptair 990.

In response to this addendum estimate, Boeing chose to verify the effects of angle of attack on elevator blowdown angle. This was accomplished by applying standard aerodynamic techniques to existing aerodynamic data for the 767-300ER. This analysis is presented in Appendix A: Evidence Assessment, *Elevator Blowdown.* The basic conclusion of this analysis is that the effects of angle of attack on elevator hinge moment and blowdown angle are very small. This means that the elevator hinge moment and blowdown data originally provided to the NTSB, and used in the March 2000 simulator evaluations of dual PCA failures, are adequate without including the effects of angle of attack.

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[1] NTSB Group Chairman Aircraft Performance Study dated May 4, 2000.

Simulations and Ground Test Validation for Hypothetical Failure Scenarios

During the early stages of the Systems Group investigation, a comprehensive list of failure conditions that could result in airplane pitch changes was developed. When compared with data from the DFDR, all of the failures on this initial list were eliminated from further consideration, with the exception of three elevator system dual failure scenarios. The Systems Group decided that these three failure scenarios required more in-depth assessment to determine the relevance of each to the accident. Therefore, the Systems Group developed a plan for evaluating each of these failures to establish whether any of them could have contributed to the accident. The following failures were evaluated:

1. Dual elevator PCA input disconnect on the right elevator.
2. Single PCA control valve jam and single PCA input disconnect on the right elevator.
3. Dual elevator PCA control valve jam on the right elevator.

Two aspects of each failure were evaluated: (1) the closeness of the matching between the elevator motion that would be produced by the failure and the elevator motion recorded on the DFDR and (2) the control capability of the airplane that would exist following the failure.

The plan for evaluating the failures was split into three phases. The first phase consisted of developing analytical predictions of the effects of each failure. The second phase was broken into two parts: (1) development of a simulator model of each failure based on analytical predictions and (2) validation of each failure by airplane testing. The third phase was an evaluation of each failure using a pilot-in-the-loop simulation.

The product of Phase 1 was a report[2] documenting the analytical effects of each of the three failures. These results indicated that none of the three failures would produce the elevator motion that was recorded on the DFDR. To validate the analytical predictions and simulation response, an airplane ground test was performed as part of Phase 2. During the testing, the actual response of the elevator system to each of the failures was recorded using calibrated flight-test instrumentation. The testing confirmed that the analytical predictions of elevator system response to these failures were correct, and that none of the three failures produced the elevator motion that was recorded on the DFDR.

Using the results of Phases 1 and 2, modifications were made to the 767-300ER engineering simulator to support the final phase of the evaluation. The validated model for each of the failures was implemented in the simulator and showed that none of the three failures produced the elevator motion that was recorded on the DFDR. In addition, each of the failure conditions was evaluated in the simulator by pilots from the NTSB, the FAA, the Egyptian Delegation, and Boeing. All of the pilots who evaluated these failures concluded that the airplane could be controlled to trimmed, level flight[3] using normal piloting techniques, and that none of the failures required exceptional piloting skill.

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[2] Boeing #B-H200-16968-ASI-R2 to the NTSB dated September 29, 2000.

[3] NTSB Systems Group Chairman Factual Report Addendum Regarding the Ground and Simulation Testing dated July 26, 2000.

Also none of these failures were consistent with the DFDR data because:

- The DFDR elevator positions did not displace to the predicted positions during the initial pitch-over.
- The elevator motion subsequent to the initial pitchover indicates that both surfaces were functioning normally.

OPERATIONS

Boeing reviewed all Boeing 767 Operations Manual procedures for the Egyptair 767 airplane. Several scenarios were considered with special attention to the procedures below and the accident flight profile recorded on the DFDR:

- Collision avoidance.
- Rapid descent.
- Engine oil pressure.
- Loss of thrust on both engines.

From Boeing's analysis, Egyptair 990 crew actions were determined to be inconsistent with the performance of standard Boeing recommended operating procedures and training for the 767 airplane.

(See Appendix A: Evidence Assessment, *Operational Procedures*, for details of Boeing's analysis of data and other information.)

SUMMARY

Performance

The data recorded on the DFDR and computed from radar returns define the sequence of events that occurred during the final minutes of Egyptair 990. A detailed description of these events is presented in Appendix A: Evidence Assessment, *Performance Data From the DFDR and Radar*. The 767-300ER engineering simulation provided a good match of the DFDR and radar-derived data. This validation is also described in Appendix A: Evidence Assessment, *Simulator Validation of DFDR and Radar Data*. This match implies that the airplane's initial pitchover from 33,000 feet is consistent with the elevator deflections recorded on the DFDR, and no external disturbances or additional pitching moments are required to match the airplane pitch angles recorded on the DFDR. During the period of time when the Mach number is beyond the dive Mach number of 0.91, the validating simulation requires a small modification in pitching moment as described in Appendix A: Evidence Assessment, *Simulator Validation of DFDR and Radar Data*. The simulation as modified indicates that the airplane has the performance to recover from the dive and climb back to approximately 24,000 feet as indicated by the radar data, even with the engines shut down and the speed brakes extended. During the dive recovery, the DFDR recorded that the left and right elevators split. This elevator behavior is consistent with a breakout between the left and right control columns in the flight deck. Control column breakout occurs by design when sufficient opposing force is applied to the control columns. This permits the left and right elevators to be commanded to move separately, producing an elevator surface split.

Systems

As discussed above, the Systems Group considered a comprehensive list of failure conditions that could result in airplane pitch changes. A detailed analysis was completed of three elevator system dual failure scenarios, which could not be ruled out without further analysis by the Systems Group. The Systems Group analysis showed that although for each failure there is some elevator motion, none of the failures produces the elevator motion that was recorded on the DFDR. An airplane ground test was performed on a representative 767 airplane during which each of the three failures was inserted. This ground testing confirmed the engineering analysis showing that none of the failure scenarios is capable of producing elevator motion that was recorded on the DFDR.

Having ruled out system failures based on the inconsistencies between the elevator failure scenarios and the elevator motion recorded on the DFDR, Boeing believes that the elevator control system was operating normally during Egyptair 990. To ensure that the postulated elevator failures were completely assessed, a simulation of the failures was prepared using the results of the airplane ground testing to model the failure effects. With the failures accurately modeled, a piloted simulation was conducted as part of the investigation activity. The simulation demonstrated that following each of the elevator failures, the airplane can be recovered quickly and trimmed to hands-off level flight. Based on the results of the failure analysis, validation testing, and simulator demonstrations, Boeing believes that none of the three elevator failure scenarios contributed to the accident.

In summary,

- Flight control surface movements recorded on the DFDR are capable of generating the airplane flight path recorded by the DFDR and radar.
- Based on the examination of the recovered wreckage, Boeing did not find any evidence of a failure condition within the airplane flight control system that could have caused or contributed to the initial pitchover or prevented recovery from the dive.
- Boeing participated in examining all potential failure conditions developed during the investigation and could not find a failure condition that: (1) matched the data recorded on the DFDR or (2) resulted in a condition that was not recoverable by the pilot.
- Therefore, Boeing does not believe that the loss of Egyptair 990 was the result of a mechanical failure of the aircraft or aircraft systems.

APPENDIX A: EVIDENCE ASSESSMENT

This appendix provides a summary of Boeing's airplane performance, systems, and operations analysis for Egyptair 990. It describes Boeing's interpretation of the digital flight data recorder (DFDR) and radar information as it relates to airplane performance. It also includes the simulation plan that was established by the National Transportation Safety Board (NTSB), Boeing's simulator validation of the DFDR and radar data, and Boeing's analysis of the effects of angle of attack on elevator hinge moments and blowdown angles. In addition, it describes Boeing's analysis and simulations of hypothetical flight control failures, and analysis of operational procedures.

PERFORMANCE DATA FROM THE DIGITAL FLIGHT DATA RECORDER AND RADAR

The flight trajectory and performance of the aircraft during the Egyptair 990 accident are based upon the information recorded on the DFDR and computed from its radar position with time. The flight performance data available on the DFDR are pressure altitude; computed airspeed; engine rpm; pitch, roll, and heading angle; vane angle of attack; and normal, longitudinal, and lateral acceleration. Mach number is not recorded. The available primary flight controls are left and right elevator angle, left and right inboard and outboard aileron angles, rudder angle, and stabilizer angle. The spoiler positions are not available. Among the flight deck controls, only the speed brake handle position and throttle resolver angle are available. The control wheel and column positions are not recorded. The flight performance data derived from the radar position information are pressure altitude, and the pitch, roll, and heading angles. A number of flight system indicators are available on the DFDR. Two additional indicators that are pertinent to this investigation of flight performance are the autopilot engagement and engine fuel cut signals.

These DFDR and radar-derived data are presented as a function of elapsed time (ET) on figure 1 (page A-4) and figure 2 (page A-5). Figure 1 is devoted to the longitudinal parameters, and figure 2 displays the lateral/directional parameters. Elapsed time is the reference time selected by the NTSB for their Aircraft Performance Study.[4] The data presented in these figures are the DFDR data supplied by the NTSB. These data end at an ET of 37 seconds. The data presented beyond this elapsed time are derived from the radar position information. The NTSB performed these derivations and supplied the radar data presented on these figures. Two additional longitudinal angles computed from the DFDR data are included on figure 1. Body

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[4] NTSB Group Chairman Aircraft Performance Study dated May 4, 2000.

angle of attack is derived from the DFDR vane angle of attack, and flight path angle is obtained by subtracting this body angle of attack from the DFDR pitch angle.

The DFDR and radar-derived data presented on these figures depict the sequence of events that occurred during the final minutes of Egyptair 990. Initially, the airplane was cruising on autopilot at an altitude of 33,000 feet and a Mach number of 0.79. It was holding a magnetic heading of approximately 80 degrees.

At or about an ET of –15 seconds, the center autopilot is disengaged. With the elevators and inboard ailerons freed from the autopilot servo commands that were holding altitude and heading, the airplane pitches down slightly and begins a slow roll to the left. At an ET near –7 seconds, the left and right throttles are retarded to idle as indicated by their throttle resolver angles. Their rate of movement exceeds the maximum auto throttle rate, which implies they were retarded manually. About 1 second after the start of the throttle movement, the left and right elevators move in the trailing-edge down (TED) direction. They eventually move about 3.6 degrees TED. Beginning at an ET near –6 seconds, the airplane begins to pitch down at an initial rate of about 4 degrees per second and then settles down to a constant rate of approximately 2 degrees per second. A nose-down pitch rate is maintained for approximately 20 seconds until a maximum nose-down pitch angle of 40 degrees is achieved near an ET of 15 seconds. During this dive at an ET of approximately 6 seconds, the left and right elevators move an additional 1.5 degrees TED. Before this additional displacement of nose-down elevator, the airplane's normal load factor is approximately 0.2 g's. After this displacement, the normal load factor reaches a minimum of –0.1 g's.

A portion of the Aircraft Performance Study[5] prepared by the NTSB is devoted to deriving corrected pressure altitude, airspeed, and Mach number using the DFDR data. Using these derived data, this study provides some additional information about this extended dive. "At about ET = 8 seconds and about 30,800 feet, the Mach number exceeded the maximum operating Mach number (0.86), and the master warning alarm sounded. At ET = 23 seconds, the Mach number reached a peak value of 0.99 at an altitude of about 22,200 feet. The maximum rate of descent during the dive was about 39,000 feet per minute at ET = 19 seconds and an altitude of about 24,600 feet."

Just beyond an ET of 14 seconds, as the airplane is passing through a corrected pressure altitude of approximately 27,900 feet, the left and right elevators begin to move trailing edge up (TEU) from their maximum TED position. As both elevators continue to move TEU, pitch angle, angle of attack, and normal load factor begin to recover. Just beyond an ET of 21 seconds, both elevators attain their neutral position, and the normal load factor reaches approximately 1.8 g's.

Just after both elevators achieve their neutral positions between an ET of 21 and 22 seconds, the left and right elevators begin to split or move asymmetrically. The right elevator reverses

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[5] NTSB Group Chairman Aircraft Performance Study dated May 4, 2000.

from the recovery direction it was traveling and moves TED. The left elevator continues to travel TEU beyond its neutral position. In a normal airplane configuration, this would be achieved by a pull on the left control column and a push on the right control column. The split between the left and right elevators continues to the end of the DFDR data at an ET of 37 seconds. The magnitude of the split varies, but the average difference is about 4 degrees. The TEU deflection of the left elevator is generally greater than the TED deflection of the right elevator, which enables the airplane to continue its recovery.

Between an ET of 21 and 23 seconds, the right and left engine fuel cut levers are switched from their "run" position to their "cutoff" position. Between an ET of 24 and 25 seconds, both throttles are advanced to their full forward position, but the earlier fuel cuts prevent the engines from responding. Between an ET of 25 and 26 seconds, the speedbrake handle is moved to its fully extended position. Coincident with this throttle and speedbrake handle activity, between an ET of 24 and 27 seconds, the left elevator moves briefly in the trailing-edge down direction. It moves from 3 degrees TEU to 1 degree TEU before moving back up to 3 degrees TEU. This brief trailing-edge down motion of the left elevator temporarily inhibits the airplane's noseup pitch rate.

During the dive recorded on the DFDR, the lateral/directional motion of the airplane is minimal. The wings remain within 10 degrees of level flight, and the airplane heading does not deviate from the original cruise heading of 80 degrees (magnetic) until the last 17 seconds of recorded data. At an ET of 20 seconds, the airplane begins to turn to the right and reaches a magnetic heading of 85 degrees at an ET of 33 seconds.

Beyond an ET of 37 seconds, the data presented on these figures are based on primary radar returns. These computed pitch, roll, and heading angles and the pressure altitude are provided by the NTSB. These calculations indicate that the airplane recovered from the dive at about 16,000 feet and then climbed back to about 24,000 or 25,000 feet. During this climb, the NTSB derivation indicates that the airplane turned 60 degrees to the right, reaching a magnetic heading of about 140 degrees. The derivation of airplane motion and altitude from radar data was terminated at an ET of 75 seconds. Beyond an ET of 75 seconds, the airplane entered a second dive that continued until impact with the ocean at an ET of approximately 150 seconds. This second dive occurred at much lower altitudes, where fewer radar returns were recorded. As a result, estimates of the airplane's altitude profile and performance were not performed.

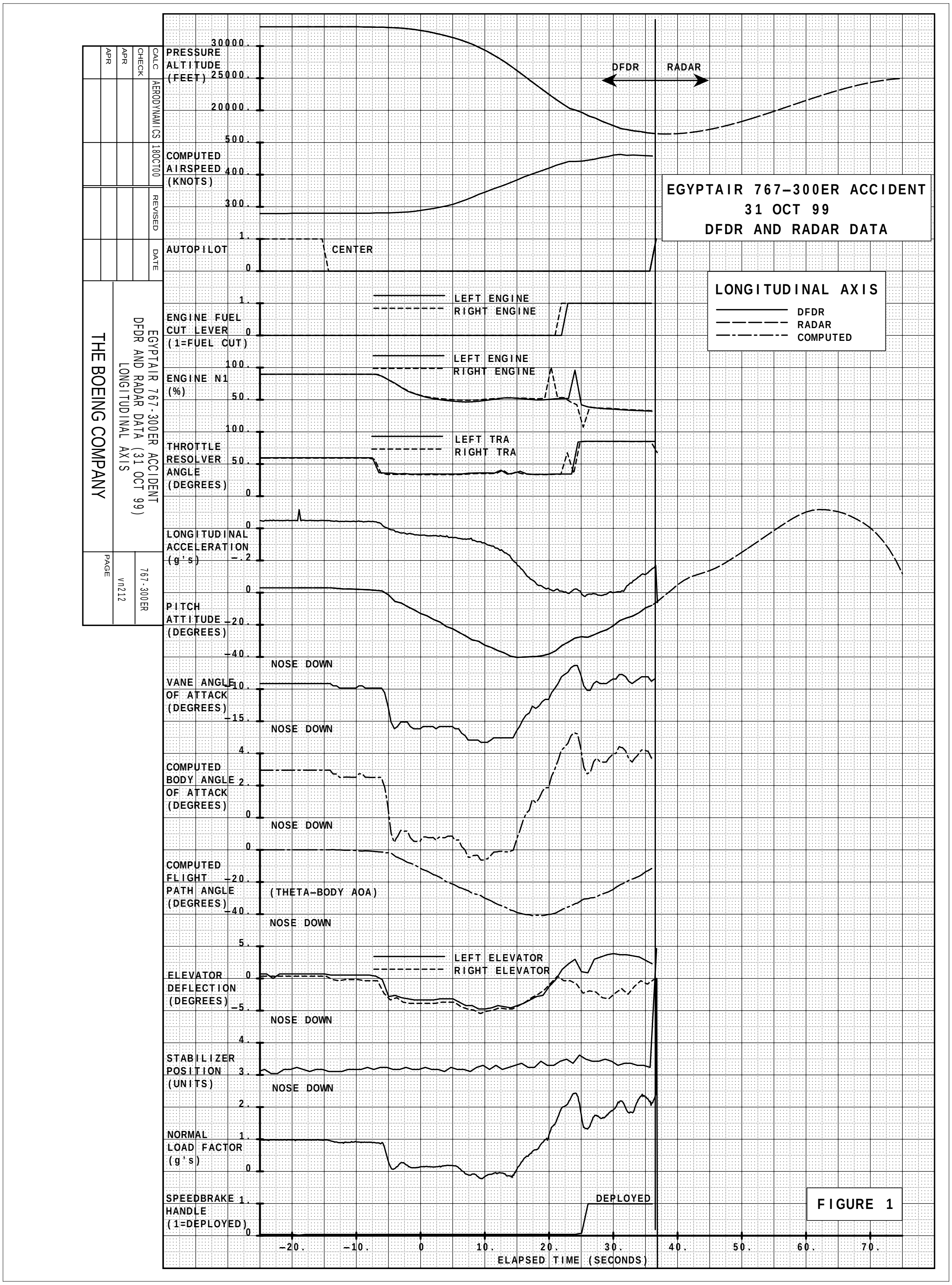
EGYPTAIR 767-300ER ACCIDENT
31 OCT 99
DFDR AND RADAR DATA
LONGITUDINAL AXIS
DFDR
RADAR
COMPUTED
PRESSURE ALTITUDE (FEET)
30000.
25000.
20000.
DFDR
RADAR
COMPUTED AIRSPEED (KNOTS)
500.
400.
300.
AUTOPILOT
1.
0
CENTER
ENGINE FUEL CUT LEVER (1=FUEL CUT)
LEFT ENGINE
RIGHT ENGINE
ENGINE N1 (%)
100.
50.
THROTTLE RESOLVER ANGLE (DEGREES)
LEFT TRA
RIGHT TRA
LONGITUDINAL ACCELERATION (g's)
-.2
PITCH ATTITUDE (DEGREES)
-20.
-40.
NOSE DOWN
VANE ANGLE OF ATTACK (DEGREES)
-10.
-15.
COMPUTED BODY ANGLE OF ATTACK (DEGREES)
4.
2.
COMPUTED FLIGHT PATH ANGLE (DEGREES)
(THETA-BODY AOA)
ELEVATOR DEFLECTION (DEGREES)
5.
-5.
LEFT ELEVATOR
RIGHT ELEVATOR
STABILIZER POSITION (UNITS)
3.
NORMAL LOAD FACTOR (g's)
SPEEDBRAKE HANDLE (1=DEPLOYED)
DEPLOYED
-20.
-10.
10.
20.
30.
40.
50.
60.
70.
ELAPSED TIME (SECONDS)
CALC
CHECK
APR
APR
AERODYNAMICS
18OCT00
REVISED
DATE
THE BOEING COMPANY
EGYPTAIR 767-300ER ACCIDENT
DFDR AND RADAR DATA (31 OCT 99)
LONGITUDINAL AXIS
767-300ER
vn212
PAGE

FIGURE 1

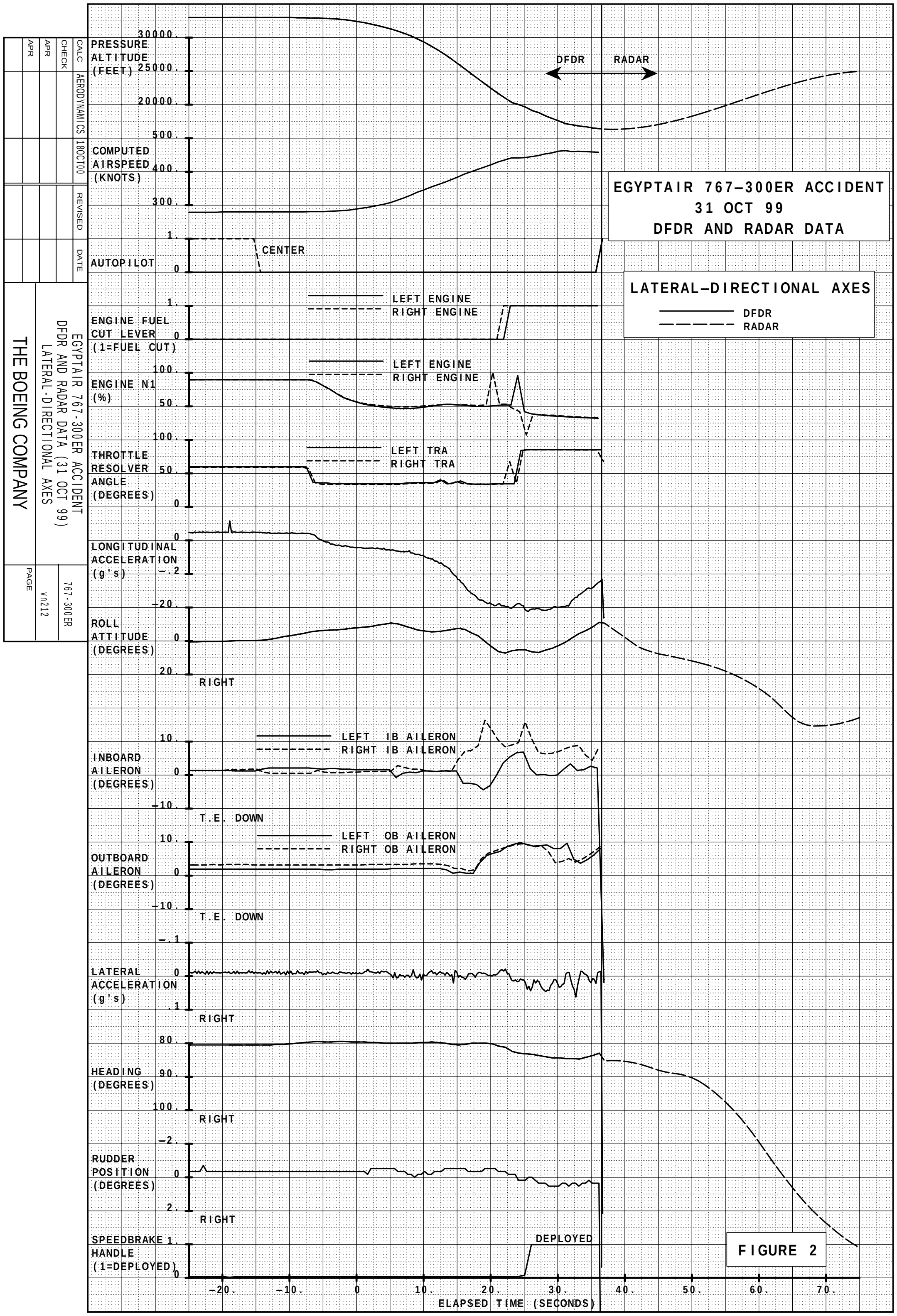

FIGURE 2

EGYPTAIR 767–300ER ACCIDENT
31 OCT 99
DFDR AND RADAR DATA

NTSB SIMULATION PLAN

The NTSB Performance Group requested the use of the Boeing 767-300ER engineering simulator (E-Cab) to support the Egyptair 990 accident investigation. Three types of simulation analyses were desired: "background" simulations, "backdrive" simulations, and "pilot-in-the-loop" simulations. The background simulations were conducted from the engineering (desktop) workstation. The goals of the background simulations were to verify the DFDR and derived radar data, validate the 767-300ER aerodynamic model modifications that were necessary beyond the dive Mach number of 0.91, and determine the control inputs necessary to replicate the flight profile using a math pilot. The backdrive simulations used the results of the background simulation as input to the E-Cab to allow visual representation of flight profile and flight deck control movements. Pilot-in-the-loop simulations allowed individuals to fly the scenarios where inputs from the flight deck directly affect airplane motion, using the updated aerodynamic model and flight control models, as necessary.

During the initial Egyptair 990 Performance Group meeting in November 1999, the NTSB, Boeing, and the Egyptian Delegation agreed to a phased simulator plan to support the Egyptair 990 accident investigation. This phased approach allowed the groups to evaluate incremental improvements to the simulation.

December 1999 Simulations

The goal of the first phase of the simulator plan was to match the DFDR and radar flight profile data through the climb to approximately 24,000 feet with the standard 767 symmetric elevator simulator model and lift, drag, and pitching moment modifications for Mach numbers beyond 0.91. A complete set of aerodynamic model adjustment data for both the December 1999 and March 2000 simulation models were supplied to the NTSB by Boeing.[6] This goal was accomplished in December 1999. The Performance and Operations groups met at the Boeing engineering simulator cab facility in Seattle, Washington, on December 8 and 9, 1999, to review the simulation progress. The groups observed the backdrive of the simulator match of the DFDR and radar data using the E-Cab. The NTSB Operations Group also had the opportunity to reproduce the flight profile with pilot-in-the-loop simulator demonstrations.

March 2000 Simulations

After the December 1999 demonstration, the group defined the goals for the next phase. The groups agreed that the next simulation phase should include the ability to account for the left and right elevator movements independently and to continue to improve the aerodynamics model for Mach numbers beyond 0.91. The Systems Group also requested the ability to model the effects of specific elevator power control actuator (PCA) failures and/or jam scenarios. These goals were met by March 2000, and the E-Cab demonstrations were conducted on March 30 and 31, 2000.

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[6] Boeing letter, B-H200-16960-ASI, dated May 12, 2000.

Because the E-Cab is an engineering tool and not a direct replica of the actual 767-300ER flight deck, the simulator limitations were reviewed before the demonstrations. The most significant limitations relative to the Egyptair 990 investigation are that the E-Cab is fixed-based (motion is not available), and the control column can only be moved symmetrically, although the March 2000 simulation accounted for the dynamics of independently moving elevators. A complete list of simulation limitations has been included in Addendum #2 to the NTSB Aircraft Performance Study.[7]

During the March 2000 simulation demonstrations, the E-Cab was again used to backdrive the data from the background simulation. The cockpit voice recorder (CVR) data was also available and was synchronized with the backdrive simulation data. The CVR allowed the participants to hear the recorded flight deck sounds while they observed the backdriven motion of the column, wheel, rudder pedals, throttles, and speed brake handle supplied by the backdrive simulation. Specific hypothetical elevator control system failures were also demonstrated during the March 2000 simulation sessions. These simulations were conducted for the NTSB Systems Group and are described in the *Dual Elevator PCA Failure Simulation* section of this appendix.

SIMULATOR VALIDATION OF DIGITAL FLIGHT DATA RECORDER AND RADAR DATA

The 767-300ER engineering simulation was used to validate the DFDR and radar-derived data for the Egyptair 990 accident. It examined the dive from 33,000 feet down to 16,000 feet and the climb back to 24,000 feet. This validating simulation is referred to as a background simulation in Addendum #2 to the NTSB Aircraft Performance Study. It used a mathematical pilot to modulate the simulator control column, control wheel, and rudder pedals to achieve a match with the DFDR and radar-derived pitch, roll, and heading angles. The background simulation that was developed for the March 2000 E-Cab evaluations is compared to the DFDR and radar data on figure 3 (page A-9) and figure 4 (page A-10). The longitudinal match is presented on figure 3, and the lateral/directional match on figure 4. The simulator control surface positions are similar to the values recorded by the DFDR. Exact matches between the simulator and recorded control positions are not expected because the DFDR control positions are filtered before they are recorded. These control position similarities imply that the dive occurred in response to the control movements recorded by the DFDR, and not as the result of unusual atmospheric conditions. During the dive, the pressure altitude and calibrated airspeed attained during the simulator match deviate from the raw DFDR data, but agree quite well with the corrected data presented in the NTSB Aircraft Performance Study. This agreement supports the accuracy of the simulation, as well as the static pressure corrections that were developed in the NTSB Aircraft Performance Study.

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[7] NTSB Group Chairman Aircraft Performance Study dated May 4, 2000.

The March 2000 simulation modeled the left and right elevators individually, which enabled it to account for the elevator split shown on the DFDR. The aerodynamic data in the 767-300ER engineering simulation end at its dive Mach number of 0.91. This simulation was enhanced with extrapolations for Mach numbers beyond 0.91 to cover the higher Mach numbers reached during the dive. Most of these extrapolations were based upon available wind tunnel data. These actual data enhancements were supplied to the NTSB by Boeing.[8] For Mach numbers above 0.91, the simulator match was performed with the actual left and right DFDR elevator angles. To achieve a very close match of the pitch angles at these extended Mach numbers, a small artificial "delta Cm trim" was introduced. This incremental pitching moment coefficient is created within the simulation. Without this delta Cm trim, the airplane still recovered from the dive, but it occurred 4 to 5 seconds later at a lower pressure altitude of approximately 14,000 feet. This delta Cm trim was included in the backdrive simulations so the participating pilots would experience the exact flight profile defined by the DFDR and radar data. This small delta Cm trim altered the aerodynamic pitching moments in the simulation at the extended Mach numbers, but did not affect the simulation of the flight controls.

Another benefit of this simulator match of the DFDR data is the calculation of the column forces and angles that were not recorded by the DFDR. These computed column forces and angles are presented on figure 3. They represent what the flight crew would experience with the elevator control system operating normally. When the left and right DFDR elevators are moving together before an ET of 21 seconds, these column forces and angles will exist at either column. When the left and right elevators split between an ET of 21 and 22 seconds, column breakout occurs when the left column is being pulled and the right column is being pushed (note: column breakout is considered normal, though it is not a standard operation). The column breakout forces and angles shown on figure 3 are based on actual breakout evaluations that were performed during ground tests on a 767-400ER. They are different from the column breakout characteristics shown on the March 2000 simulator matches (figures 10a, 12a, and 12c) published in Addendum #2 to the NTSB Aircraft Performance Study.[9] The March 2000 breakout characteristics were based on pre-ground-test estimates. Based upon the ground tests, the estimated March 2000 pull forces are reduced by 25 to 30 percent, while the push forces are unchanged. As for the column breakout angles, the ground tests indicate that the estimated pull angles are reduced by approximately 2 degrees, while the estimated push angles are increased by approximately 2 degrees.

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[8] Boeing letter #B-H200-16960-ASI to the NTSB dated May 12, 2000.

[9] NTSB Group Chairman Aircraft Performance Study dated May 4, 2000.

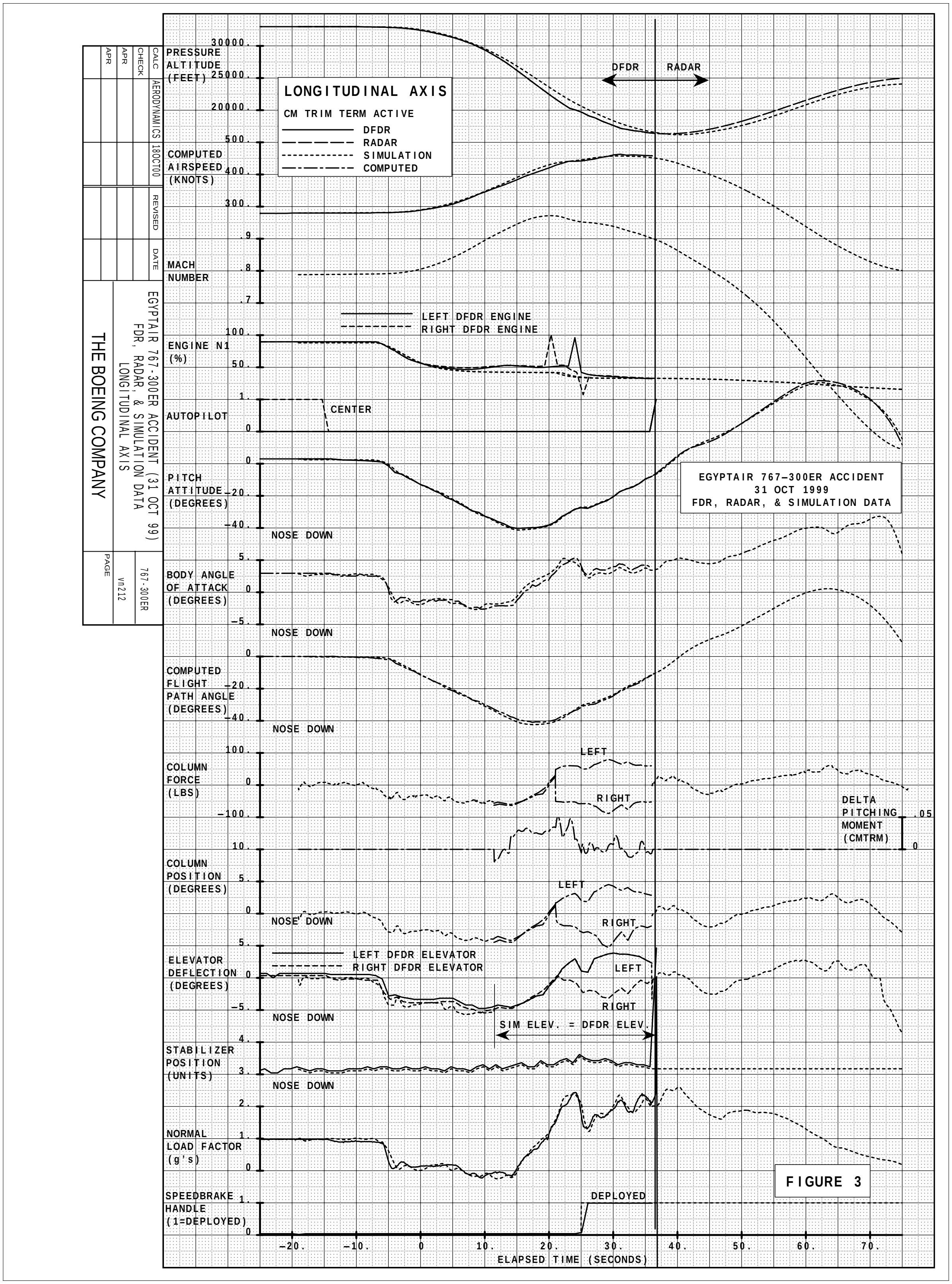
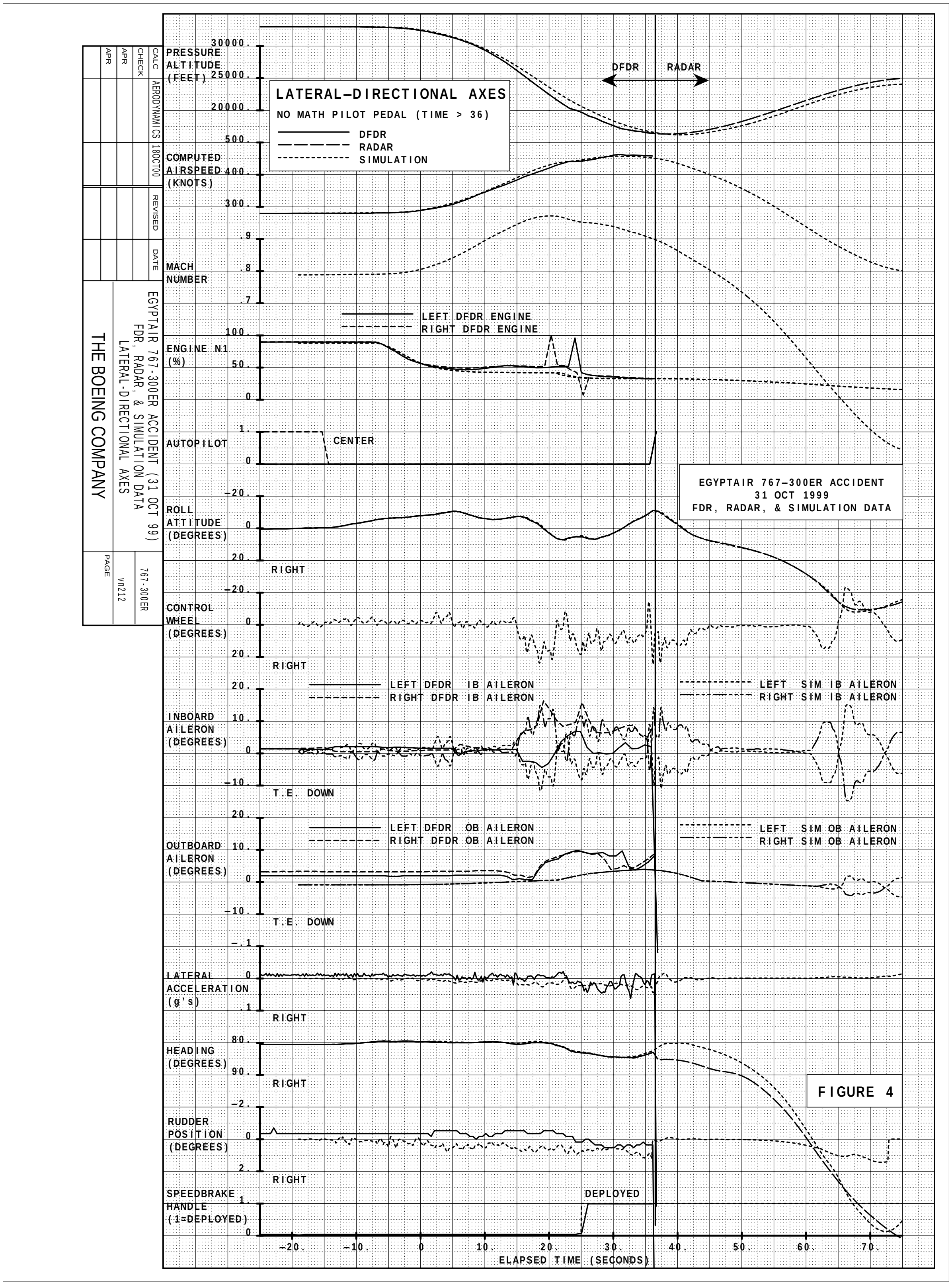

LONGITUDINAL AXIS
CM TRIM TERM ACTIVE
DFDR
RADAR
SIMULATION
COMPUTED
PRESSURE ALTITUDE (FEET)
30000.
25000.
20000.
DFDR
RADAR
COMPUTED AIRSPEED (KNOTS)
500.
400.
300.
MACH NUMBER
.9
.8
.7
LEFT DFDR ENGINE
RIGHT DFDR ENGINE
ENGINE N1 (%)
100.
50.
AUTOPILOT
1.
0.
CENTER
PITCH ATTITUDE (DEGREES)
0.
-20.
-40.
NOSE DOWN
EGYPTAIR 767-300ER ACCIDENT
31 OCT 1999
FDR, RADAR, & SIMULATION DATA
BODY ANGLE OF ATTACK (DEGREES)
5.
0.
-5.
NOSE DOWN
COMPUTED FLIGHT PATH ANGLE (DEGREES)
0.
-20.
-40.
NOSE DOWN
COLUMN FORCE (LBS)
100.
0.
-100.
LEFT
RIGHT
DELTA PITCHING MOMENT (CMTRM)
.05
0
COLUMN POSITION (DEGREES)
10.
5.
0.
NOSE DOWN
LEFT
RIGHT
LEFT DFDR ELEVATOR
RIGHT DFDR ELEVATOR
ELEVATOR DEFLECTION (DEGREES)
5.
0.
-5.
LEFT
RIGHT
NOSE DOWN
SIM ELEV. = DFDR ELEV.
STABILIZER POSITION (UNITS)
4.
3.
NOSE DOWN
NORMAL LOAD FACTOR (g's)
2.
1.
0.
SPEEDBRAKE HANDLE (1=DEPLOYED)
1.
0.
DEPLOYED
-20.
-10.
0
10.
20.
30.
40.
50.
60.
70.
ELAPSED TIME (SECONDS)
CALC
CHECK
APR
APR
AERODYNAMICS
18OCT00
REVISED
DATE
THE BOEING COMPANY
EGYPTAIR 767-300ER ACCIDENT (31 OCT 99)
FDR, RADAR, & SIMULATION DATA
LONGITUDINAL AXIS
PAGE
767-300ER
vn212

FIGURE 3


LATERAL–DIRECTIONAL AXES
NO MATH PILOT PEDAL (TIME > 36)
DFDR
RADAR
SIMULATION
DFDR
RADAR
PRESSURE ALTITUDE (FEET)
30000.
25000.
20000.
COMPUTED AIRSPEED (KNOTS)
500.
400.
300.
MACH NUMBER
.9
.8
.7
LEFT DFDR ENGINE
RIGHT DFDR ENGINE
ENGINE N1 (%)
100.
50.
0
AUTOPILOT
1.
0
CENTER
EGYPTAIR 767–300ER ACCIDENT
31 OCT 1999
FDR, RADAR, & SIMULATION DATA
ROLL ATTITUDE (DEGREES)
–20.
0
20.
RIGHT
CONTROL WHEEL (DEGREES)
–20.
0
20.
RIGHT
LEFT DFDR IB AILERON
RIGHT DFDR IB AILERON
LEFT SIM IB AILERON
RIGHT SIM IB AILERON
INBOARD AILERON (DEGREES)
20.
10.
0
–10.
T.E. DOWN
LEFT DFDR OB AILERON
RIGHT DFDR OB AILERON
LEFT SIM OB AILERON
RIGHT SIM OB AILERON
OUTBOARD AILERON (DEGREES)
20.
10.
0
–10.
T.E. DOWN
LATERAL ACCELERATION (g's)
–.1
0
.1
RIGHT
HEADING (DEGREES)
80.
90.
RIGHT
FIGURE 4
RUDDER POSITION (DEGREES)
–2.
0
2.
RIGHT
SPEEDBRAKE HANDLE (1=DEPLOYED)
1.
0
DEPLOYED
–20.
–10.
0
10.
20.
30.
40.
50.
60.
70.
ELAPSED TIME (SECONDS)
CALC
CHECK
APR
APR
AERODYNAMICS
18OCT00
REVISED
DATE
EGYPTAIR 767-300ER ACCIDENT (31 OCT 99)
FDR, RADAR, & SIMULATION DATA
LATERAL-DIRECTIONAL AXES
THE BOEING COMPANY
767-300ER
vn212
PAGE

ELEVATOR BLOWDOWN

A portion of Addendum #1 to the NTSB Aircraft Performance Study[10] computed the elevator blowdown angles that existed during the dive and initial recovery of Egyptair 990. The effect of angle of attack was incorporated in these calculations because this effect was not included in the blowdown angles provided to the NTSB by Boeing.[11] Addendum #1 accounted for angle of attack with a two-step method. First it determined the angle of attack at the horizontal tail using a theoretical expression for downwash angle. Then it adjusted the elevator hinge moments for these changes in tail angle of attack using an estimated slope of elevator hinge moment coefficient with tail angle of attack.

Boeing chose to verify these angle-of-attack effects on the elevator blowdown angles. This was accomplished by computing the downwash angles at the horizontal tail and the changes in elevator hinge moment coefficient with tail angle of attack using standard aerodynamic techniques. The downwash angles were determined using the tail on and off pitching moments provided to the NTSB by Boeing.[12] The changes in elevator hinge moment coefficient with horizontal tail angle of attack were determined from the same wind tunnel test that provided these hinge moments without these effects. The effects of angle of attack were obtained during this testing, but they were not included in the published data.[11] They were considered to be secondary in nature and were excluded due to data storage limitations. Like the original hinge moment coefficients, these new wind tunnel coefficients were adjusted to match the original flight-test results.

Using these newly derived downwash angles, the tail angles of attack were determined for the accident dive out to a Mach number of 0.91. The body angles of attack derived from the DFDR vane angles of attack and the DFDR stabilizer angles were used in this determination. These same angles along with the DFDR elevator angles were then applied to the newly derived set of elevator hinge moment coefficients to provide the coefficients that existed during the dive. These coefficients were then combined with control surface area and chord, and the dynamic pressures that existed during the dive to define the actual hinge moments that were acting on the elevator surfaces. These dynamic pressures were based upon the corrected Mach numbers and altitudes provided in the NTSB Aircraft Performance Study.

These elevator hinge moments define the elevator blowdown angles that will exist during the dive. Using the actuator geometry and load pressure characteristics of the elevators,[11] these blowdown angles were determined for one hydraulic system operating and with a dual power control actuator (PCA) failure. As was noted in Addendum #1 to the NTSB Aircraft Performance Study, the net hinge moment with a dual PCA failure is equivalent to 78 percent

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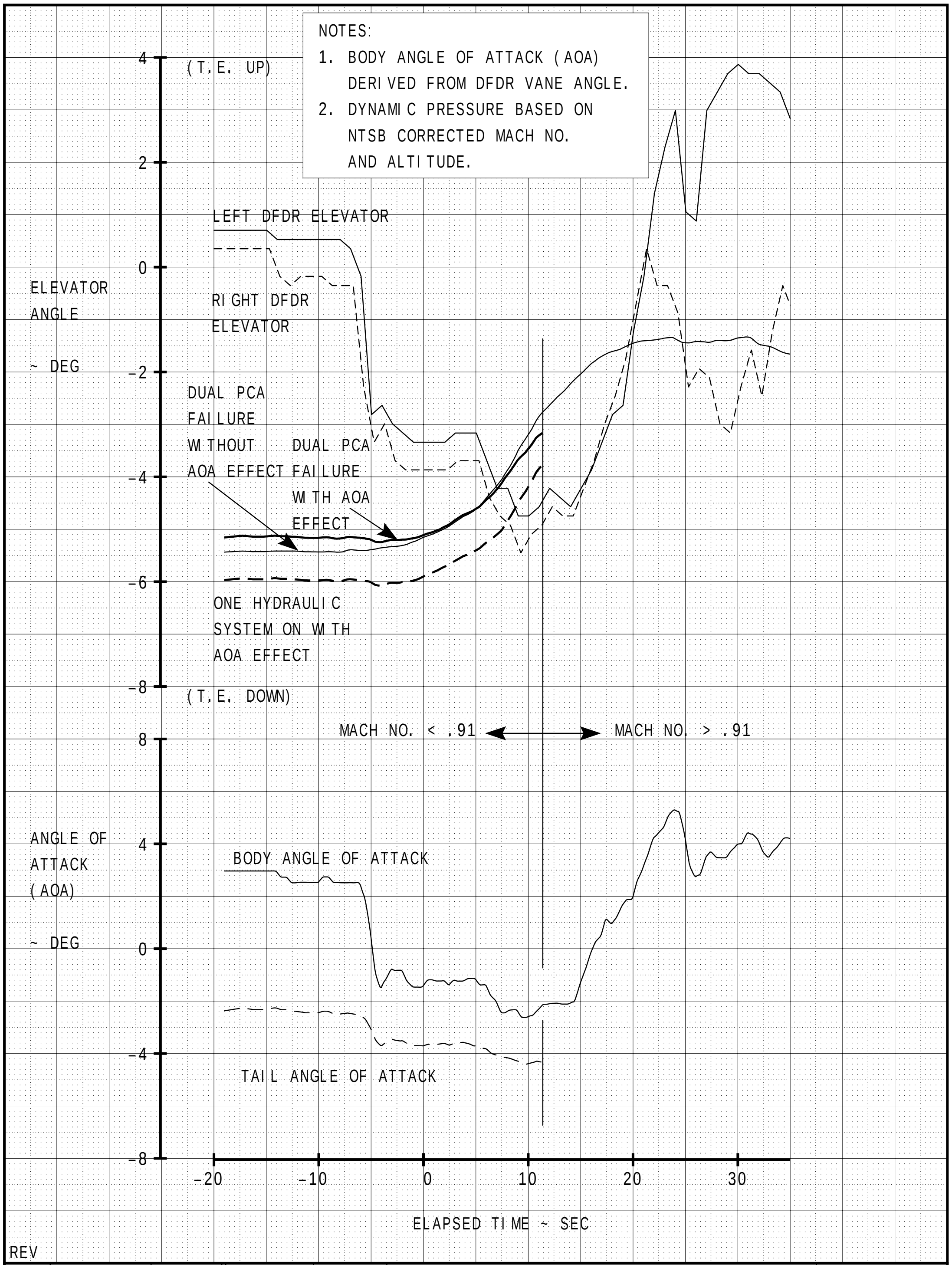
[10] NTSB Group Chairman Aircraft Performance Study dated May 4, 2000.

[11] Boeing Document D613T161, Flight Control System Data for the 767 Training Simulator.

[12] Section 5 of Boeing Document D611T305, Aerodynamic Data for the 767-300ER Crew Training Simulator.

of the maximum force with one hydraulic system operating. They are plotted versus elapsed time on figure 5 (page A-13). The actual elevator angles recorded by the DFDR are also shown, along with the body and tail angles of attack that were used in this analysis. The elevator blowdown angles based upon hinge moment coefficients that do not account for angle of attack are also presented for the dual PCA failure. They are presented for the entire DFDR time interval because the original elevator hinge moments were extended beyond a Mach number of 0.91. These Mach extended hinge moments and blowdown angles are the data that were used in the March 2000 simulator evaluations of dual PCA failures. These simulations are described in this appendix in the *Dual Elevator PCA Failure Simulation* section.

This analysis shows that the effects of angle of attack on elevator hinge moment and blowdown angle are quite small (as much as 0.3 degrees of elevator blowdown angle for a portion of the dive). This minimal effect justifies the level and shape of the elevator blowdown data used in the March 2000 evaluations of hypothetical dual PCA failures. It also supports the exclusion of angle of attack as a variable during the original formulation of elevator hinge moment coefficients.



NOTES:
1. BODY ANGLE OF ATTACK (AOA) DERIVED FROM DFDR VANE ANGLE.
2. DYNAMIC PRESSURE BASED ON NTSB CORRECTED MACH NO. AND ALTITUDE.

CALC	AERODYNAMICS	18OCT00	REVISED	DATE	ELEVATOR BLOWDOWN EFFECT OF ANGLE OF ATTACK EGYPT AIR 990 (OCT 31 1999)	767-300ER
CHECK						FIGURE 5
APPD.						
APPD.					BOEING	PAGE

ANALYSIS AND SIMULATIONS OF HYPOTHETICAL FLIGHT CONTROL FAILURES

Background

During the early stages of the investigation of the Egyptair 990 accident, the Systems Group met to develop a plan for evaluating any airplane system failure that could be relevant to the investigation. Many system failures were assessed during this stage, but the focus of the Systems Group activities quickly turned to the flight control system, and specifically the pitch control systems. Of all the failure scenarios assessed by the Systems Group, there were three that the group decided could be relevant to the investigation. The group's decision was based on the similarity of the effects of these three postulated failures to the data recorded on the DFDR. Boeing was then tasked with providing detailed documentation of the effects of each of the three failures. The three failures covered in the Boeing documentation were:

1. Dual elevator PCA input disconnect.
2. Single PCA control valve jam and single PCA input disconnect.
3. Dual elevator PCA control valve jam.

A description of the effects of each of these failures on one elevator control surface is presented below. All forces are referenced to the control column.

Following the dual PCA failure analysis discussion, there is a discussion of the ground testing and simulation of these failures. The ground testing was done by inserting each of the three failures on a test airplane and recording the system effects using certified flight test instrumentation. The results of the testing and analysis were used to model the effects of each of the three failures in the 767-300ER engineering simulator. Once completed, the simulation model representing each of the three failures was coupled with the validated aerodynamic model (discussed above), and the integrated simulation was used to demonstrate these failures to pilots from the Operations Group.

Dual Elevator Power Control Actuator Input Disconnect

Summary of Effects

- Steady-state position of failed surface—80 percent[13] of single PCA blowdown.
- Steady-state position of nonfailed surface—this elevator remains at neutral.
- Subsequent control of nonfailed elevator is available from either column with normal feel forces; autopilot will control nonfailed elevator normally.

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[13] The value of 80 percent, which is used throughout this section, is slightly different than the value of 78 percent used in the previous section. The reason for the difference is the assumption of 3,000 psi maximum system pressure in this section versus 2,950 psi maximum system pressure in the previous section.

Explanation

This failure condition can be caused by failure of any of the components that comprise the PCA input linkage system, including the bellcranks. The affected surface would be driven away from neutral by the two failed actuators and would apply a force of 5 pounds in the direction of the failure to the slave cable through the lost motion override mechanism. This force would be reacted by the slave cable lost motion override mechanism on the nonfailed elevator. Because the slave cable mechanisms on both elevators have the same breakout force setting, the net force applied to the input of the nonfailed elevator would be zero; hence, there would be no movement of this elevator and no change in the forces required at the control column to position the elevator. The autopilot or either pilot would still be able to control the nonfailed elevator normally. The failed elevator would continue moving away from neutral until reaching a position equivalent to 80 percent of the single PCA blowdown position.

Single PCA Control Valve Jam and Single PCA Input Disconnect

Summary of Effects

- Steady-state position of failed surface—80 percent of single PCA blowdown.
- Steady-state position of nonfailed surface—position equivalent to 15 pounds on feel curve at given flight condition.
- Subsequent control of nonfailed elevator is available from either column with 15-pound bias in the direction of the jammed PCA; autopilot will continue to control nonfailed elevator but has reduced force authority in the direction opposite failed elevator.

Explanation

The failed elevator would be driven away from neutral by the two failed actuators, and the nonfailed elevator would remain under the control of the pilot or autopilot (the autopilot has sufficient authority to override the effects of the jammed control valve). The failed elevator would apply a force of 5 pounds to the slave cable through the slave cable override mechanism, and this force would be reacted by an equal and opposite force from the override mechanism on the nonfailed elevator. The net result would be no force applied to the PCA input from the override mechanism. The final position of the failed elevator would be equivalent to 80 percent of the single PCA blowdown position.

The nonfailed elevator would remain under the control of either the pilot or the autopilot. However, the jammed PCA control valve would cause a force bias of 15 pounds to be applied to the system. This force bias would cause the nonfailed surface to move to an offset position corresponding to 15 pounds of feel force and would result in reduced autopilot authority in the direction opposite the jammed PCA.

Dual Elevator PCA Control Valve Jam

Summary of Effects

- Steady-state position of failed surface—80 percent of single PCA blowdown.
- Steady-state position of nonfailed surface—position equivalent to 30 pounds on feel curve at given flight condition.
- Subsequent control of nonfailed elevator is available from either column with a 30-pound force bias within the limitations noted below; autopilot control is available only in the direction of the failed surface.

Explanation

The failed elevator would be driven away from neutral by the two failed PCAs, and the nonfailed surface would remain under the control of the pilots. The final position of the failed elevator would be equivalent to 80 percent of the single PCA blowdown position. The slave cable lost motion override devices apply zero net force to the input side of the system because the forces from the left and right devices are equal and opposite and therefore exactly nullify each other.

The nonfailed elevator would remain under the control of either pilot. However, the jammed PCA control valve would cause a force bias of 30 pounds to be applied to the system. This force bias would cause the nonfailed surface to move to an offset position corresponding to 30 pounds of feel force.

Dual Elevator PCA Failure Ground Test

The objective of the ground test was the validation of the analytical predictions of the elevator PCA failure scenarios documented by Boeing.

The two single-failure scenarios and three dual-failure scenarios tested in a two-phase ground test were:

- Single PCA input disconnect.
- Dual PCA input disconnect.
- Single PCA control valve jam.
- Single PCA control valve jam and single PCA input disconnect.
- Dual PCA control valve jam.

Results from the ground test were as predicted by engineering analysis.

A 767-400ER model aircraft located at Boeing Field in Seattle, Washington, was used as a testbed for the ground tests. It was equipped with flight-test instrumentation in support of certification of the 767-400ER. This instrumentation allowed the required test parameters to be easily and accurately recorded. The Systems Group agreed that this airplane was an acceptable testbed to validate the analytical predictions of the selected elevator PCA failure scenarios.

Testing was planned and completed in two separate phases:

Phase 1: Demonstration of single and dual PCA input disconnects—completed March 29, 2000.

Phase 2: Demonstration of a single PCA control valve jam, a single PCA input disconnect combined with a single PCA control valve jam, and dual PCA control valve jams—completed April 20, 2000.

Phase 1

Phase 1 of the elevator dual fault ground test was conducted on March 29, 2000, with the participation of several representatives from the NTSB, the Federal Aviation Administration (FAA), the Egyptian Delegation, and Boeing. Two PCA failure scenarios were examined, with the failures inserted on the right elevator: (1) inboard PCA input disconnected and (2) inboard and middle PCA inputs disconnected. Data was also recorded for the baseline condition with all PCAs connected. For each condition, column sweeps were conducted from the pilot and copilot control columns. Additionally, “split” sweeps were done with one column held fixed at neutral and the other moved fore and aft. Conditions were run at zero airspeed (base elevator feel pressure) and at a simulated airspeed of 370 knots (elevator feel pressure of 770 psi), which was consistent with the Egyptair 990 conditions recorded on the DFDR.

The results of the Phase 1 ground test confirmed the failure effect analysis previously provided by Boeing.

As predicted, a single PCA input disconnect allowed control of both elevator surfaces from either column. There was an offset of approximately 1.5 degrees of the elevator surface with the disconnected PCA input. The offset was caused by the loads of the disconnected PCA on the elevator surface.

As predicted for the dual elevator PCA input disconnect conditions, the failed surface traveled to a position equivalent to 80 percent of the single PCA blowdown position, or full travel elevator nose-down position, because no airloads existed during the ground test. As expected, the nonfailed elevator control surface did not move as a result of the failure. Control of the nonfailed surface was available from either column with normal feel forces.

Phase 2

Phase 2 of the elevator dual fault ground test was conducted on April 20, 2000, with the participation of several representatives from the NTSB, the FAA, the Egyptian Delegation, and Boeing. Three PCA failure scenarios were examined, with the failures inserted on the right elevator: (1) middle PCA control valve jammed, (2) middle PCA control valve jammed and the inboard PCA input disconnected, and (3) middle PCA and inboard PCA control valves jammed. For each condition, column sweeps were conducted from the pilot and copilot control columns. Conditions were run at zero airspeed (base elevator feel pressure) and at a simulated airspeed of 370 knots (elevator feel pressure of 770 psi).

The results of the Phase 2 ground test confirmed the failure effect analysis provided by Boeing.

For the single PCA control valve jam scenario, both elevator surfaces were controllable from either column. The nonfailed surface moved nose down to an equivalent of approximately 15 pounds of column force, while the jammed side surface moved approximately 1.5 degrees more nose down than the nonfailed side. The offset was caused by the loads of the jammed PCA on the elevator surface.

For the single PCA control valve jam combined with a second PCA input disconnected failure scenario, the failed surface traveled to a position equivalent to 80 percent of the single PCA blowdown position, or full travel elevator nose-down position because no airloads existed during the ground test. As predicted, the jammed PCA backdrove the nonfailed surface until the associated PCA input pogo broke out due to the opposing feel and centering forces. The nonfailed surface moved nose down to an equivalent of approximately 15 pounds of column force. Control of the nonfailed surface was available from either column.

For the failure scenario with two jammed PCAs, the failed surface traveled to a position equivalent to 80 percent of the single PCA blowdown position, or full travel elevator nose-down position because no airloads existed during the ground test. As predicted, the two jammed PCAs backdrove the nonfailed surface until the associated PCA input pogos broke out due to the opposing feel and centering forces. The nonfailed surface moved nose down to an equivalent of approximately 30 pounds of column force. Control of the nonfailed surface was available from either column.

Ground test data plots originally submitted to the NTSB[14] contained instrumentation biases on the captain’s and first officer’s control column force. Due to temperature effects, the column force instrumentation biases varied during the testing. The column force instrumentation biases were offsets and had no effect on the gain. At the request of the NTSB Systems Group chairman, instrumentation biases were removed from both the captain’s column force and first officer’s column force, and the data was resubmitted to the NTSB.[15]

Dual Elevator PCA Failure Simulation

A simulation session was conducted on the Boeing 767-300ER engineering simulator on March 31, 2000, in support of the Egyptair 990 accident investigation. Participants in the simulation

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[14] Boeing letter #B-H200-16956-ASI to the NTSB dated May 10, 2000.

[15] Boeing letter #B-H200-17018-ASI to the NTSB dated July 24, 2000.

session included the NTSB, the FAA, the Egyptian Delegation, and Boeing. The objective of the simulation session was to evaluate the acceptability of airplane control following each of the three dual elevator PCA failure scenarios and to compare this failure scenario data with the Egyptair 990 DFDR data.

The simulation session used the validated 767-300 airplane simulation that was modified so that three different types of dual elevator PCA faults could be inserted on the right elevator with the click of a button. The three types of dual elevator PCA failure scenarios modeled in the simulator were: (1) dual elevator PCA input disconnects, (2) a single elevator PCA control valve jam combined with a single elevator PCA input disconnect, and (3) dual elevator PCA control valve jams. The modifications to the simulation were based on a Boeing analysis of the system-level failure effects of the dual elevator PCA faults, which was later confirmed by ground testing on a 767 airplane. This analysis and the results of ground testing were submitted to systems group members in attendance.

The insertion of dual elevator PCA input disconnects on the right elevator has one failure effect. The failure effect is that the right elevator moves nose down to 80 percent of the single PCA blowdown limit, which varies as a function of impact pressure. While the right elevator ceases to respond to pilot commands, the left elevator continues to respond normally to pilot commands from either control column. The insertion of dual elevator PCA input disconnects results in a very large and immediate split between the two elevator positions because the failed elevator moves as a direct result of the failure while the nonfailed elevator does not. Pilot actions to counter this failure increase the magnitude of the elevator split as the left elevator is moved in the nose-up direction.

The insertion of a PCA control valve jam and a PCA input disconnect on the right elevator produces two failure effects. The first failure effect is that the right elevator ceases to respond to pilot commands and instead moves nose down to 80 percent of the single PCA blowdown limit, which varies as a function of impact pressure. The left elevator continues to respond to pilot commands from either control column; however, the second effect of this type of failure is that a 15-pound nose-down bias force is applied to the control column. At cruise conditions, the insertion of this type of fault causes a large and immediate split between the two elevator positions. Pilot actions to counter this failure increase the magnitude of the elevator split as the left elevator is moved in the nose-up direction.

The insertion of dual elevator PCA control valve jams on the right elevator produces two failure effects. The first failure effect is that the right elevator ceases to respond to pilot commands and instead moves nose down to 80 percent of the single PCA blowdown limit, which varies as a function of impact pressure. The left elevator continues to respond to pilot commands from either control column. However, the second effect of this type of failure is that a 30-pound nose-down bias force is applied to the control column. In accordance with the failure mode, the simulator model also prevents the fault-induced nose-down deflection of the left elevator from exceeding that of the right elevator. At cruise conditions, the insertion of this type of fault causes a moderate initial split between the two elevator positions. Pilot actions to counter this failure increase the magnitude of the elevator split as the left elevator is moved in the nose-up direction.

The results from the simulator indicate that a dual PCA failure is not consistent with the elevator behavior recorded on the Egyptair 990 DFDR. This indicates that a dual elevator PCA failure was not responsible for the pitch upset experienced on Flight 990. For the two types of dual elevator PCA failures that included a PCA input disconnect, the simulator showed that a large split between the two elevator surfaces occurs immediately after the fault is inserted. In contrast, the two elevator control surface positions recorded on the DFDR did not show any significant split until late in the dive. When a dual elevator PCA control valve jam was inserted, the simulator shows that the maximum elevator surface deflection occurs immediately after the fault was inserted, and then decreases as the dynamic pressure increases during the ensuing airplane dive. In contrast, the two elevator control surface positions recorded on the DFDR continue to increase for 15 seconds following the initial nose-down upset. Any dual elevator PCA fault cannot possibly result in two elevator surface positions that increase as the dynamic pressure increases. In addition, the two elevator positions recorded on the DFDR develop a large split late in the dive with both elevators moving rapidly in opposite directions. This elevator motion late in the dive is not related to changes in impact pressure as would be required if a dual-elevator PCA fault had been present.

Before the hypothetical occurrence of a dual elevator PCA failure, it has been presumed that a single failure already existed on one of the elevators. There is no evidence of a single elevator PCA control valve jam on this aircraft before its last flight. The complete set of DFDR data supplied to Boeing by the NTSB includes five takeoffs, including the one before the accident. On the ground, an elevator PCA control valve jam will result in both elevators deflecting approximately 5 degrees. The DFDR data shows no such elevator deflections before any of these five takeoffs.

Pilots representing the NTSB, the Egyptian Delegation, and Boeing evaluated the controllability of the airplane with each type of dual elevator PCA fault present. The dual elevator PCA faults were inserted with the simulator initialized at the flight conditions that existed on Egyptair 990 immediately before its dive. The test conditions included the airplane free response to the failure, an immediate pilot corrective response to the failure, pilot corrective response to the failure after a 5-second wait, and pilot corrective response to the failure after a 20-second wait. Each of the tested dual elevator PCA failure scenarios resulted in the airplane pitching down. The pilot response needed to counter any of these dual elevator PCA faults is simply to pull the control column aft. Excessive column forces are not required and can be applied from either control column. Once the airplane pitch upset is arrested, the aircraft can be trimmed to hands-off level flight. As stated in the NTSB Systems Group chairman's summary of the simulator session and agreed to by all test participants, "all failure scenarios were recoverable to level flight, and all failure scenarios could be trimmed to hands-off level flight." This simulator testing showed that even if a dual elevator PCA fault does occur, the airplane is controllable.

The simulation session showed that none of the dual elevator PCA failure scenarios produce results consistent with the elevator behavior recorded on the Egyptair 990 DFDR. All of the pilots who evaluated these failures concluded that the airplane could be controlled to trimmed, level flight using normal piloting techniques, and that none of the failures required exceptional piloting skill.

Component Examination

The recovered wreckage from Egyptair 990 was reviewed by the Systems Group, which included representatives from Boeing. During the review, the group identified several flight control system components. These components were subjected to more detailed review at NTSB and Boeing facilities. Among the components that were subjected to detailed review were all of the recovered elevator PCAs and input bellcranks to determine whether there was evidence that would indicate these components contributed to the accident. After detailed review of these components, there was no evidence discovered that indicates any of them contributed to the accident. A summary of the findings from the detailed review of the recovered elevator PCAs and bellcranks is provided below.

Boeing engineering specialists participated with members of the NTSB Systems Group by examining selected wreckage in Seattle and Washington, D.C. Group activities and findings have been documented by the NTSB.[16, 17] One of these findings included a cracked shear rivet on the number 5 bellcrank. The significance of the cracked shear rivet with respect to the bellcrank failure could not be determined from the examination of this part. Furthermore, failure of two bellcrank shear joints on the same elevator is one of the failure conditions that the Systems Group evaluated in detail and showed that this failure does not produce the elevator motion recorded on the DFDR, nor does the failure result in unacceptable airplane handling characteristics.

A second finding was from the control valve assembly for elevator PCA number 3. The pin that attaches the spring guide to the control valve slide was found sheared, and the control valve bias spring was found with one coil over the outside diameter of the spring guide. This relationship between the spring guide and the spring coil was studied by Boeing to determine whether it could result in a control valve jam. There was no evidence from the examination that the spring coil or spring guide had contacted adjacent components such that control valve jamming could result. Dual PCA valve jamming on the same elevator is one of the failure conditions that the Systems Group evaluated in detail and showed that this failure does not produce the elevator motion recorded on the DFDR, nor does the failure result in unacceptable airplane handling characteristics.

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[16] NTSB Group Chairman's Factual Report dated May 26, 2000, including Addenda 1 and 2.
[17] NTSB Metallurgy Report #00-071 dated July 19, 2000, including errata contents.

OPERATIONAL PROCEDURES

Boeing participated as members to the Operations Group, CVR Group, and DFDR Group. We evaluated scenarios from the sounds recorded on the CVR and the data recorded on the DFDR relative to the normal and nonnormal 767 operating procedures recommended by Boeing. This evaluation included analysis of factual information collected by these groups and the use of the 767-300ER engineering simulator.

Even though applicable nonnormal procedural callouts were not recorded on the CVR, Boeing evaluated the following scenarios with 767 operational procedures and compared them to the flight profile and data recorded on the DFDR:

- Collision avoidance.
- Rapid descent (767 Boeing Flight Crew Training Manual, pages 2.31 and 2.32).
- Engine oil pressure (767 Boeing Operations Manual, page 03.05.10).
- Loss of thrust on both engines (767 Boeing Operations Manual, page 03.05.05).

In evaluating the collision avoidance scenario, even though there was no traffic collision avoidance system (TCAS) installed on the accident airplane, we concluded that the flight profile recorded on the DFDR was not consistent with Boeing's training and recommendations for a rapid descent maneuver. For example, when the autopilot was disconnected, the airplane continued in level flight for approximately 8 seconds before the pilot flying initiated any control input. This lack of control input is not consistent with what a pilot would do to avoid another flying airplane (or object). If the collision avoidance maneuver was initiated after the 8-second period, then the magnitude of the pitch attitude and duration of rapid descent is not consistent with an avoidance maneuver.

Boeing trains flight crews to perform a rapid descent for several reasons. There are two methods used to perform a rapid descent:

1. maximum use of the autoflight system (autopilot and autothrottle remain engaged).
2. manual control.

Boeing highly recommends and trains to the maximum use of the autoflight system to accomplish the rapid descent maneuver.

In the accident, the autopilot was disconnected. Consequently, our evaluation assumed the pilot flying was performing a manual maneuver. As stated in the Boeing Flight Crew Training Manual (FCTM) for manual flight, the rapid descent is performed:

> *To manually fly the maneuver, disconnect the autothrottles and retard the thrust levers to idle. Smoothly extend speed brakes, disconnect the autopilot, and smoothly pressure the nose down to initial descent attitude (approximately 10 degrees nose down).*

> *About 10 knots before reaching target speed (MMO-VMO), slowly increase the pitch attitude to maintain target speed. Keep the airplane in trim at all times. If MMO-VMO is inadvertently exceeded, change pitch smoothly to decrease speed.*
>
> *Approaching level off attitudes, smoothly adjust pitch attitude to reduce rate of descent. The speedbrake lever should be returned to the down detent when approaching the desired level off altitude. After reaching level flight, add thrust to maintain long-range cruise or other desired speed.*

In comparing this recommended procedure to the actual flight profile recorded on the DFDR, several inconsistencies were noted:

1. The pilot flying did not extend the speedbrakes initially.
2. The pilot flying pitched the airplane from 1 degrees airplane nose up to –40 degrees airplane nose down. This compares to –10 degrees recommended by the FCTM.
3. The pilot flying and the remaining crew increased airplane airspeed from 280 knots to 380 knots during the initial dive maneuver. Boeing recommends using MMO-VMO (0.86 Mach—353.6 knots at FL 266) minus 10 knots, a substantially lower airspeed than recorded.
4. During the initial dive, the airplane pitch was not decreased to maintain a target speed.
5. The pilot flying made no initial attempt to trim the airplane.

Boeing concluded that the flight profile recorded on the DFDR did not match a typical rapid descent profile.

Next, we reviewed the flight profile recorded on the DFDR before both engines were shut down. We assumed, based on the zero-g load factor trace and the engine oil pressure discrete recorded on the DFDR, that the crew saw two engine oil pressure lights illuminate. (It is known by the investigation that this annunciation may occur during zero-g flight conditions from the 767 airplane certification program.) Based on this information, Boeing looked at the scenarios below, even though these associated checklists were not heard to be verbally called for on the CVR, and engine oil pressure began to recover just before the engine fuel switches were moved from RUN to CUTOFF.

- Engine oil pressure (read and do checklist).
- Engine failure/shutdown (read and do checklist).
- Loss of thrust on both engines (memory checklist).

Accident flight data showed that the thrust levers were CLOSED just before the initial pitch-over and before the engine oil pressure discrete was recorded on the DFDR. Approximately 28 seconds after the throttles were closed, a member of the crew moved the fuel control switches from RUN to CUTOFF.

In the Engine Oil Pressure “read and do” procedure, Boeing recommends pilots accomplish the Engine Failure/Shutdown procedure when the engine oil pressure is below the redline limit. This procedure is as follows:

> *THRUST LEVER ....CLOSED*
> *Engine conditions permitting, operate at idle for 2 minutes to allow the engine to cool and stabilize. Disengage the autothrottle if on. [Autothrottles use not recommended under engine inoperative conditions.]*
>
> *FLIGHT CONTROL SWITCH ....CUTOFF*
>
> *APU (If available) ....START*
> *[Provides second generator source.]*

In the accident flight, after the flight control switches were moved to CUTOFF, there was not a successful attempt to regain an alternate source of electrical power because the DFDR stopped recording.

Another scenario assumes the flight crew misinterpreted the engine oil pressure indication with the loss of thrust on both engines. Boeing trains the following procedure to be accomplished from crew memory.

> *ENGINE START SELECTORS ....FLT*
>
> *FUEL CONTROL SWITCHES ....CUTOFF*
>
> *When EGT begins to decrease:*
> *FUEL CONTROL SWITCHES ....RUN*

It is unknown from the CVR or DFDR whether the crew selected the engine start switches to the FLIGHT position, but it is known that the fuel control switches were selected to the CUTOFF position as recorded on the DFDR. The last memory item of the procedure *FUEL CONTROL SWITCHES ....RUN* was not completed in the 16 seconds between selection of CUTOFF and the loss of the DFDR data.

In all three of these scenarios, Boeing concluded that the expected pilot actions were not consistent with crew actions recorded on the DFDR.

APPENDIX B: SYSTEMS

This appendix provides a basic description of the normal operation of each of the primary flight control systems and the electrical and hydraulic power systems that interface with the flight controls. The system descriptions below provide some background for understanding the material in Appendix A.

SYSTEM DESCRIPTION AND OPERATION

The 767-300ER flight control system uses conventional columns, rudder pedals, control wheels, and a speedbrake lever to control hydraulically powered surface actuators. The primary control surfaces consist of two elevators, a single rudder, four ailerons, and six pairs of spoilers. The spoilers assist the ailerons for lateral control and are also used as in-air and on-ground speedbrakes. A moveable horizontal stabilizer provides pitch trim.

Pilot inputs to the column, wheel, and rudder pedals are transmitted to the elevators, ailerons, and rudder, respectively, through mechanical linkages and cable systems. The spoilers are controlled electrically by sensors that are connected to the control wheels and speedbrake lever. They provide inputs to the spoiler control modules (SCM), which process the electronic signals to produce position control signals for the spoiler actuators.

Horizontal stabilizer trim is controlled electrically through thumb switches on the outboard grip of each control wheel; alternate trim is available through a pair of switches on the center aisle stand. The stabilizer is powered by hydraulic motors. Aileron trim and rudder trim are both powered electrically and are controlled through switches on the center aisle stand.

The 767 flight control system includes several subsystems to help meet various requirements and provide control augmentation. These systems include a rudder ratio changer, yaw damper, outboard aileron lockout, and Mach trim.

Elevator Control System

The elevator control system is used to control the airplane pitch attitude. Two elevators are used for maneuvering, with pitch trim provided by the horizontal stabilizer. Elevator control is provided through the pilot's or copilot's control column or by the autopilot servos. The elevator control system is fully powered with no manual reversion capability.

The two control columns are mechanically linked together by a torque tube and jam override mechanism. Dual cable systems are used to transmit the pilot inputs to the rear quadrants. The pilot's cables are routed above the cabin ceiling, and the copilot's cables are routed through the floor beams. The aft quadrants are also mechanically connected through a jam override mechanism. Mechanical linkages connect the aft quadrants to the inputs of the surface actuators. For control path redundancy, there is a slave cable connected between the two elevators to allow position control of both elevators in the event of a linkage disconnect between the aft quadrants and the power control actuator (PCA) inputs.

Each elevator control surface is controlled by three hydraulic actuators, each of which is powered by an independent hydraulic system. The actuators also provide surface restraint for flutter suppression.

Pilot feel forces are provided by a hydromechanical feel system. The feel unit, which is connected to both aft quadrants, provides the feel and centering characteristics. The feel force is generated by a combination of mechanical and hydraulic devices. A hydraulic feel computer generates a variable pressure, based on schedules of pitot impact pressure and horizontal stabilizer position. This variable pressure, with the assistance of a small actuator and mechanical linkages, produces variable column feel gradients.

Stabilizer Control System

The stabilizer control system controls the position of the moveable horizontal tail, which is used for pitch trim.

Manual stabilizer control is provided through thumb switches on the outboard grip of the pilot's and copilot's control wheels. The stabilizer can also be controlled through switches mounted on the center control stand between the pilots' seats. The stabilizer control system includes an automatic mode, which provides a Mach trim augmentation function. The stabilizer is also operated by the autopilot.

The stabilizer is actuated by a dual-load-path ballscrew actuator, which is driven by either or both of two hydraulic motors through a differential (rate-summed) gearbox. One motor is powered by the left hydraulic system, and the other is powered by the center system. The ballscrew is prevented from rotating by a primary and a secondary brake, whenever the actuator is not operating.

Each hydraulic motor is controlled by a separate stabilizer trim control module (STCM). Two independent commands, an ARM and a CONTROL, must be provided to an STCM before it will engage the motor that it controls. For pilot operation, both motors are activated. For autopilot and Mach trim operation, only one motor is activated, resulting in half of the manual-trim rate. The rate of each motor is variable and is scheduled as a function of elevator feel pressure produced by the elevator feel system. When hydraulic pressure is applied to a motor, that motor's secondary brake is released.

Switches are used to limit the maximum range of travel of the stabilizer. Separate limits are implemented for flaps-up and flaps-down operation. Manually operated cutout switches are located on the center control stand near the thrust levers. These switches can be used to deactivate the stabilizer trim system by shutting off hydraulic pressure and hence depressurizing the STCMs in the unlikely event of unscheduled trim. Column-actuated cutout switches allow the stabilizer to move in a direction that follows elevator control inputs through the column, but will prevent excessive movement in the opposite direction.

Lateral Control System—Ailerons and Spoilers

The lateral control system uses two ailerons—one inboard and one outboard—and six spoilers on each wing to control airplane roll attitude. Lateral control is provided through the pilot's or copilot's control wheel or by the autopilot servos. Control of the spoilers for in-air and on-ground speedbrakes is provided through the speedbrake lever. Some lateral control is also provided by the autopilot servos and the aileron trim system. The lateral control system is fully powered with no manual reversion capability.

The ailerons are controlled mechanically through control cables that run through the fuselage to the wheel well. From there, they run to three lateral central control actuators (LCCA), which provide mechanical boost to drive the wing cables and the autopilot interface to the system. The output of the LCCAs drives wing cables, which provide the input to the inboard and outboard aileron PCAs. Each aileron is driven by two PCAs, both of which are controlled by independent hydraulic systems. The outboard ailerons are locked to a faired position for high-speed flight by a lockout mechanism controlled electronically. The two control wheels are mechanically linked together through a jam override mechanism. The aft quadrants are also mechanically connected through a jam override mechanism.

The spoilers are controlled electrically. Triple wheel position sensors located below each control wheel and six speedbrake lever position sensors provide commands to the spoiler control modules. Six spoiler control modules combine the signals from the wheel and speedbrake lever sensors to provide position commands to electrohydraulic servo valves on the spoiler actuators. Each control module controls a symmetrical pair of spoilers—one on each wing. The spoiler control modules also receive actuator position information from sensors in the spoiler actuators, allowing closure of the actuator servo loops. The spoiler control system is a monitored, redundant system. Each spoiler panel is controlled by a single actuator.

An autospeedbrake function is provided to deploy all of the spoilers automatically at touchdown or during a refused takeoff. With the speedbrake lever in its ARMED position, the autospeedbrake system logic will command the autospeedbrake actuator to drive the lever to its fully deployed position at touchdown. The autospeedbrake system will also activate the autospeedbrake actuator to deploy the lever during a refused takeoff.

Pilot feel forces are provided by a mechanical feel system. The feel unit, which is connected to the captain's aft quadrant, provides the feel and centering characteristics. The feel force is generated by a spring-cam mechanism.

The aileron trim system provides lateral axis trim by adjusting the zero-force position of the centering unit. A pair of switches on the center aisle stand control a single-rate electric actuator, which is connected to the feel and centering mechanism.

Rudder Control System

The rudder control system is used to provide directional control of the airplane, yaw damping, and gust load alleviation. Primary rudder control is provided through the pilot's and copilot's rudder pedals. Some rudder control is also provided by the autopilot rollout-guidance servos and the rudder trim system.

The rudder surface is controlled by three hydraulic actuators, each of which is powered by an independent hydraulic system. The actuators also provide surface restraint for flutter suppression. The rudder has no manual reversion capability.

Primary rudder control is provided by the pilot's and copilot's rudder pedals. The rudder pedals are mechanically linked together at the jackshaft of each pedal set. The pedals are connected to the aft control installation by a single set of cables routed through in the crown. Pilot commands are transmitted from the aft cable quadrant to a ratio-changing mechanism by dual control rods. The ratio changer adjusts the gearing between the pedals and the rudder as a function of calibrated airspeed and limits the maximum rudder available from the pedals as speed increases.

Dual control paths connect the output of the ratio changer to a summing linkage, which series-sums the yaw damper servo commands with the pedal inputs. This summing linkage is connected to the rudder PCAs through two control paths.

Pilot feel forces are generated artificially by the feel and centering unit, which includes a cam, cam follower, and spring. The feel unit connects to the aft quadrant.

The rudder trim system allows the pilot to adjust the zero-force position of the feel and centering unit. A rotary switch and knob located on the center aisle stand control an electric trim actuator attached to the feel unit. A position sensor in the actuator provides trim position to an indicator located adjacent to the trim switch.

Yaw damping, turn coordination, and body modal suppression are provided through the two independent yaw damper servos. The servos are controlled independently, and their output positions are summed mechanically. Yaw damper control and monitoring are discussed in a subsequent section.

The rudder pedals also connect to the nose gear steering control system through a centering and interconnect mechanism. When the nose gear is retracted, the nose gear steering system is held at neutral, and movement of the pedals causes the interconnect mechanism to break out of detent. With the nose gear down, rudder control system movements are transmitted to the nose gear control valve through the interconnect mechanism.

Airplane Electrical Power

The 767 electrical power system provides 115-V ac and 28-V dc power for various uses. The power is distributed through the following buses:

- Left and right main ac buses.
- Left and right 28-V dc buses.
- Standby bus.
- dc standby bus.
- dc autoland bus.
- ac autoland bus.

Under normal conditions, the left and right generators provide 115-V ac three-phase power to their respective buses. These buses power the 28-V ac buses through transformers and the 28-V dc buses through transformer rectifier units (TRU). In the event of an electrical failure, the APU generator and the main battery can be used to provide additional power. The loss of either generator will result in the connection of the left and right main ac buses through the bus tie breakers (BTB) and a disconnect of the utility functions. The standby buses will switch to the main battery if the main ac bus voltage drops below a predefined threshold. The dc standby bus is powered directly from the battery; whereas, the standby ac buses are connected to the main battery through an inverter.

Essential flight control operation is independent of electrical power. However, the following functions are powered from the standby system to minimize crew work load following the complete loss of normal ac electrical power.

- Spoiler panels (1, 5, 6, 7, 8, 12).
- Left stabilizer trim, aileron lockout module (SAM).
- Rudder trim.

Airplane Hydraulic Power

Three hydraulic systems are provided on the 767 airplane. The left system is powered by one engine-driven pump (EDP) and one electric motor pump, which is powered by the right main electrical bus. The right system is powered by one EDP and one electric motor pump, which is powered by the left main electrical bus. The center system is powered by two electric motor pumps, an air-driven pump, and a ram air turbine (RAT).

Each of the flight control systems (pitch, roll, yaw) are powered by all three hydraulic systems. The systems are separated to the maximum extent practical.

APPENDIX C: GLOSSARY

Backdrive simulation	Uses the results of the background simulation as input to the simulator cab to allow visual representation of the flight profile and the flight deck control movements.
Background simulation	Simulations conducted from an engineering workstation using the 767-300ER simulation model. It used a mathematical pilot to modulate simulator control column, control wheel, and rudder pedals to achieve a match with the DFDR and radar-derived pitch, roll, and heading angles. It was also used to validate the aerodynamic data modifications that were added for Mach numbers beyond the dive Mach number of 0.91.
BTB	Bus tie breaker
CVR	Cockpit voice recorder
Delta CM trim	Created within a simulation, it represents the incremental pitching moment coefficient that is needed to match the DFDR pitch angle using the left and right DFDR elevator angles.
DFDR	Digital flight data recorder
DFDR filtering	The filtering of control surface positions before they are recorded on the DFDR. This filtering introduces a time lag that filters out the higher frequency motion of the control surfaces.
Downwash angle	An angular measurement of the downward displacement of the airflow behind the wing as the wing develops lift. The aerodynamic downwash angles used in Boeing simulations are effective angles that represent the integrated effect of the wing's wake on the horizontal tail.

E-Cab	The 767-300ER engineering simulation cab used during the December 1999 and March 2000 demonstrations of the Egyptair 990 accident.
EDP	Engine-driven pump
EICAS	Engine indication and crew alerting system
ET	Elapsed time
FCTM	Boeing Flight Crew Training Manual
LCCA	Lateral central control actuator
MMO-VMO	The maximum operating limit Mach number/airspeed. The Mach number/airspeed may not be deliberately exceeded in any region of flight.
NTSB	National Transportation Safety Board
PCA	Power control actuator
Pilot-in-the-loop simulations	Simulations that allowed individuals to fly the simulator from the E-Cab flight deck and directly affect airplane motion using the updated aerodynamic model and the cab controls.
Primary radar returns	The signals that are reflected directly off the aircraft and returned to the radar antenna.
RAT	Ram air turbine
SAM	Stabilizer trim/Aileron lockout Module

SCM	Spoiler control modules
Secondary radar returns	The signals received from the transponder located in the aircraft.
STCM	Stabilizer trim control module
TCAS	Traffic collision avoidance system
TED	Trailing edge down
TEU	Trailing edge up
TRU	Transformer rectifier unit