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BOEING

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B-H200-16968-ASI-R1

Mr. Scott Warren, AS-40
National Transportation Safety Board
490 L'Enfant Plaza, SW
Washington, DC 20594

Subject: Split Elevator Failure Scenario - Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Reference: a) Our letter B-H200-16882-ASI, 08 February 2000
b) Our letter B-H200-16837-ASI-R1, 02 December 1999
c) Our letter B-H200-16854-ASI, 18 December 1999

Dear Mr. Warren:

After review of the reference a) letter, you requested Boeing to incorporate your editorial comments to make the Failure Scenarios more consistent with references (b) and (c). Please find enclosed a revision of reference (a) to accommodate your request.

If you have any questions, please do not hesitate to call.

Very truly yours,

[redacted]

for: Ronald J. Hinderberger
Director, Airplane Safety
Org. B-H200, M/S 67-PR
Telex 32-9430, STA DIR AS
[redacted]

Enclosure:
- Boeing Table, *767 Split Elevators Failure Scenarios,* items 1-18

Cc: Mr. Greg Phillips, NTSB, AS-10

Revision 1 – to remove the proprietary nature of the letter per Scott Warren's request.

767 Split Elevators Failure Scenarios

#	Failure Scenario	Failure Effect	Disposition
1	Single failed elevator body cable	Small elevator offset and limited elevator control from column on side of failure.	This failure would not have caused initial nose-down elevator input recorded.
2	Erroneous stick nudger activation with and without stiff spring	25 pound nose-down force bias (higher if spring is stiff).	This failure does not match the magnitude or rate of the initial nose-down elevator input recorded and it would not have caused the elevators to split.
3	Failed slave cable	Cable friction increase.	This failure would not cause any elevator input and it would not cause elevators to split.
4	Air in hydraulic system and elevated return pressure	Same effect as rate jam, except the condition would be transient.	This failure would not have caused initial elevator input recorded (approx. 1 degree max). Elevator deflection would only last as long as the return transient existed.
5	Position jam in system	Further motion of the elevator on side of jam is inhibited, break-out force is 50 pounds up to 2 degrees of elevator then 65 pounds plus half normal feel forces.	This failure would not have caused initial elevator input, but could cause elevator split; however, both elevators move after the split, indicating there was no jam.
6	Rate jam in system (valve or valve input linkage jam) on a single PCU	Surface would be driven to a position corresponding with 15 pounds at the column for the given flight condition, then input pogo would break-out. 15 pound force bias would remain for further column inputs.	This failure would not have caused initial elevator input.
7	Single linkage disconnect downstream of feel unit	2 degree offset in elevators due to slave cable lost motion. Both elevators can still be commanded by either pilot.	This failure would have resulted in a constant 2 degree offset between the left and right elevators.

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#	Failure Scenario	Failure Effect	Disposition
8	Failed component falling on elevator cables	This could potentially result in some elevator input.	Although this failure could potentially cause some elevator input, there would not be an associated elevator split.
9	Failure of feel unit ground path	System would lose mechanical ground path (no centering), but both surfaces would continue to respond to pilot inputs.	No elevator split would result from this failure.
10	Cable tension regulator failure	Same effect as single body cable failure.	This failure would not have caused initial nose-down elevator input recorded.
11	Dual actuator input failure	Failed actuators would drive system in the direction of the failure until the elevator feel unit produced enough centering force to override the two failed-PCU input pogos. At this point, the input pogos would deflect and disconnect the input side of the system from the output of the actuators and the system would reach equilibrium at this position. Commands of the opposite elevator by either the pilot or first officer are possible in either direction. See the discussion below for a detailed description of the specific effects on control from either column.	Although the initial elevator travel is close to what this failure would produce, the subsequent elevator behavior is not consistent with the failure. See the discussion below for a detailed assessment of this failure with respect to the FDR data.
12	Hydraulic system failure to one surface	Affected surface would be limited to smaller deflections due to reduced blow down limit.	This failure would not have caused initial elevator input. There is no indication of hydraulic system failure. This failure would result in an offset of the left and right elevators, however not a split (one TE up, other TE down).

767 Split Elevators Failure Scenarios

#	Failure Scenario	Failure Effect	Disposition
13	Aft pressure bulkhead failure	Elevator cables could be deflected by this failure, although it is unlikely that this would be the only effect from bulkhead failure.	Although this failure could potentially cause some elevator input, there would not be an associated elevator split. Also, there is no indication of this failure from any other systems (hydraulic systems, pressurization system).
14	Elevator position transducer disconnect (e.g. erroneous indication of split on FDR data)	Position signal recorded on FDR would not track actual elevator movements.	Both elevator position signals track well during initial input. Airplane motion is consistent with recorded elevator motion.
15	Asymmetric hinge moment due to external effect	Large external hinge moment difference between elevators could cause split.	This would not have caused initial elevator input. Hinge moment difference would have to be extremely large to drive elevators differentially.
16	Differential pilot inputs	N/A	The system can be commanded such that the elevators move differentially.
17	Autopilot servo jam and hardover or offset	Both surfaces would be driven hardover or to position corresponding to servo output. Unaffected side can still be commanded after fwd and aft overrides are operated.	Both elevators move after the split, indicating no autopilot servo valve jam condition.
18	Output disconnect of two actuators on the same surface	Affected surface would be limited to smaller deflections due to reduced hinge moment.	This would not have caused initial elevator input. This failure will result in an offset of the L and R elevators, however not a split (one TE up the other TE down).

<u>Scenario 11: Dual PCU Failure on Same Elevator in Same Direction</u>

The following discussion provides a detailed description of the effects of the dual PCU failure mode summarized in the table above. The discussion is provided to clarify the effects of the failure and to evaluate this failure mode relative to the FDR data recorded during Egypt Air Flight 990. In addition, a brief description of the 767 elevator actuation system is provided.

There are two different types of specific failures that need to be considered to address this failure mode completely: 1) A simultaneous jam of the main control valve in two of the three power control units (PCU's) at an offset position on the same elevator and at the same time; and 2) A failure in the input linkage in two of the three PCU's on the same elevator (note that the first of these failures is latent). Each of these cases is discussed below following the actuation system description.

In Revision B of this transmittal, an additional failure combination has been added to the description below. The additional failure is a combination of the first two failures: one PCU has a latent input linkage failure and a second PCU on the same surface has a main control valve jammed. This failure combination is described below in a new section titled Case 3. Also, a correction to the description of the effects of failure Case 2 has been added. The correction is based on the results of a more comprehensive analysis of the interaction between the slave cable override mechanism and the rest of the elevator system following this failure. To support the analysis, a test was conducted using a removed slave cable override mechanism to determine the force that would be applied to the elevator system input by the mechanism attached to the failed elevator. The findings from this test were then used to determine the effect of this added force on the system. The results of this analysis are described below in the section titled Case 2.

Elevator Actuation System Description:

The 767 has two elevators that are attached to the moveable horizontal stabilizer (see Figure 1 for a schematic of the elevator control system). In normal operation, the left and right elevators move together in response to pilot or autopilot commands. Each elevator is positioned by three independent hydraulic actuators, each of which is powered by a separate hydraulic system. Commands from the pilot or autopilot are transmitted to the actuators via cables and push rods to the input of the actuators. In response to a position command, the control valves in the three actuators (see Figure 2 for a schematic of the actuator) move to an open position, which causes high-pressure hydraulic fluid to be directed to the actuator pistons. This causes the pistons to move in the direction of the input command until the desired position is reached. When the actuator pistons reach the commanded position, the feedback linkage moves the control valve back to a closed position and the hydraulic fluid flow is shut off. With the control valve at neutral and hydraulic flow shut off, the static load holding capability is the 20% higher than the maximum hinge moment capability of one actuator (see Note 4 below for an explanation of this).

In the event of passive failure (i.e. loss of output force capability) of any two of the three actuators on one elevator, the remaining actuator provides sufficient output force to move the elevators to the positions
required to maintain pitch control; however, hinge moment capability is reduced to one third of the normal capability. In the event of an active failure (i.e. a runaway or hardover) of one or more actuator, compressible links (pogos) are installed at the input of each actuator. These pogos provide a means of isolating the failed actuator from the rest of the system and allow the pilots to retain control of the position of the elevators to ensure pitch control is maintained following the failure.

To provide an additional layer of protection from active PCU failures, there are also shear rivets installed in the elevator PCU input linkage. If an active PCU failure were to occur and the pogo did not break out as designed, the shear rivet would fail when a column force of 52 pounds is applied at either column. Once the shear rivet is failed, the column forces would return to normal. Details of this failure mode are discussed below. Active failure of an actuator can be caused by failure of the input linkage or by restricted motion of the control valve inside the actuator at an offset position. Each of these failure cases is discussed in detail below.

Case 1: Two of three main control valves on one elevator are restricted to an offset position in the same direction at the same time (note that first failure is NOT latent):

Description of failure: Two of the three PCU control valves on one surface are restricted at an offset position at the same time and in the same direction. In order for this failure to occur, the control valves would first have to be moved, by pilot or autopilot input, to an offset position then jam there.

Effects of failure with Autopilot engaged:

Summary of Effects:

- *Steady-state Position of Failed Surface – 80% of single PCU Blow-down*
- *Steady-state Position of Non-Failed Surface – Position equivalent to 5 pounds on feel curve at given flight condition*
- *Subsequent control of non-failed elevator is available from either column with a 30 pound force bias within the limitations noted below; autopilot control available only in direction of failed surface*

Explanation:

When the failure occurs, the affected elevator would be driven to a position away from the rig neutral position (see Note 5 for a description of the rig neutral position) by the failed actuators. The autopilot servo would respond by commanding the elevators back toward neutral to maintain the original flight path until the servo reaches its authority limit of 25 pounds (see Note 1). The failed actuators would continue driving the surface away from neutral until the input pogos on the failed actuators compress at a force of 30 pounds (see Note 1). The extra 5 pounds to compress the pogos is provided by the feel unit, which provides feel and centering forces proportional to airspeed. At this point, the system input would be deflected an amount equivalent to 5 pounds of feel force at the given flight condition (Figure 3 shows the family of curves describing the relationship between feel force and elevator position). When this force equilibrium is reached, the input side of the system would be decoupled from the failed actuators and the opposite elevator would stop moving. Note also that the slave cable lost motion override devices apply zero net force to the input side of the system since the forces from the left and right devices are equal and opposite and therefore exactly nullify each other. The elevator on the side of the failed actuators would continue moving away from neutral until reaching a position where air loads balance the forces from the failed actuators pushing away from neutral and the non-failed actuator pushing toward neutral. This position would be equivalent to the blow down position for a single PCU with 2400 psi delta pressure across the piston (see Note 2 for an explanation of the net hinge moment resulting from this failure), or 80% of single PCU blow down. Following this failure, autopilot-commanded elevator inputs in the direction opposite the PCU failure would not be possible. An autopilot caution level EICAS message would be set, accompanied by an aural alert.

Effects of failure with Autopilot disengaged:

Summary of Effects:

- *Steady-state Position of Failed Surface – 80% of single PCU Blow-down*
- *Steady-state Position of Non-Failed Surface – Position equivalent to 30 pounds on feel curve at given flight condition*
- *Subsequent control of non-failed elevator is available from either column with a 30 pound force bias within the limitations noted below; autopilot control available only in direction of failed surface*

Explanation:

With the autopilot disengaged, and assuming neither pilot was opposing the failure by providing resistive force at the column, the failed actuators would push the elevator system away from neutral, and the autopilot would not be available to provide a resistive force. The final position of the system would be the position corresponding to the feel force required to deflect the two PCU input pogos (30 lbs., see Note 1) for the specific flight condition at the time of the failure. Note also that the slave cable lost motion override devices apply zero net force to the input side of the system since the forces from the left and right devices are equal and opposite and therefore exactly nullify each other (for a more thorough explanation of this force balance, see failure Case 2 below).

The failed surface would continue moving to a position where airloads balance the net forces acting on the surface (see Note 2). The exact surface position at which the forces of the actuator would be balanced by air loads is a function of airspeed; as airspeed increases, the surface position would decrease and as airspeed decreases, the surface position would increase.

After the elevators reach a steady-state position, either pilot would be able to command both elevators in the direction of the failure and the unaffected elevator in the direction opposite the failure.

The pilot on the same side as the failed elevator would encounter forces equal to the override forces of two PCU input pogos (15 lbs. each for a total of 30 lbs., see Note 1) plus the normal feel forces for the given flight condition up to the point where the input pogos bottom out. At this point, the pilot would have to provide enough force to shear the input shear rivets at the PCU input crank (52 lbs. each for a total of 104 lbs., see Note 1), just upstream of the pogos, in order to command additional elevator in this direction. It is unlikely that the pogos would ever bottom out since the travel available from them is equivalent to 21 degrees of elevator in the direction opposite the failed elevator position. Once the shear rivets are sheared, the forces to continue to deflect the non-failed elevator would revert to the normal feel forces since the shear rivet failure would have completely decoupled the system input from the failed actuator (i.e., the pogo override forces would no longer be required to deflect the surface). There would be no limit in the pilot's ability to command the opposite elevator – the asymmetry limiter would not limit travel since there would be no relative motion of the two aft quadrants. The ultimate limit in this pilot's ability to command the non-failed surface is defined by the position where the system break-out devices engage. This occurs when the pilot applies a force of 130 pounds to the column.

The column forces for the pilot on the side opposite the failed elevator would be slightly different. Initially, both the column forces and the elevator response would be the same as for the other pilot. When the total column force from this pilot reaches approximately 70 pounds (see Note 3), the forward and aft system overrides would break out and the columns would move differentially. For further column deflections, the force gradient would be reduced to half the normal feel unit gradient because only half of the feel unit would then be providing the gradient due to the system break outs. Also, the asymmetry limiter would limit the total differential travel available to 20 degrees from the position where the column break-out first occurred.

Case 2: Two of three PCU's input linkage fail on the same surface (note: that the first failure is latent for up to 400 hours)

Effects of failure with Autopilot engaged:

Summary of Effects:

- *Steady-state Position of Failed Surface – 80% of single PCU Blow-down*
- *Steady-state Position of Non-Failed Surface – this elevator remains at neutral*
- *Subsequent control of non-failed elevator is available from either column with normal feel forces; autopilot will control non-failed elevator normally*

Explanation:

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 non-failed elevator. Since the slave cable mechanisms on both elevators have the same break-out force setting, the net force applied to the input of the non-failed elevator would be zero. This is because the override mechanism on the non-failed elevator is restrained by the PCU's on that surface, which remain in the position commanded by the autopilot. The load path for applying force from the slave cable to the non-failed elevator PCU inputs is through the override mechanism on the non-failed elevator. A force equilibrium would therefore be established between the slave cable override mechanisms on the failed and the non-failed elevators. The mechanism on the failed elevator would apply a force in the direction of the failure, and the mechanism on the non-failed elevator would apply an equal and opposite force to the slave cable. The result is no net force applied to the PCU input linkage. The autopilot servo would still be able to control the non-failed elevator normally. The failed elevator would continue moving away from neutral until reaching a position equivalent to 80% of the single PCU blow down position.

Effects of failure with Autopilot disengaged:

Summary of Effects:

- *Steady-state Position of Failed Surface – 80% of single PCU Blow-down*
- *Steady-state Position of Non-Failed Surface – this elevator remains at neutral*
- *Subsequent control of non-failed elevator is available from either column with normal feel forces; autopilot will control non-failed elevator normally*

Explanation:

The effects would be similar to the case with the autopilot engaged. The non-failed elevator would remain at the position commanded by the pilot and the failed elevator would travel to a position equivalent to 80% of the single PCU blow down position. Control of the non-failed surface would be available from either column and the feel forces would be the same from either column. The feel forces would be slightly higher following this failure due the additive force gradient of the slave cable override mechanism that has to be reacted by the pilot to move the non-failed elevator in the direction opposite the failed elevator. The added force gradient is 0.20 pounds of column force per degree of elevator, so it is likely that the flight crew would not detect the effect of this added force. Also, the asymmetry limiter would not limit differential elevator travel.

Case 3: One of three PCU's input linkage fails and an independent PCU control valve jams on the same surface (note that first failure is latent for up to 400 hours)

Effects of failure with Autopilot engaged:

Summary of Effects:

- *Steady-state Position of Failed Surface – 80% of single PCU Blow-down*
- *Steady-state Position of Non-Failed Surface – Position equivalent to 15 pounds on feel curve at given flight condition*
- *Subsequent control of non-failed elevator is available from either column with 15 pound bias in the direction of the jammed PCU; autopilot will continue to control non-failed elevator but has reduced force authority in direction opposite failed elevator*

Explanation:

Initially, the failed elevator would be driven away from neutral by the two failed actuators and the non-failed elevator would remain under the control of the autopilot since the autopilot servo has sufficient force authority (25 pounds) to override the input pogo (15 pounds) of the PCU with the jammed control valve. As the failed elevator moves away from neutral, the non-failed elevator would be commanded in the opposite direction by the autopilot to control airplane pitch. 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 non-failed elevator. The net result would be no force applied to the PCU input from the override mechanism. The final position of the failed elevator would be equivalent to 80% of the single PCU blow down position. The non-failed elevator would remain under the control of the autopilot. The autopilot servo authority would be reduced to 10 pounds in the direction opposite the jammed PCU for the non-failed elevator.

Effects of failure with Autopilot disengaged:

Summary of Effects:

- *Steady-state Position of Failed Surface – 80% of single PCU Blow-down*
- *Steady-state Position of Non-Failed Surface – Position equivalent to 15 pounds on feel curve at given flight condition*
- *Subsequent control of non-failed elevator is available from either column with 15 pound bias in the direction of the jammed PCU; autopilot will continue to control non-failed elevator but has reduced force authority in direction opposite failed elevator*

Explanation:
The effects would be similar to the case with the autopilot engaged. Assuming that neither pilot restrains the column when it gets back driven by the input pogo from the jammed PCU, the non-failed surface would travel to a deflection equivalent to 15 pounds on the feel curve for the flight condition at the time of the failure. The failed surface would travel to a position equivalent to 80% of the single PCU blow down position. 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 non-failed elevator. The net result would be no force applied to the PCU input from the override mechanism.

Control of the non-failed surface would be available from either column and the feel forces would be the same from either column. Feel force would be the normal forces produced by the elevator feel unit plus a 15 pound bias in the direction of the failed PCU's. The ability of the pilot on the same side as the failed elevator to command the non-failed elevator would ultimately be limited by the system break-out devices. When a force of 115 pounds is applied to this column, the break-out devices would engage and no further input to the non-failed elevator would be possible by this pilot.

Note 1: Forces given are equivalent forces at the control column.

Note 2: With 2 PCU's pushing away from neutral and one PCU pushing toward neutral, the net force moving the elevator away from neutral is derived as follows:

> (2 * (Actuator Piston Area (sq. in)) * (3000 psi)) – (1 * (Actuator Piston Area (sq. in)) * (3600 psi))
>
> 3600 psi is appropriate for the single PCU since it is being back driven by the two failed PCU's, so the internal relief valve must be activated which requires 3600 psi.
>
> This is equivalent to:
>
> 1 * (Actuator Piston Area (sq. in)) * (2400 psi)

Therefore, the net force applied to the surface is equivalent to 80% of the maximum force for a single PCU in the direction of the failed PCU's.

Note 3: The column force at which the system overrides break out is determined as follows:

Because the elevator system has two separate cable runs that are bussed together at the forward and aft ends, forces applied to either column are shared equally between the two cable runs. This is true until the differential force between the two cables reaches a value equivalent to the override break out force of 50 pounds at the column. When this happens, the overrides break out and the column to which force is being applied will continue moving while the other column remains at the position where the differential forces reached 50 pounds.

For normal operation, differential cable loads do not reach the break out level until column force equals approximately 100 pounds. At this force, there is a cable load of approximately 50 pounds (equivalent column force) in each cable. The feel unit is attached to each aft quadrant, as shown in Figure 1, and each feel unit connection provides approximately half of the total feel forces, therefore the centering force at each aft quadrant at this instant is approximately 50 pounds acting in a direction to return the system to neutral. The column force to move the system to this point is applied to only one column, so the load in the opposite cable is transferred through the system break outs and the differential load across the break outs reaches 50 pounds when the total column force equals 100 pounds.

With the dual PCU failure present, there is an additional force at the aft quadrant on the side of the failure equal to 30 pounds, which is the force required to override the two PCU input pogos. This force is added to the centering force from the feel unit at this aft quadrant and when the total reaches 50 pounds, the system overrides break out. This happens when the total column force reaches 70 pounds; 30 pounds to override the pogos; and 40 pounds split equally between the two cables.

Note 4: When the main control valve of one of the elevator PCU's is at neutral (which is the case whenever the PCU piston is not moving), the load holding capability of the PCU is 20% higher than the maximum output force of the actuator. Following is an explanation of this characteristic.

The maximum output force from any one elevator PCU is achieved when the maximum available hydraulic system supply pressure (3000 psi) is applied to one side of the actuator piston and hydraulic system return pressure (50 psi) is applied to the opposite side of the piston. This condition gives a differential pressure of 2950 psi across the actuator piston and when multiplied by the actuator piston area gives the maximum output force capability of the actuator.

For a failure condition where one of the actuators is being backdriven by the output of the other two actuators, there is a pressure relief valve installed in the actuator which allows hydraulic fluid flow from one side of the actuator piston to the other. For the failures being considered above, the two failed PCU's would have to drive against the holding force of the non-failed PCU. The holding force is established by the pressure value at which the relief valve opens and allows fluid flow from one side of the piston to the other. In the case of the 767 elevator PCU's the cracking pressure of the relief valves is 3600 psi. Therefore, the maximum holding force of one elevator PCU is 3600 psi multiplied by the actuator piston area. In the event of a dual PCU failure with both failures in the same direction, the total force moving the elevator away from neutral is:

2 * Maximum Output Force of a Single PCU = 2 * Ap (piston area) * 2950 psi,

and the total force moving the elevator toward neutral is:

1 * Maximum Holding Force of a Single PCU = 1 * Ap * 3600 psi

The steady-state net force applied to the elevator is then:

Net Force = (2 * Ap * 2950) – (1 * Ap * 3600) = 1 * Ap * 2300 psi,

which is equivalent too slightly less than 80% (2300/3000) of one PCU maximum output force capability.

Note 5: All references to the neutral elevator position above refer to the production rig position of the elevator. The elevator rig position is established by first positioning the stabilizer at zero degrees with respect to the fuselage reference line (i.e. the stab chord parallel to the fuselage longitudinal axis). With the stabilizer in this position, the elevator rig position is then established by fairing the elevator with respect to the stabilizer.