Selected Non-Proprietary
Correspondence from Boeing to Systems Group Chairman

Subjects:
Autopilot Disconnect Warning
Stick Nudger operation
Dual Elevator PCA Jam Ground Test
Split Elevator Failure Scenario, 21 July 2000
Split Elevator Failure Scenario, Effects of Airloads
Split Elevator Failure Scenario, 29 Sep 2000
Elevator System Response to Hydraulic Power On
CG and Elevator Position Data
Potential Elevator System Failure Scenarios

18 December 1999 to 27 June 2001

79 pages

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

BOEING

18 December 1999
B-H200-16853-ASI

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

Subject: Autopilot Disconnect Warning - Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Dear Mr. Warren:

As part of the System Group activity to support the subject investigation, you asked Boeing to provided information on whether or not there are any failure modes that would cause the autopilot to disengage without warning.

An autopilot disconnect warning is issued to the flight crew whenever the autopilot has disconnected and the pilot or copilot must take control of the airplane The warning is provided via the autopilot dedicated warning lights, the master warn lights, the master audio warn, and the EICAS warn message.

The warning function has been implemented with high integrity. Redundant signal paths, power sources, and displays have been employed to ensure adequate warning for an autopilot disconnect. An adequate warning is defined as the dedicated autopilot warning or EICAS warning message, along with the master warning light or the master aural warning.

The following design features provide the redundancy necessary for an adequate warning:

- Two separate warning circuits within the FCC, one entirely in hardware and the other in software and hardware, as well as two separate interfaces to the warning elements are provided.
- Separate power sources, local DC and Battery are provided for the two warning circuits as well as the master warning light and the master aural warning.
- The software controlled warning from all three FCC's activate for a disconnect.
- The dedicated warning and the EICAS warning are separate and form a redundant function.
- The master aural warning and master warning light are separate and form a redundant function.
- The software controlled warning circuitry within the FCC is tested prior to autopilot engagement.

Based on the above, we know of no single failure, including power or FCC dislodging in the rack, that can inhibit the disengage warning function. During the airplane certification, an analysis was performed that showed that the probability of an autopilot disconnect without warning is extremely improbable (less than 10^{-9}).

We are prepared to discuss this material with you and members of the Systems Group, or furnish more information, until we have provided a satisfactory explanation. If you have any questions, please do not hesitate to call.

BOEING

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]

cc: ✓G. Phillips, NTSB AS-10
P. D. Weston, NTSB AS-30
J. O'Callagahn, NTSB RE-60

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

21 December 1999
B-H200-16858 -ASI

BOEING

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

Subject: Stick Nudger Operation - Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Dear Mr. Warren:

You requested Boeing to provide a detailed description of the effects of inadvertent stick nudger activation combined with a stiff or rigid spring in the stick nudger mechanism.

The enclosed Figure 1 is a schematic of the 767-stick nudger system. The enclosed Figure 2 provides a more detailed schematic of the stick nudger actuator and feel and centering unit. The stick nudger electric actuator is pivot mounted on the feel and centering unit and when extended rotates a crank assembly. *(Both stall warning cards in the Warning Electronics Unit command the actuator to extend when the airplane is in the air, the flaps/slats are retracted, and the angle of attack is slightly beyond the stall warning threshold – i.e. stick shaker).* The crank assembly pulls on the stick nudger spring. The spring is attached to the upper (Captain's) feel unit input crank.

If the 767-stick nudger actuator is activated, a nose down force is applied to the feel and centering unit over 5.5 seconds. The force input is equivalent to 25 lb. at the column. The commanded TE down position of the elevators is dependent on the stabilizer setting and airspeed.

If the stick nudger actuator is inadvertently activated <u>and</u> the mechanism spring is stiff or rigid, it is possible that a nose down force greater than 25 lb. could be applied to the column. This is assuming the actuator has sufficient power to rotate the mechanism crank assembly against the stiff or rigid spring and pull the feel unit input crank out of the feel unit cam detent position. Hence, the resulting commanded TE down position of the elevators would be greater than with stick nudger activation alone.

A review of the Egypt Air 990 FDR data shows that inadvertent stick nudger activation by itself, or combined with a stiff or rigid nudger mechanism spring, did not occur. The magnitude and rate of the initial nose down elevator command is not consistent with stick nudger activation. Also, stick nudger activation would not cause the elevators to split. In addition, after the elevators were split, if the stick nudger were activated, the Captain's (left elevator) would be commanded nose down since the nudger mechanism spring is attached to the upper (Captain's) feel unit input crank. However the FDR elevator's position data shows that the Captain's side was commanded nose up.

We are prepared to discuss this material with you and other participants of the investigation, or furnish more information, until a satisfactory explanation is provided.

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

Very truly yours,

[redacted]

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

Enclosure:
- Figure 1, 767 Stick Nudger System Schematic
- Figure 2, 767 Stick Nudger Actuator and Feel and Centering Unit

cc: G. Phillips, NTSB AS-10
P.D. Weston, NTSB, AS-30
J. O'Callaghan, NTSB, RE-60

WIRING DIAGRAMS
27-32-31

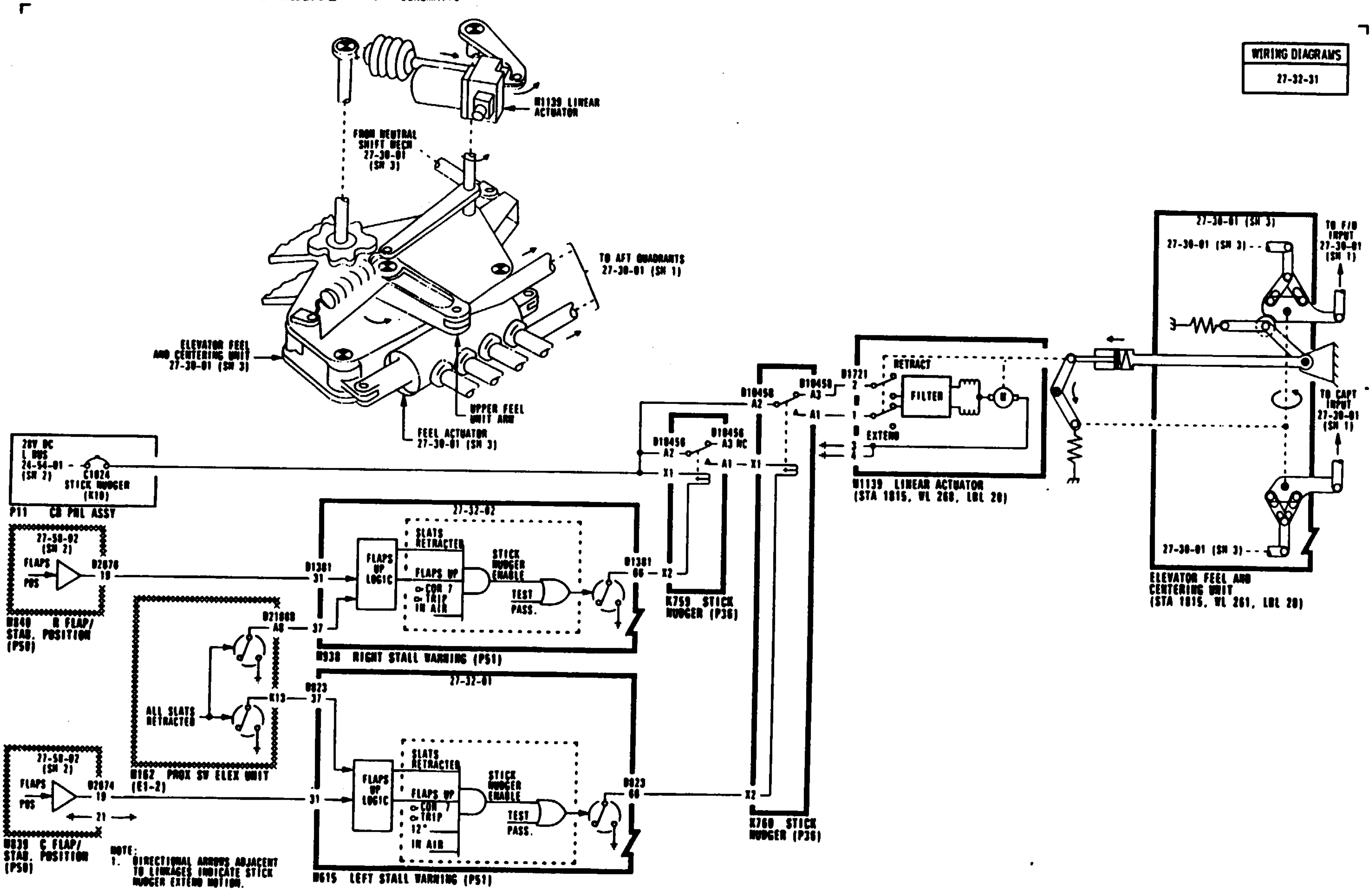


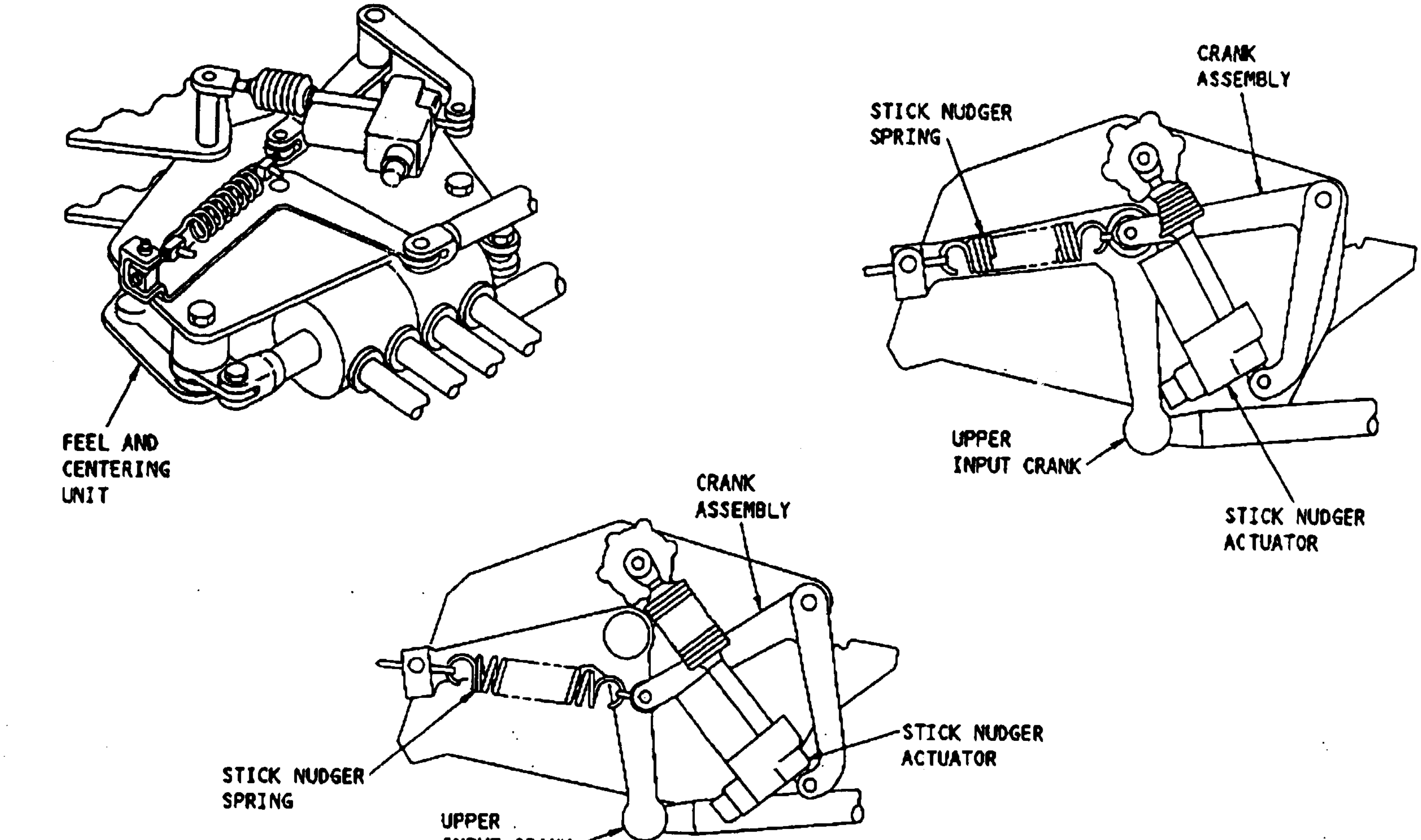
Figure 1

001-300	STICK NUDGER

DRAWING NO: 02007211
PAGE DATE: OCT 20/89
DCU: AA
CHANGE: MISC 92415 MISC 93997

27-32-03
PAGE 102

Figure 2



767 STICK NUDGER

01/17/92

992852

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

18 July 2000
B-H200-17005-ASI

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

BOEING

Subject: Dual Elevator PCA Jam Ground Test - Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Reference: a) Your e-mail request, 29 June 2000
b) Letter B-H200-16969-ASI, 17 May 2000
c) Letter B-H200-16956-ASI, 10 May 2000
d) Letter B-H200-16933-ASI, 24 April 2000

Dear Mr. Warren:

In reference (a), you requested Boeing's assistance to address comments developed by the Egyptian Delegation to Addendum 4 of the Systems Group factual report for the subject accident. Subsequent to reference (b) through (d), you further explained in the e-mail that these comments overlap, and could initially be divided into four general areas and later addressed more specifically, if necessary. The four general areas suggested were:

1. There were concerns regarding the forces observed on the data prior to the individual column sweeps. These concerns regarding the forces also showed up in the values displayed when the columns split out relative to each other – due Friday, July 14, 2000.

2. The columns split at force values that did not match expectations – due Friday, July 21, 2000.

3. The values of the column positions and/or elevator positions before a control sweep did not correspond exactly with those same values after a control sweep at the same force levels – due Friday, July 28, 2000

4. Other comments regarding specific failure effects.

Our response to item 1 is as follows:

BOEING

Summary

The column force data that was recorded during the 767 Dual Elevator PCA Failure ground testing and plotted in the reference (c) document includes significant instrumentation biases. These column force instrumentation biases were introduced during the process of modifying the instrumentation to implement direct column force measurements. Due to the urgency of completing the dual PCA failure testing, no attempt was made to remove the column force instrumentation biases during the calibration process. The column force instrumentation biases were observed to shift during the course of a full day of testing due to temperature effects, however the biases remained constant during each test condition, as shown in the enclosed plots and discussed in detail below. For this reason, the column force instrumentation biases should be removed by subtracting the force necessary to make the initial hands-off column force equal to zero prior to each test condition. With no pilot forces applied to the control column, the indicated column force should be close to zero regardless of whether or not any faults were inserted into the elevator system at the time.

With the column force instrumentation biases removed from the test data presented in the reference (c) document, the test results validate the expected, analytical results.

Background

The reference (c) document presents data from two airplane ground tests on a 767-400ER airplane, VQ001, that were conducted in order to demonstrate the system level effects of single and dual elevator PCA input failures. During test 010-05 on March 29, 2000, the system level effects were demonstrated for single and dual elevator PCA input disconnects. During test 010-18 on April 20, 2000, the system level effects were demonstrated for single elevator PCA input jams, dual elevator PCA input jams, and a single PCA input jam combined with a single PCA input disconnect.

This document provides information regarding the source and nature of the biases observed on the column force instrumentation during tests 010-05 and 010-18.

Column Force Instrumentation

During VQ001 tests 010-05 and 010-18, the two control columns were instrumented in order to directly measure the column force being applied to each control column. The direct measurement of column forces was needed in order to support test conditions where two pilots were making simultaneous inputs. This required reconfiguring the standard control column instrumentation on the test airplane.

The standard column force instrumentation configuration on VQ001 does not allow the direct measurement of column forces. In the standard configuration, the strain gages that are located at the base of the Pilots and Copilots columns are electrically tied together. The gage on the non-driven column compensates for any forces applied to it by electrically subtracting out the load. When equal forces are applied on both columns simultaneously, the net output is zero. The standard control column force instrumentation is configured as shown in Boeing Flight Test Instrumentation drawings Z6-25-80 and Z6-25-81 which are included as figures 1 and 2, respectively. Each column has two 1000Ω strain gage bridges ('A' and 'B') installed per 69Y13141 Strain Gage Installation – Pilots and Copilots Column Stick Force to measure bending. To measure the pilot's column force (Measurement Number 3060107, Stick Force Pilot's), the 'A' gages on each column are wired together. To measure the first officer's column force (Measurement Number 3064204 Stick Force Copilot's) the 'B' gages on each column are wired together.

To allow for the direct independent measurement of each column force on VQ001, it was necessary to electrically separate the gages on the column. In order to maintain the electrical circuit, strain gage simulator (bridge completion) circuits were constructed to match the resistance provided by the original strain gage circuit. These simulators were installed in place of the gages which are installed on the opposite control column during the standard configuration. For measurement "3060107 Stick Force Pilot's", the simulator replaced the 'A' gage on the Copilots side. For measurement "3064204 Stick Force Copilot's", the simulator replaced the 'B' gage on the pilots side.

The strain gage simulator is made using four 1000Ω trim potentiometers arranged in a Wheatstone bridge configuration. The resistance of each leg of the Wheatstone bridge could be measured and adjusted independently. Prior to the installation of the strain gage simulator, the resistance of the strain gages on the control columns were measured. The simulator then was adjusted to match the resistance of that gage. After the simulator was adjusted to match, it was hooked up to the circuit and the engineering unit output was verified on the flight test data system. It should be noted that the adjustment of the simulator is critical and it was impossible to exactly match the gage being replaced because of the difficulty of manually adjusting the trim potentiometers. Because the gage resistance could not be matched exactly, a bias was introduced to the column force data observed on the flight test data system. While the biases could have been removed by adjusting the software calibration of the output, no effort was made to remove these instrumentation biases during the calibration process. The force biases for this type of instrumentation system are a known and accepted phenomenon and are known not to compromise the accuracy of the recorded data once the bias is removed.

The strain gage simulator circuits were installed and the potentiometers were adjusted prior to test 010-05 and prior to test 010-18. For this reason, different column force instrumentation biases would typically be introduced for each test on each column.

Magnitude of Column Force Biases

BOEING

The magnitude of the column force bias can be easily determined at moments in time when no pilot force is being applied to a particular control column. By definition, the instrumented column force should equal zero when no pilot force is applied. The column force bias is thus equal to instrumentation output when no pilot force is applied.

Figure 3 shows a plot of the captain's column force versus the captain's column position for a typical test condition in which the first officer alone made the column inputs. Since no pilot force was being applied to the captain's column during this condition, this plot shows the captain's column force bias directly.

Figure 3 has three characteristics that warrant explanation. The captain's column force bias is seen to be a positively sloped curve with very little hysteresis that is never equal to zero.

The positive slope characteristic on the column force bias of figure 3 is caused by the effect of gravity on the column mass located above the strain gage. Since our column force instrumentation derives "applied column force" based on a measurement of the total strain at the base of the control column, it is unable to distinguish between the applied pilot forces and the column mass unbalance forces. Since the magnitude of the column mass unbalance forces are roughly only +/- 1 pound of column force relative to those at zero degrees of column, they can be ignored without introducing any significant error. If greater accuracy is desired, the column mass unbalance forces could be accounted for in any computations because they are simply a function of the column angle.

There is very little hysteresis on the column force bias of figure 3. This minimal hysteresis is to be expected for slow column sweeps since there are no friction elements between the strain gage and the top of the control column. The fact that there is no hysteresis shows that the instrumented column force readings are repeatable during a test condition. Some hysteresis could occur on the column force bias trace as a result of either something bumping into the column or due to sudden changes in column velocity. Sudden changes in column velocity produce an inertial force that is sensed by the strain gage at the base of the column. Since most of our testing involved slow column sweeps, column force bias effects due to the column inertia are very small and can be ignored.

BOEING

The column force bias shown in figure 3 is never equal to zero. This is a direct result of not removing the instrumentation bias during the calibration procedure. Since a normal calibration procedure would adjust the column force instrumentation output to read zero at the zero degree column angle, the column force instrumentation bias in this figure is about –6.5 pounds of column force. The magnitude of column force instrumentation bias is significant and needs to be subtracted from the total indicated column force in order to obtain the pilot applied force.

The captain's column force biases during test 010-05 are shown in figure 4. Figure 4 was created by plotting the captain's column force versus the captain's column position for all test conditions in which the first officer alone made the column inputs. Figure 4 is the same as figure 3 except that the column force biases were measured at different times throughout the day. Figure 4 shows a bunch of parallel lines. The fact that the lines in figure 4 don't lay right on top of each other shows that the column force instrumentation bias at zero degrees of column shifted during the course of the day within the range of –6.5 to –8.0 pounds of column force. The fact that these lines are parallel to each other demonstrates that even though the bias shifted throughout the course of the testing as a result of temperature changes, the gain of the instrumented column force was unaffected. Since the same mass unbalance force caused the characteristic slope of these lines, any change to the gain of the instrumented column force would have resulted in non-parallel lines.

The First Officer's column force biases during test 010-05 are shown in figure 5. Figure 5 was created by plotting the first officer's column force versus first officer's column position for all test conditions where the captain alone made the column inputs.

The captain's column force biases during test 010-18 are shown in figure 6. The First Officer's column force biases during test 010-18 are shown in figure 7. These plots were generated using the same methods described above for figures 4 and 5.

Examination of figures 4, 5, 6, and 7 reveals that the column force instrumentation biases all shifted during the course of the day's testing. The cause of this shifting is changes in temperature during the course of the testing. During the design of the strain gage simulator circuits, no attempt was made to produce biases that were constant with respect to temperature. For figures 4, 5, and 6, the shift in the column force instrumentation bias is less than +/- 2 pounds of column force which is relatively small compared to the magnitude of column forces being measured.

For figure 7, the column force instrumentation bias on the first officer's column during test 010-18 varied from 6 lbs to 22 lbs. This is significantly more shift in the bias than that observed during any other test. Test 010-18 was conducted with 3 main test configurations: (1) single input jams, (2) single input jam plus a single disconnect, and (3) dual input jams. Switching between test configurations during test 010-18 required significant amounts of time because elevator PCAs had to be removed and replaced to produce an input jam. A review of the test conditions completed in each of these three test configurations shows that the column force bias values didn't shift more than a few pounds for the test conditions within a single configuration. The major shifts occurred between main test configurations when large temperature shifts occurred while the airplane configuration was changed.

While the column force instrumentation biases were observed to shift some during the course of a full day of testing, the biases remained constant during each test condition. For this reason, the column force instrumentation biases should be removed by subtracting the force necessary to make the initial hands-off column force equal to zero prior to each test condition.

Figure 8 shows a plot of column force versus column position during a column sweep on VQ001 at base feel pressure. Figure 9 shows a plot of column force versus column position during a column sweep on VQ001 when the feel pressure was set to 770 psi. In both figures 8 and 9, the VQ001 test data matched well with the predictions once the column force instrumentation biases were removed. This demonstrates that the column force test data gathered from VQ001 can be easily corrected by removing the instrumentation biases and that the forces measured by the instrumentation once this is done is accurate.

Conclusions:

- The observed biases in control column force measurements are due to instrumentation biases introduced by the methods used to allow independent left and right column force measurements. This configuration is non-standard for Boeing flight test airplanes and consequently, the instrumentation installed on the test airplane was modified to support the objectives of the dual elevator PCA failure testing.
- The bias values shifted during the course of the testing under the influence of temperature changes. For this reason, the column force instrumentation biases should be removed by subtracting the force necessary to make the initial hands-off column force equal to zero prior to each test condition.

- The column force instrumentation installed on the test airplane produces accurate and repeatable measurements of the applied column forces once the bias value is removed.

We are planning to provide our response to items 2 and 3 no later than the requested dates. If you have any questions, please do not hesitate to call.

Very truly yours,

BOEING

[redacted]

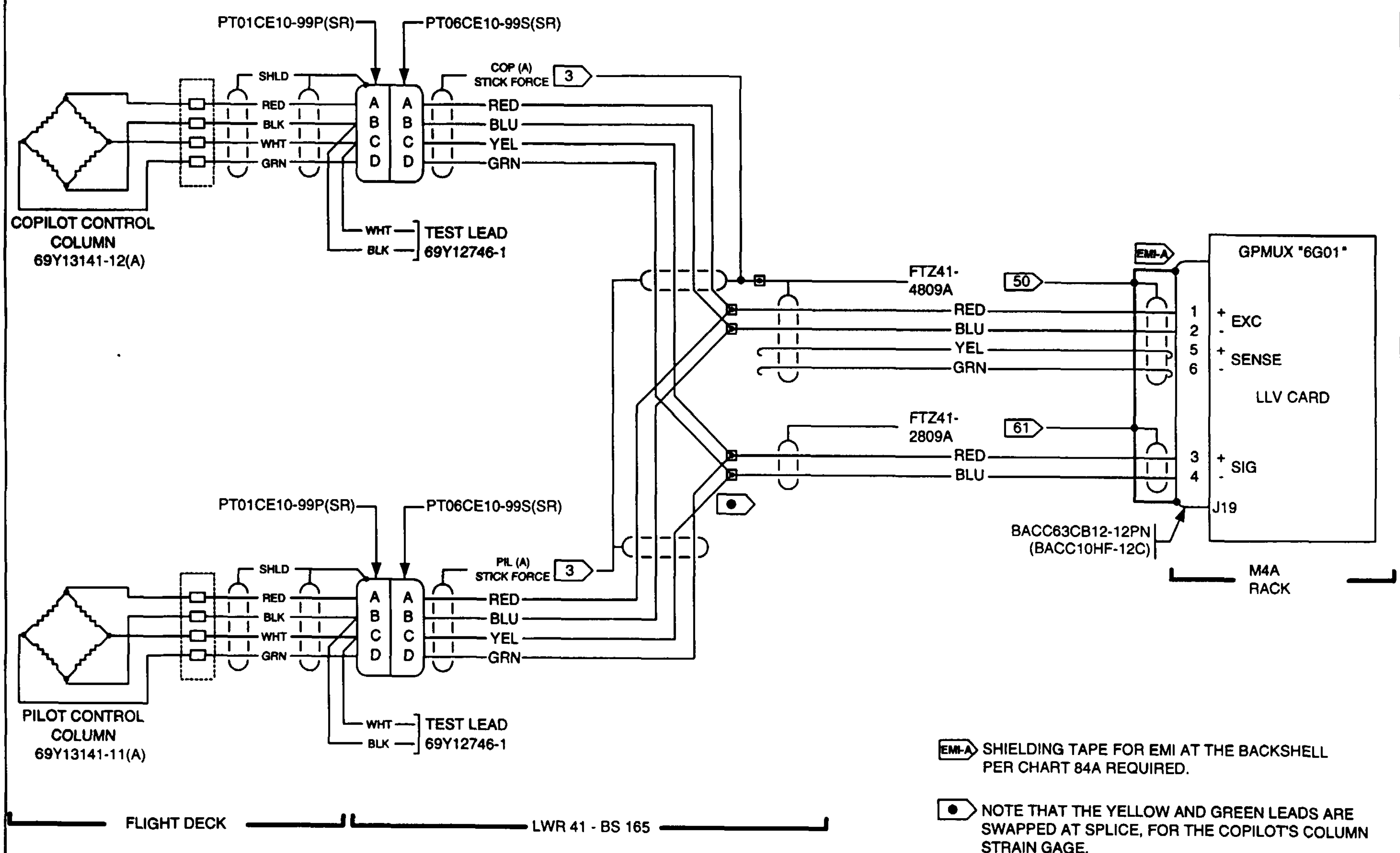
for Ronald J. Hinderberger
Director, Airplane Safety
Org. B-H200, M/S 67-PR
Telex 32-9430, STA DIR AS
[redacted]

Encl.:
- Boeing figures 1-9

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

Figure 1

MN 3060107 STICK FORCE PILOTS

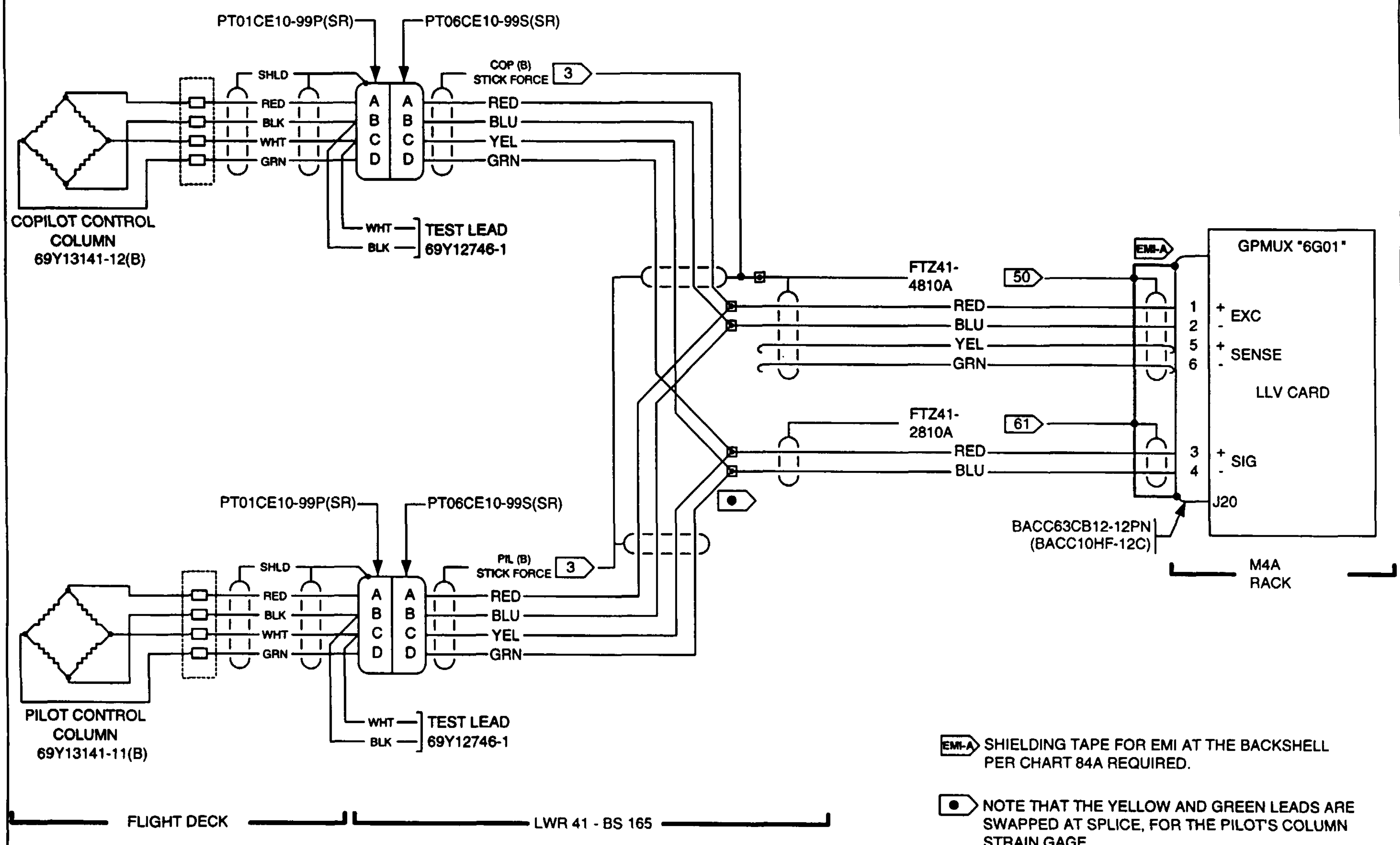


BOEING® FLIGHT TEST INSTRUMENTATION WIRING DIAGRAM	MODEL	DRAWING NO.	AIRPLANE	TITLE	DATE	PAGE NUMBER
	767-400	61Y12209	VQ001	ELEVATOR STICK FORCE (PILOT'S)	07/17/00	Z6-25-80

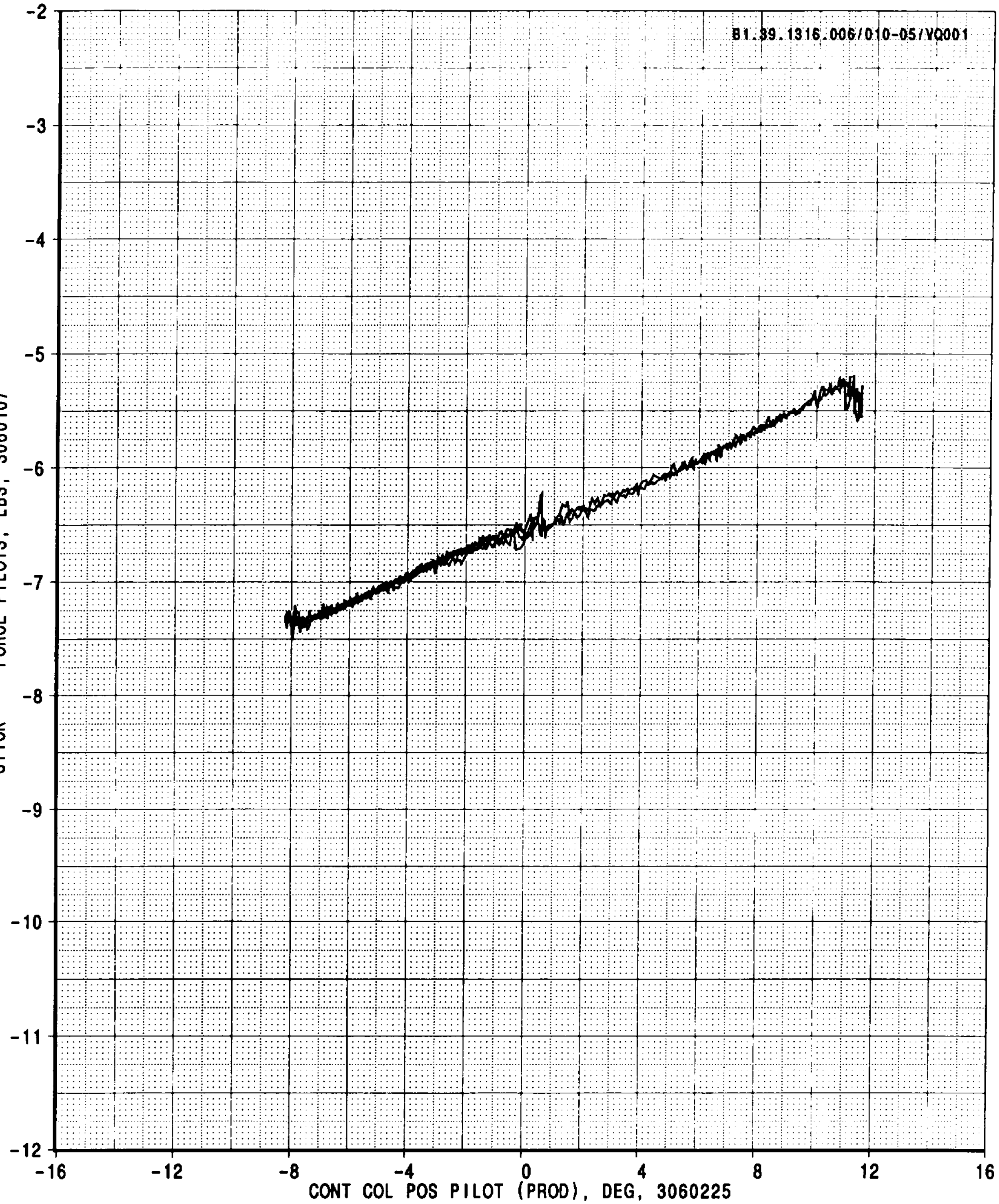
Enclosure to: B-H200-17005-ASI

Figure 2

MN 3064204 ELEV STICK FORCE COPLTS

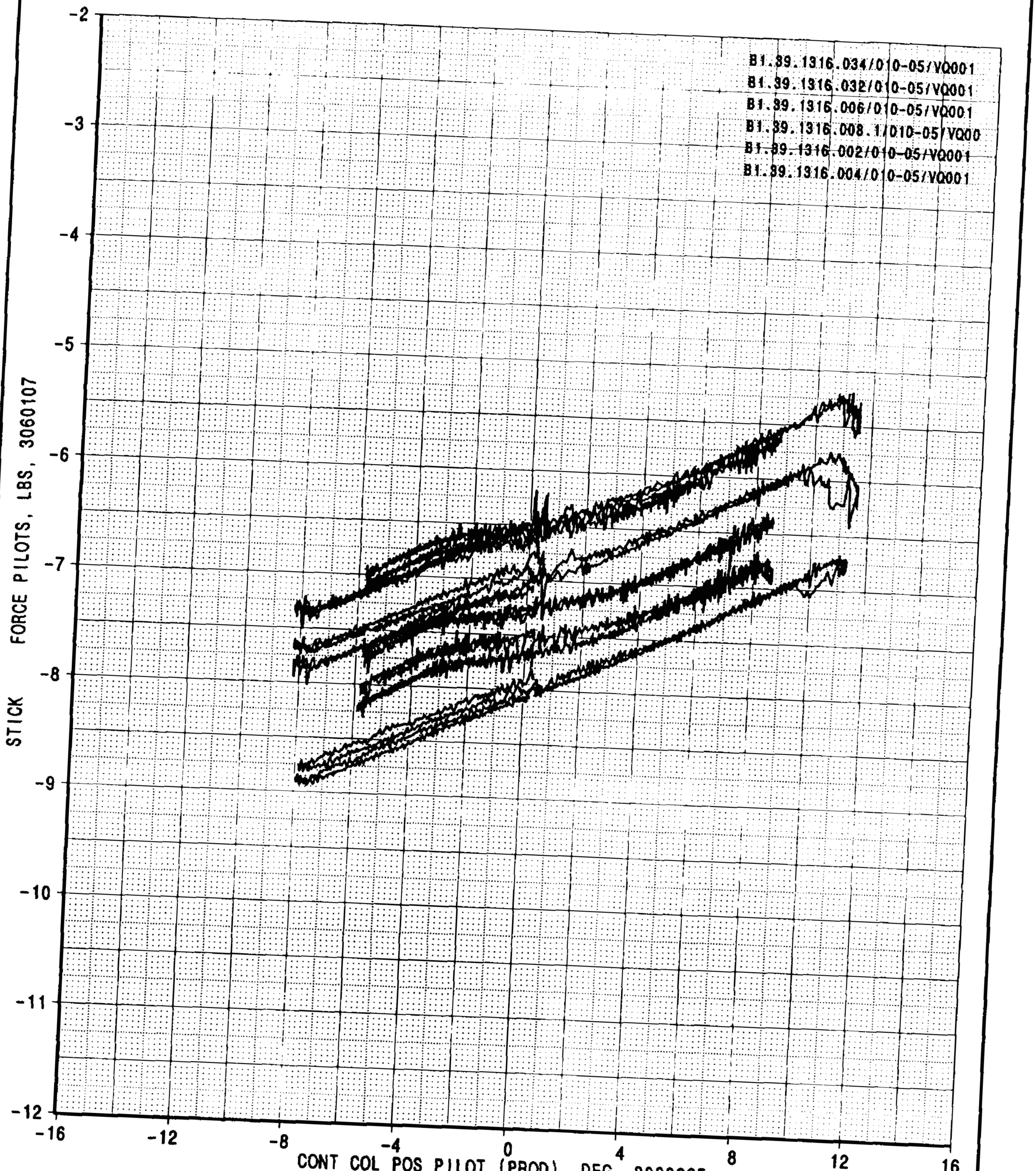


BOEING FLIGHT TEST INSTRUMENTATION WIRING DIAGRAM	MODEL	DRAWING NO.	AIRPLANE	TITLE	DATE	PAGE NUMBER
	767-400	61Y12209	VQ001	ELEVATOR STICK FORCE (COPIL'S)	07/17/00	Z6-25-81



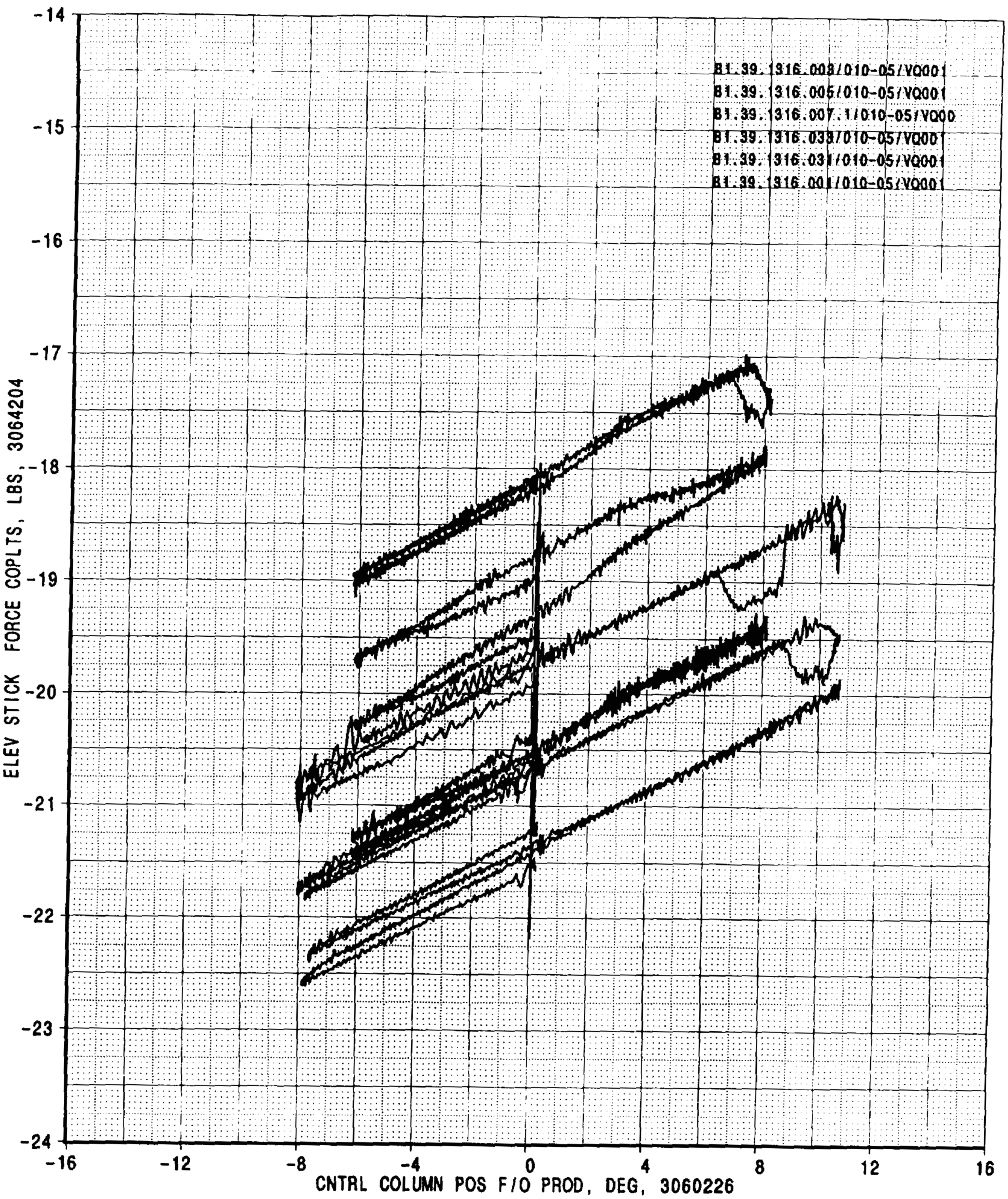
[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4630.esb
[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4631.esb
[C]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4494.esb
[D]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.6261.esb

CALC	B. Cook	17Jul00	REVISED	DATE	Captain's Column Force Bias During Test Condition 006 of Test 10-05	767-400ER VQ001
CHECK						Figure 3
APPD.						
APPD.					BOEING	PAGE 10 of 16



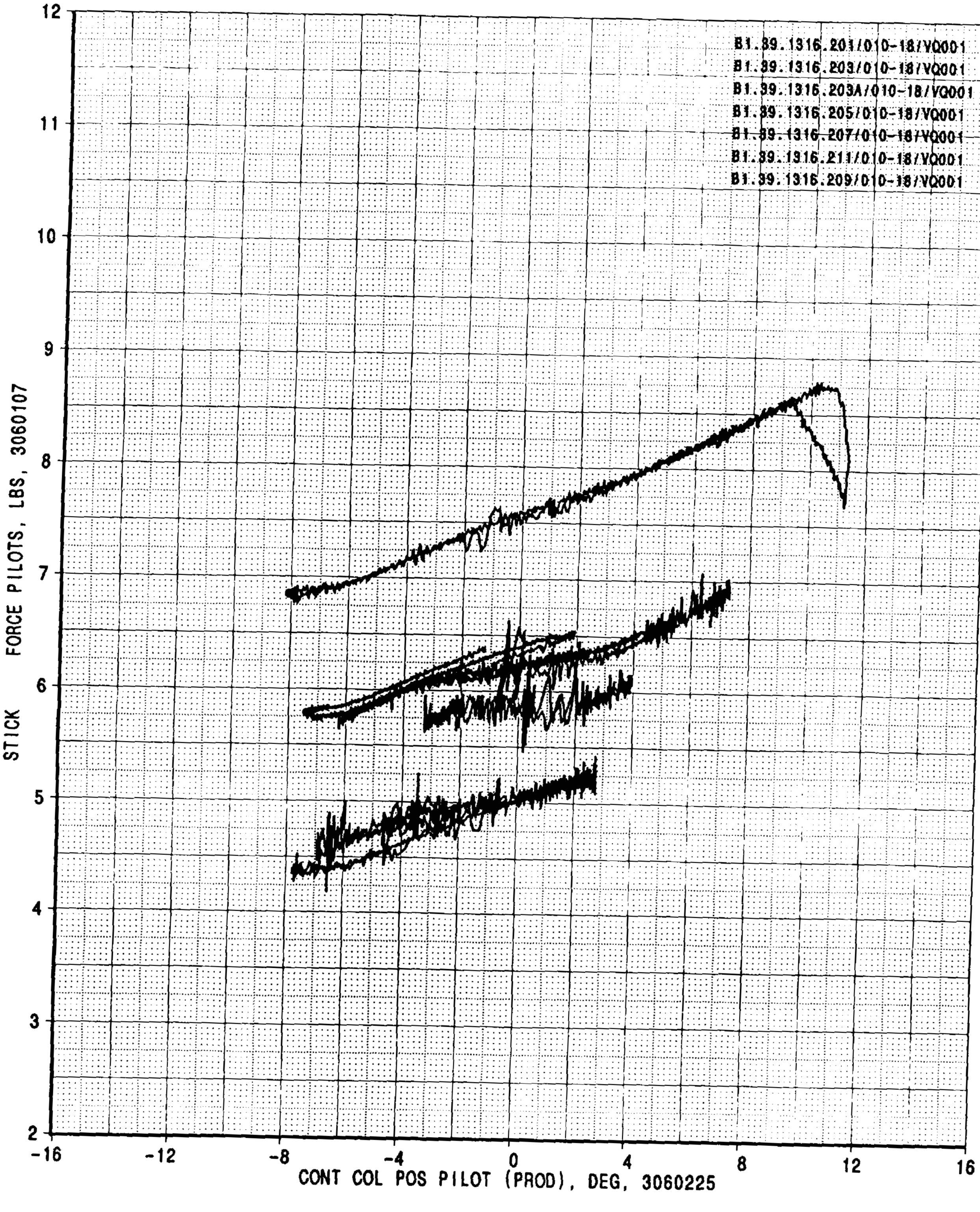
[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4631.esb
[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4630.esb
[C]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4494.esb
[D]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.6261.esb

CALC	B. Cook	17Jul00	REVISED	DATE	Captain's Column Force Biases During Test 10-05	767-400ER VQ001
CHECK						Figure 4
APPD.					BOEING	PAGE 10 of 16
APPD.						



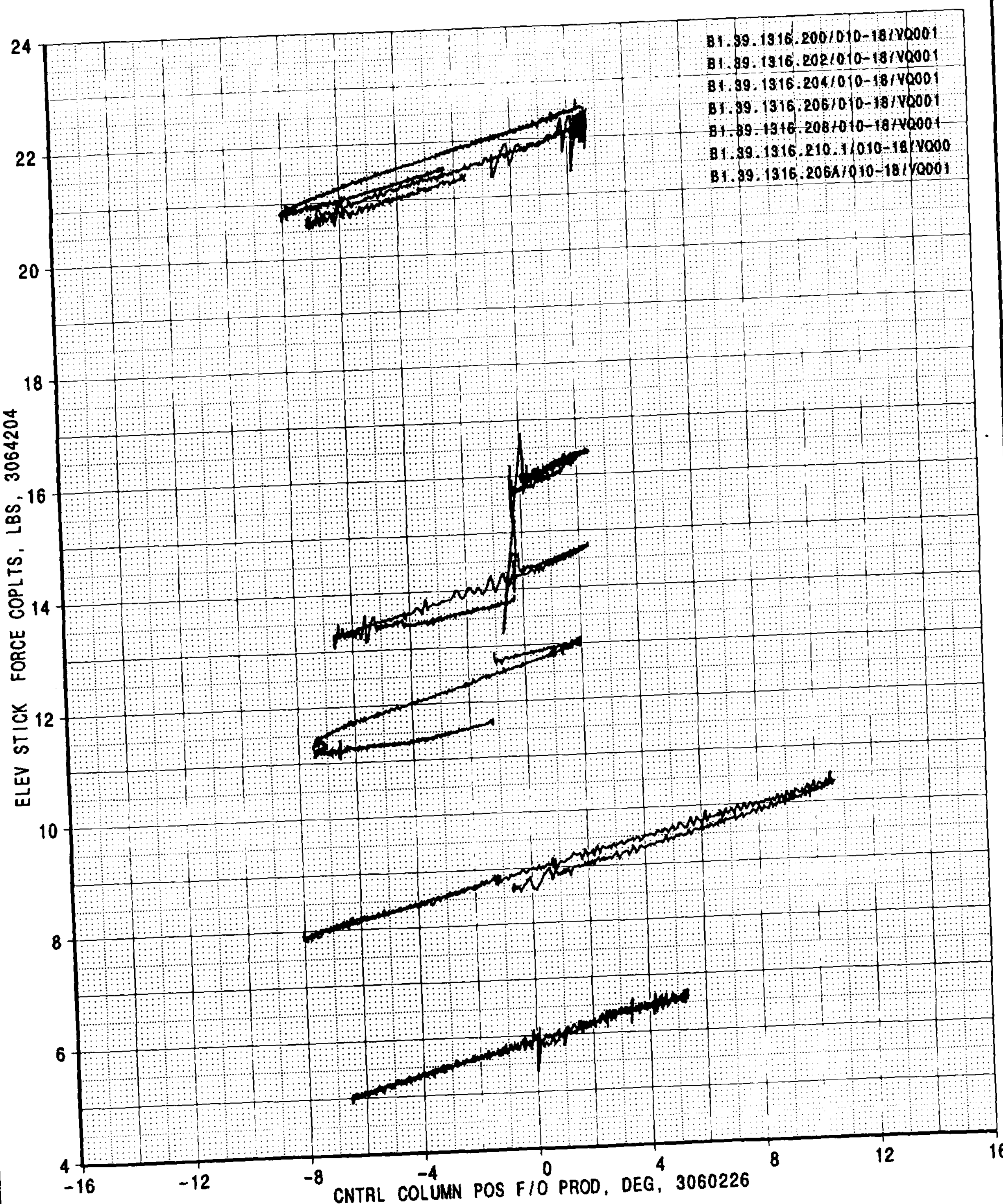
[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4494.esb
[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4630.esb
[C]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4631.esb
[D]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.6261.esb

CALC	B. Cook	17Jul00	REVISED	DATE	First Officer's Column Force Biases During Test 10-05	767-400ER VQ001
CHECK						
APPD.						Figure 5
APPD.					BOEING	PAGE 12 of 16



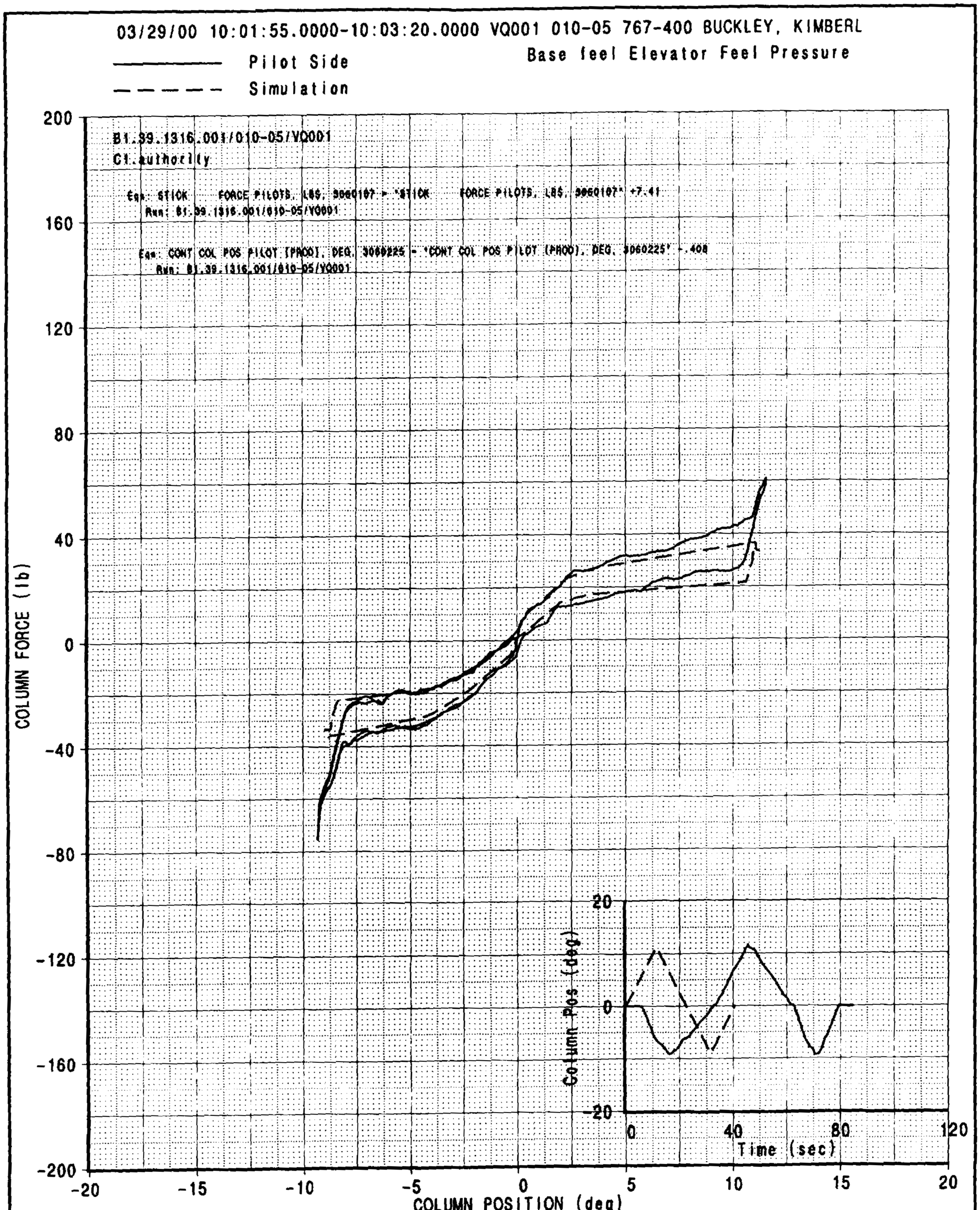
[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.5804.esb
[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.6262.esb

CALC	B. Cook	17Jul00	REVISED	DATE	Captain's Column Force Biases During Test 10-18	767-400ER VQ001
CHECK						Figure 6
APPD.					BOEING	PAGE 13 of 16
APPD.						



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.5804.esb
[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.6262.esb

CALC	B. Cook	17Jul00	REVISED	DATE	First Officer's Column Force Biases During Test 10-18	767-400ER VQ001
CHECK						Figure 7
APPD.					BOEING	PAGE 14 of 16
APPD.						



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.6261.esb

[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/gt_sim_mod/182colsweeps.esb

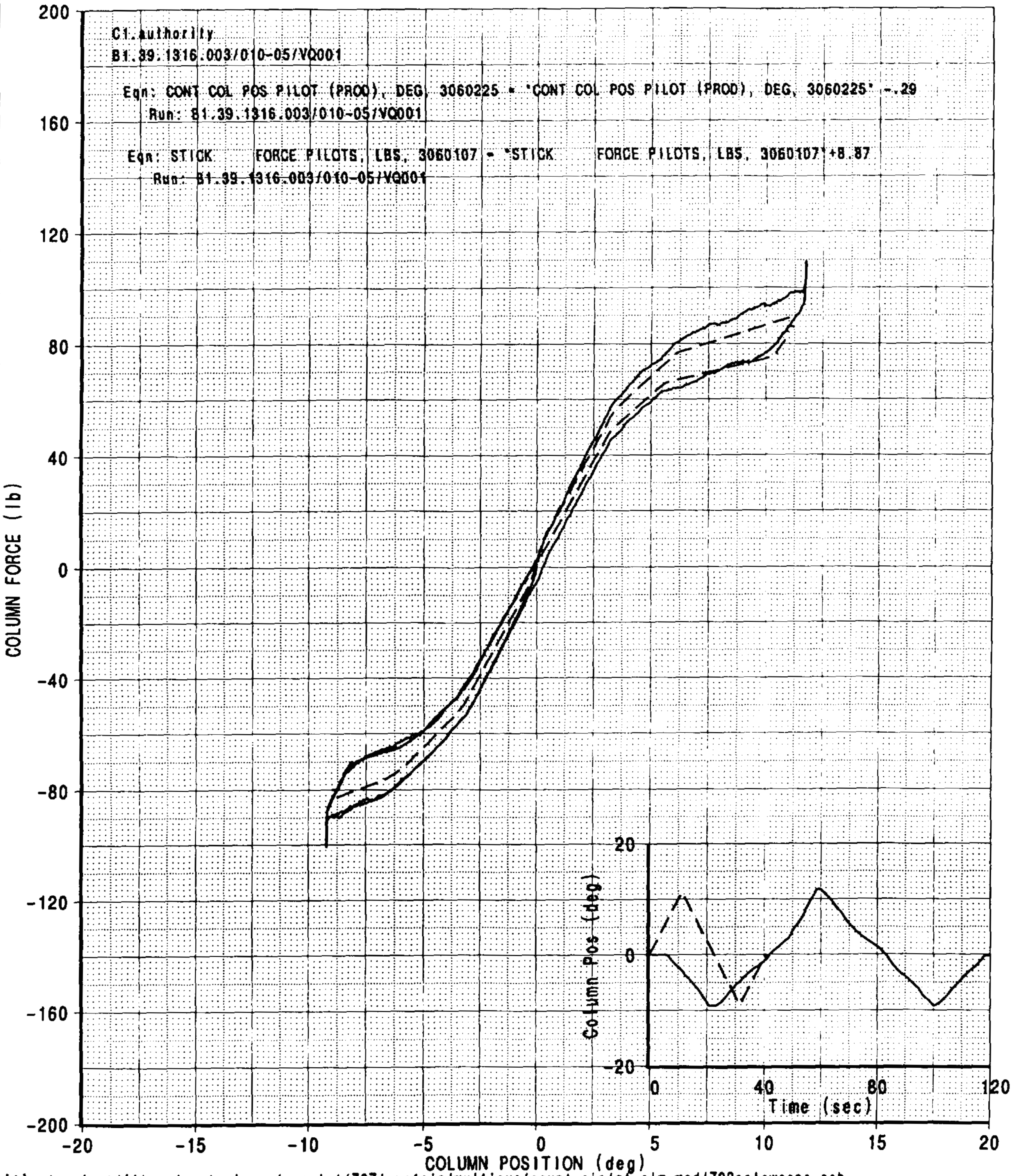
CALC	B.Richardson	17Jul00	REVISED	DATE	Ground Test/Simulation Proof of Match Base Feel Sweep with Biases Removed	767-400ER VQ001
CHECK						Figure 8
APPD.						
APPD.					BOEING	PAGE 15 of 16

03/29/00 10:33:15.0000-10:35:20.0000 VQ001 010-05 767-400 BUCKLEY, KIMBERL

770 psi Elevator Feel Pressure

——— Pilot Side

– – – – Simulation



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/gt_sim_mod/792colsweeps.esb

[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_05/VQ001.010_05.4494.esb

CALC	B.Richardson	17Jul00	REVISED	DATE	Ground Test/Simulation Proof of Match 770 psi Feel Sweep with Biases Removed	767-400ER VQ001
CHECK						Figure 9
APPD.					BOEING	PAGE 16 of 16
APPD.						

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

BOEING

21 July 2000
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.

767 Split Elevators Failure Scenarios

#	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.

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

BOEING

22 August 2000
B-H200-17042-ASI

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

By Express Mail

Subject: Split Elevator Failure Scenario, Effects of Airloads on Control Surface Motion – Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Reference: a) Letter B-H200-16968-ASI, 21 July 2000
b) Flight Controls Systems Data for the 767 Training Simulator, Boeing Document D613T161

Dear Mr. Warren:

You requested Boeing to provide a description of the effects of in-flight airloads on the position of the non-failed elevator surface for the dual PCA failure conditions discussed in the reference (a) letter.

For any given elevator position command, the effect of airloads on a non-failed control surface position is the same regardless of whether the dual PCA fault or normal pilot forces generated the command. Airloads influence the ability of an elevator control surface to reach its commanded position, but they have no effect on the command itself. Some dual PCA failures have an influence on the command to the non-failed elevator.

Some dual elevator PCA failures do influence the elevator position command. The presence of a dual elevator PCA input disconnect has no effect on the position command of the non-failed elevator because all of the forces in the system are identical to those in normal operation. The presence of a single elevator PCA disconnect combined with a single PCA input jam on the same elevator control surface results in the failed elevator surface transmitting a force into the feel unit which is equal to the force required to override one PCA input pogo. In the absence of any compensating pilot forces, this pogo override force will bias the position command of the non-failed elevator surface in the direction of the failed elevator motion. The presence of a dual elevator PCA input jam on the same control surface will result in the failed elevator surface transmitting a force into the feel unit equal to the force required to override two PCA input pogos. In the absence of any compensating pilot forces, these pogo override forces will also bias the position command of the non-failed elevator in the direction of the failed elevator motion.

The sum of all forces acting on the elevator control system determines the elevator position commands. The sum of the forces includes the input forces such as normal pilot forces and PCA input pogo override forces (if any) and the resistive forces such as the feel unit forces, system friction, damping, and inertial forces. Once the elevator position commands are known, the effect of airloads on a non-failed elevator surface can be determined using the normal method defined in the reference document.

BOEING

The reference (b) document, which has been submitted to the NTSB, provides a model of the elevator PCA in Figure 3.6-7. This model shows how to compute the effect of airload on the elevator surface position at different flight conditions. The input to this model is the elevator position command, δ_{ecom}. The output of this model is the actual elevator surface position, δ_e. For any steady state elevator position command in this model, airloads are responsible for all of the difference between the elevator position command and the actual elevator surface position (i.e. $\delta_{ecom} - \delta_e$).

For cases where the elevator position commands are not steady state, the quantity $\delta_{ecom} - \delta_e$ is affected by the PCA loop dynamics in addition to the airloads. The reason for this is that there is a lag between the time a PCA receives a position command and the time that the PCA actually positions the surface in response to the command. In order to determine the effect of just the airloads on the elevator surface position when the elevator position commands are not steady state, we need to consider two cases: no blowdown and blowdown. If the elevator surface is not experiencing blowdown, the effect of airloads in the model is to make the actual elevator surface position different than the position command by the quantity P_L/K_S where P_L is the equivalent aerodynamic load and K_S is a constant which represents the PCA stiffness. The equivalent aerodynamic load, P_L, is computed as a function of: the dynamic pressure of the airstream (q), the hinge moment coefficient of the elevator surface (C_H), the PCA load factor constant (K_L), the number of pressurized elevator PCAs (n), and the length of the effective moment arm of the elevator PCA (L_{EMA}). P_L can take on both positive and negative values depending on whether the airloads resist or aid the motion of the control surface, respectively. If the equivalent aerodynamic load, P_L, acts in opposition to the direction of commanded surface motion and becomes greater than or equal to the differential hydraulic supply pressure to the actuators, P_S, then the elevator surface is experiencing "blowdown" or stall. During blowdown, additional elevator commands will not result in any additional elevator surface travel. The blowdown limits of the elevator control surface are shown in Figures 3.7-1 to 3.7-15 of the reference (b) document. If the elevator surface is experiencing blowdown, then the airloads are responsible for all of the difference between the elevator position command and the actual surface position (i.e. $\delta_{ecom} - \delta_e$) because the PCA is not responding to the changes of the elevator position command.

Please contact us if you have any questions.

BOEING

Very truly yours,

[redacted]

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

cc: Mr. Greg Phillips, NTSB, AS-10
Mr. John O'Callaghan, NTSB, RE-60

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

29 Sep 2000
B-H200-16968-ASI-R2

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

BOEING

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

Reference: a) Our letter B-H200-16968-ASI-R1, 21 July 2000
b) Our letter B-H200-16968-ASI, 17 May 2000
c) Our letter B-H200-16882-ASI, 08 February 2000
d) Our letter B-H200-16837-ASI-R1, 02 December 1999
e) Our letter B-H200-16854-ASI, 18 December 1999

Dear Mr. Warren:

After review of the reference c) letter, you requested Boeing to incorporate your editorial comments to make the Failure Scenarios more consistent with references (d) and (e). 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]

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
Captain S. Kelada, EgyptAir

Revision 1 – to remove the proprietary nature of the letter per Scott Warren's request.
Revision 2 - to add references (a) and (b) per NTSB request to reflect the complete revision record of this letter.

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.

767 Split Elevators Failure Scenarios

#	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).

Scenario 11: Dual PCU Failure on Same Elevator in Same Direction

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 stab

Analysis of FDR data relative to the Dual PCU Failure:

The data from the FDR shows that the initial airplane pitch down was caused by a nose-down elevator deflection of approximately3 degrees at time 01:49:54. With the conditions existing at this time in the flight, the dual PCU valve jam (Failure Case 1 described above) would have produced an elevator deflection of approximately 4 degrees for both the left and right elevators. This assumes that the autopilot was disengaged – as indicated in the FDR data - and further assumes that neither pilot was opposing the motion of the column caused by the failure. Following the failure, either pilot could command the non-failed elevator in the direction opposite the failed elevator, as described in detail above. A split between the failed elevator and the non-failed elevator would result from either pilot commanding the non-failed elevator in opposition to the failed elevator (see description above for details). There is no split between the elevators shown in the FDR until approximately 25 seconds after the initial nose-down elevator input. This indicates that if a dual PCU valve jam had caused the initial elevator input, there was no pilot corrective action during this 25-second period.

In the event of the combined failure discussed above in Failure Case 3, the initial elevator deflection would have been approximately the same as described above (4 degrees) for the failed elevator. However, the non-failed elevator would have deflected to only 1.5 degrees which is the point where the force from the input pogo of the jammed PCU is balanced by the centering force from the feel unit (see the column force versus elevator deflection curve in Figure 3.5).

An additional effect from the dual PCU valve jam that is relevant to the FDR data is the blow-down characteristic of the elevator as a function of airspeed. As airspeed increases, the elevator positions would tend to move back toward neutral due to the higher hinge moments applied to the failed elevator and the higher feel forces applied to the input system. During the dive that followed the initial nose-down elevator input, the speed increased to a value that would have caused the failed elevator to move back toward neutral to a position of approximately 2.5 degrees. At this specific flight condition (airspeed = 350 knots and altitude = 29,000 feet at time 01:50:09) the elevator deflections shown on the FDR are 4.75 degrees for one surface and 5.1 degrees for the other. These elevator deflections would not have been possible at this flight condition if the dual PCU failure had been present.

Finally, both elevators travel together as they move toward neutral just prior to the split shown in the FDR data at time 01:50:20. This would not have happened if the dual PCU failure had been present. In the presence of this failure, the failed elevator would remain deflected in the direction of the failure an amount equal to 80% of a single PCU blow down. At the flight condition existing when the elevators reached neutral (time 01:50:20), the blow down position of the failed surface would have been approximately 2 degrees if the dual PCU failure had been present.

Conclusion from FDR data analysis:

Based on the analysis of the FDR data summarized above, the data is inconsistent with how the 767 elevator systems would respond to the dual PCU failures detailed in the above discussion.

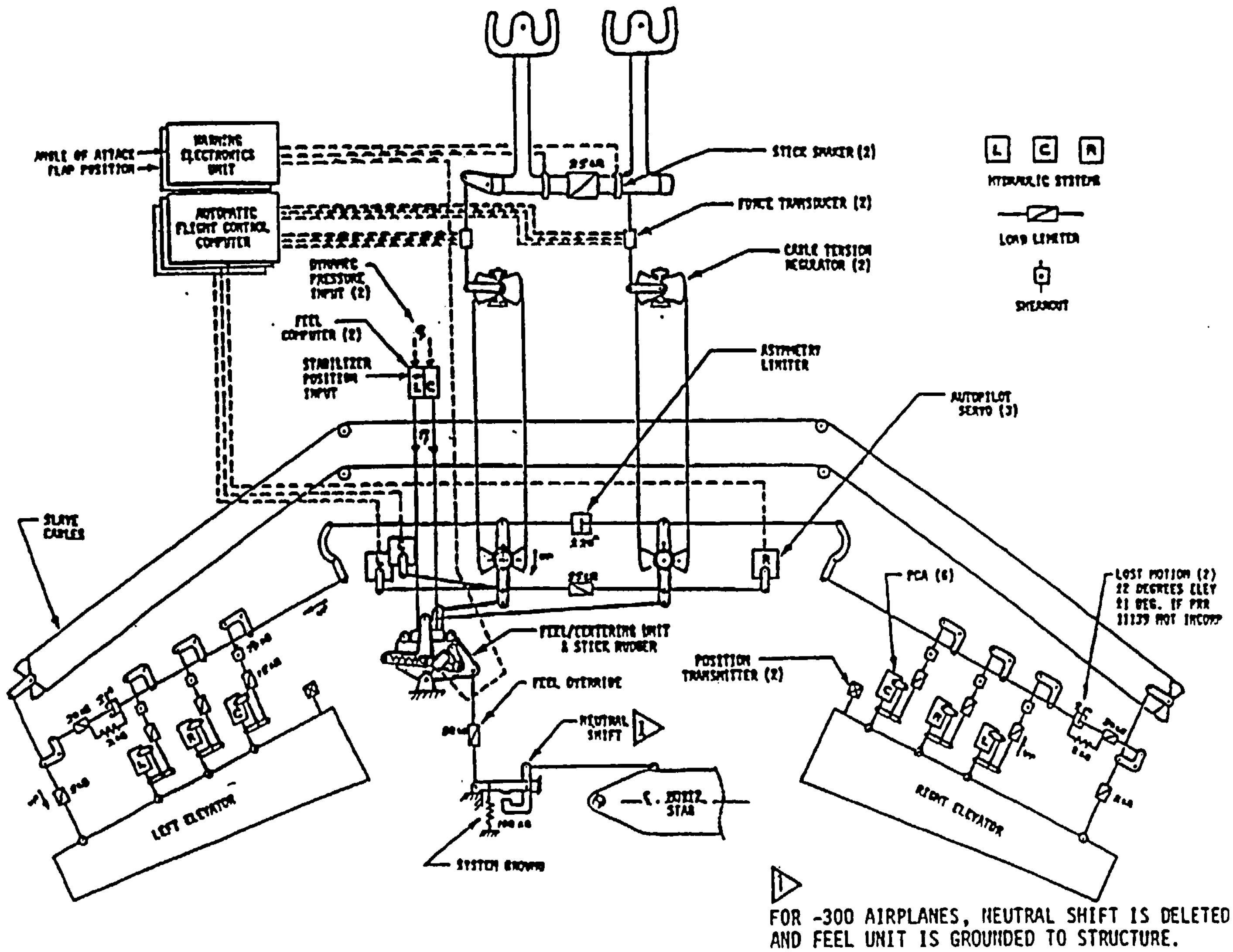
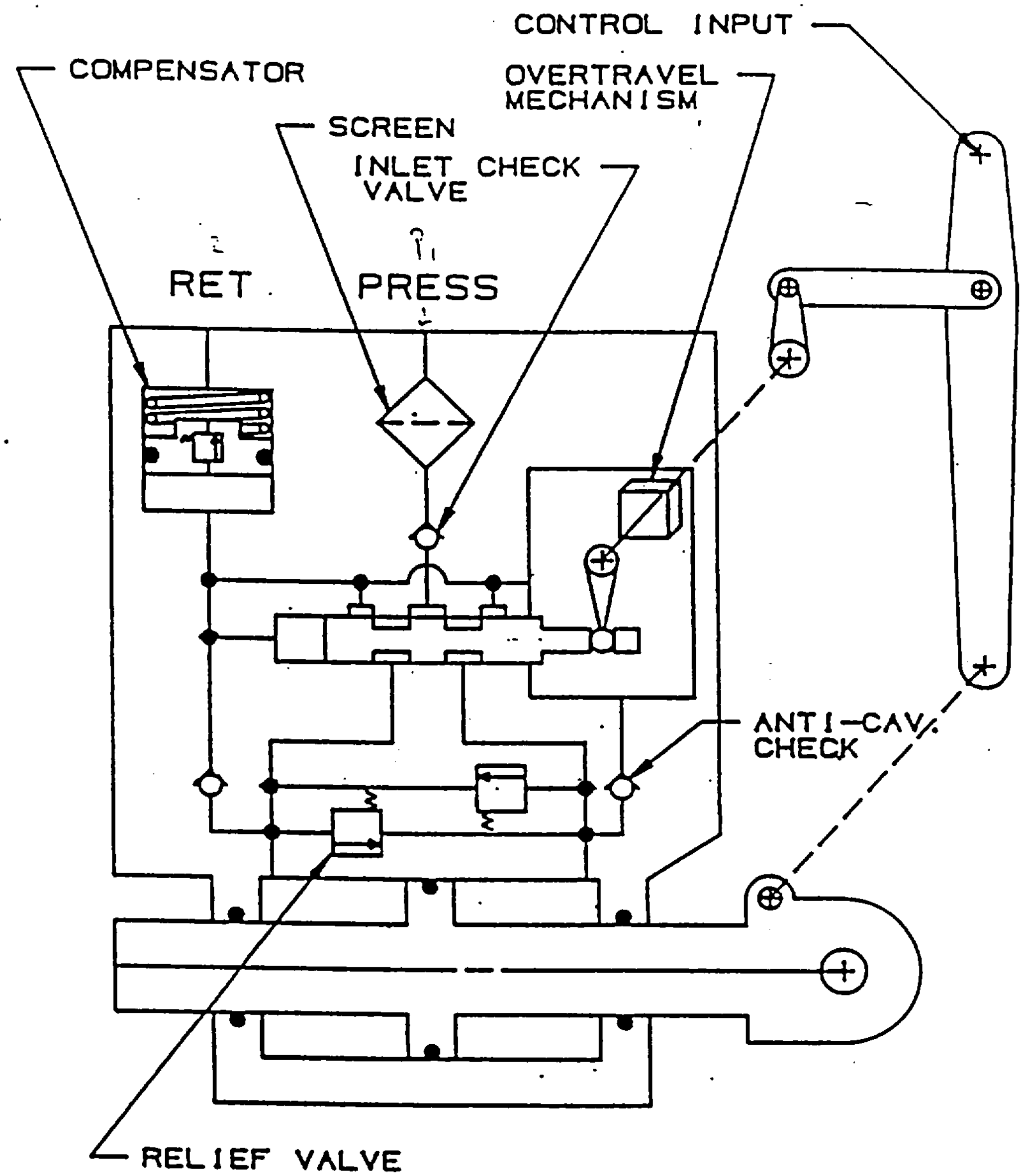


Figure 1, Elevator Control Schematic

SYM E



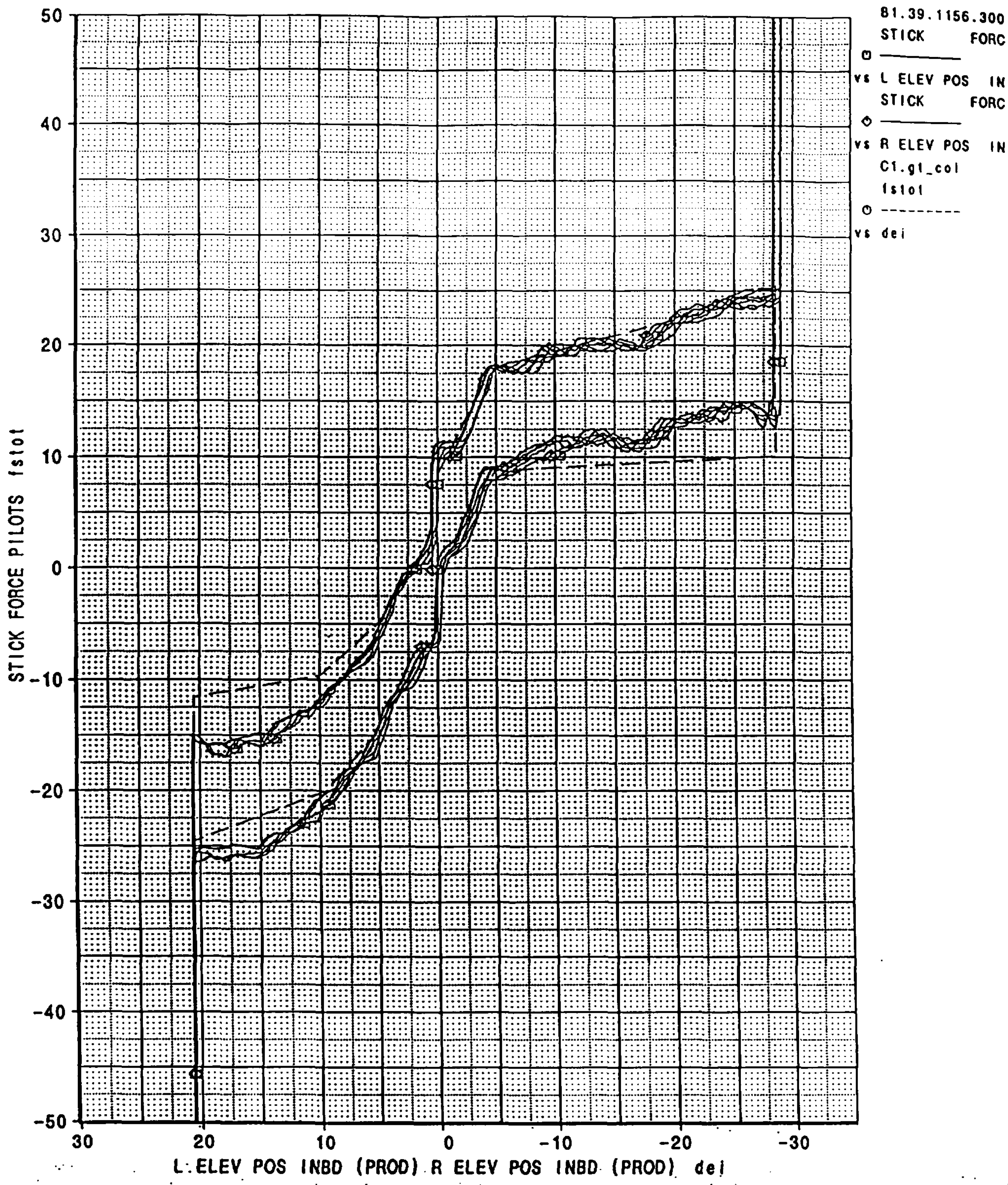
SCHEMATIC

FIGURE 2

767 Elevator PCU

THE BOEING COMPANY	CODE IDENT NO. 81205	SIZE A	
	SCALE		SH 1 PAGE 65

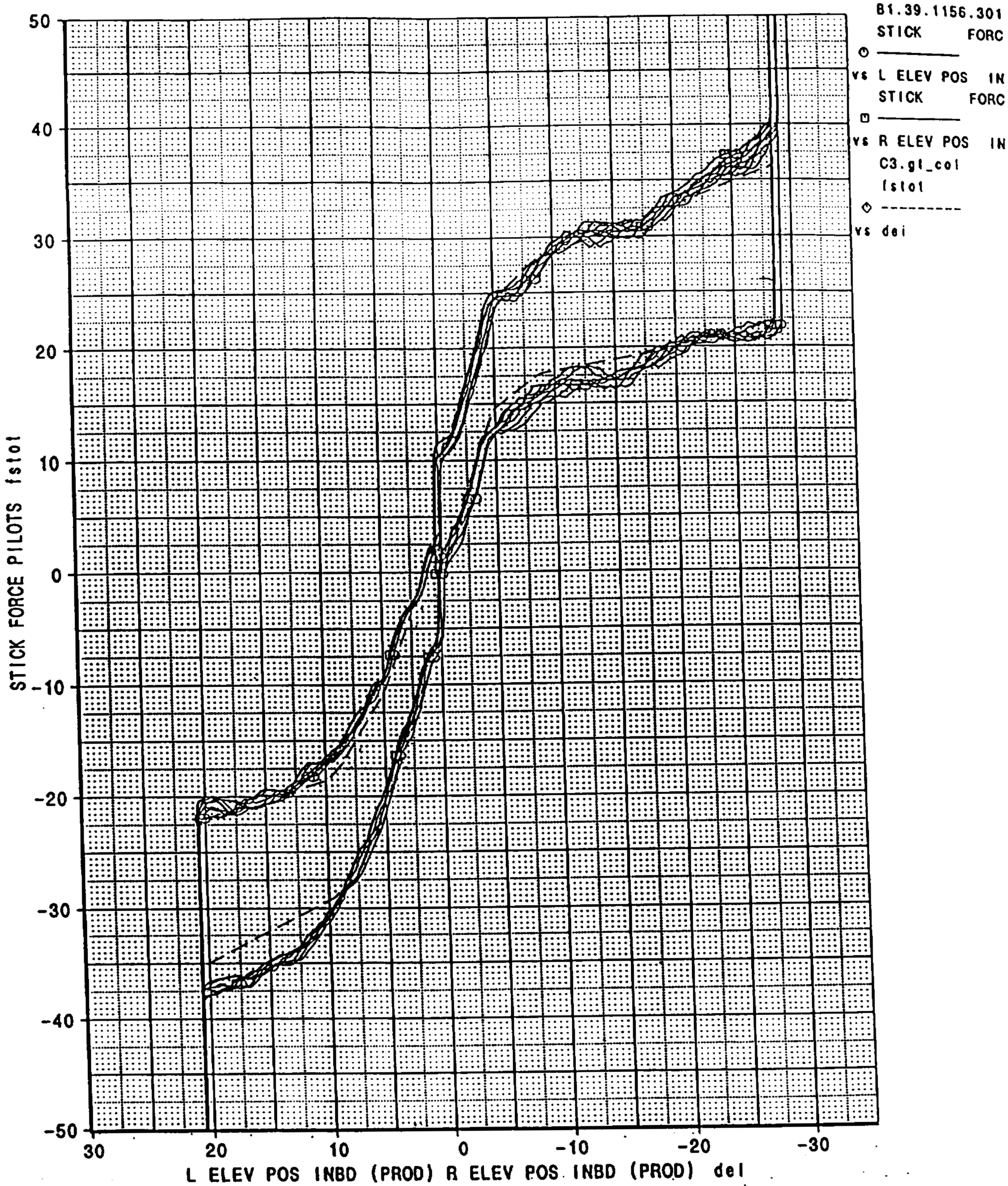
Biases Removed: Stick Force +0.425 lbs



[A]: /project/fltsys/flt_test/data/VQ001/VQ001.000_12.3664.esb
[B]: /acct/pkb1662/d.sim_767/gt_column.esb

CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 300 Slow Captain's Column Sweep with Feel Pressure = Off	767-400
CHECK						Fig 3.1
APPD.						
APPD.					BOEING	PAGE 17

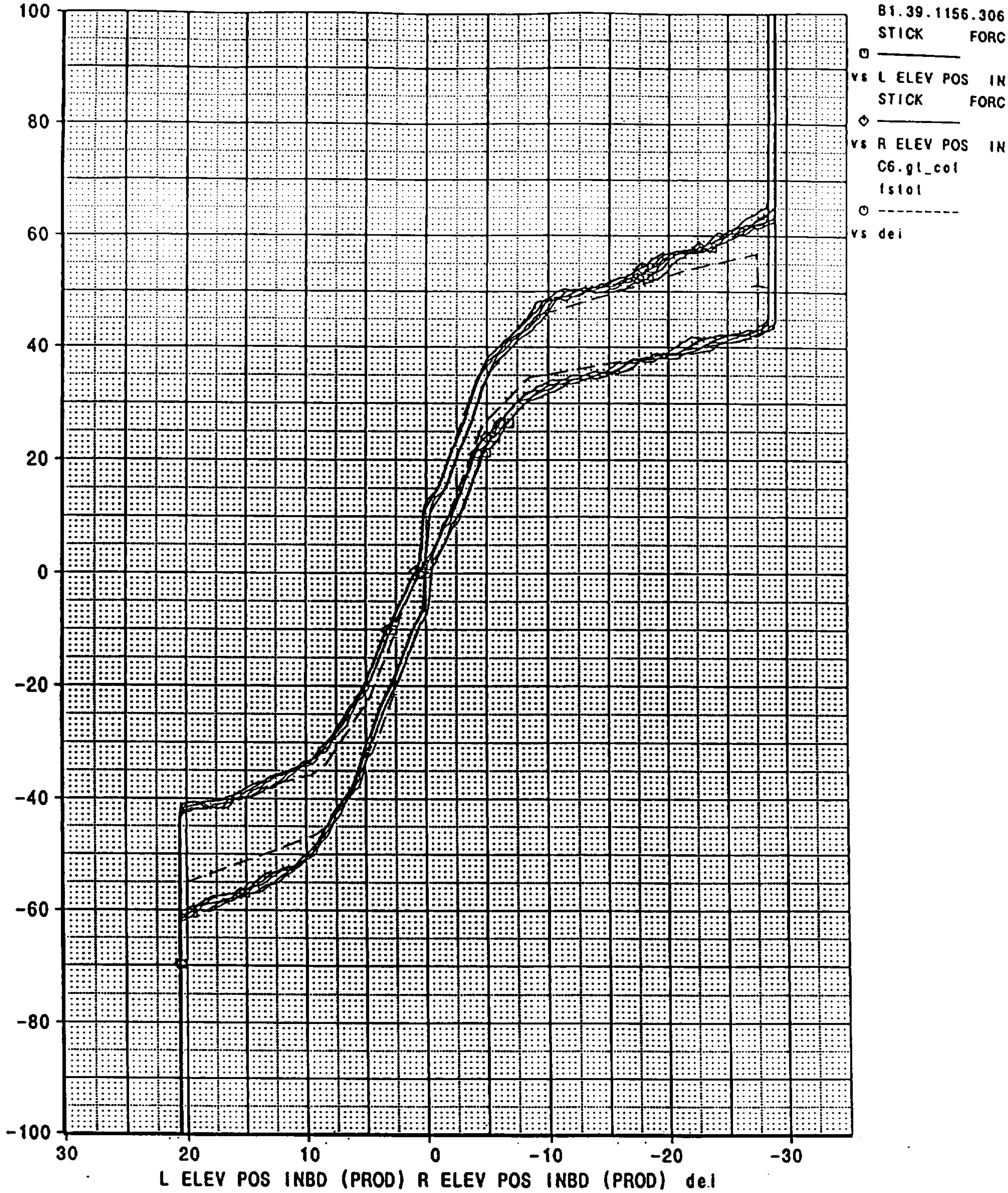
09/19/99 20:37:45.0000-20:41:00.0000 VQ001 000-12 767-400 ARENT, LAUREN, E
Biases Removed: Stick Force +0.425 lbs



[A]: /project/fltsys/flt_test/data/VQ001/VQ001.000_12.3664.esb
[B]: /acct/pkb1662/d.sim_767/gt_column.esb

CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 301 Slow Captain's Column Sweep at Base Feel with Hydraulic Reservoir Pressure = 0 psig	767-400 Fig 3.2
CHECK						
APPD.						
APPD.					BOEING	PAGE 18

09/19/99 21:14:20.0000-21:16:55.0000 VQ001 000-12 767-400 ARENT, LAUREN, E
Biases Removed: Stick Force +0.425 lbs

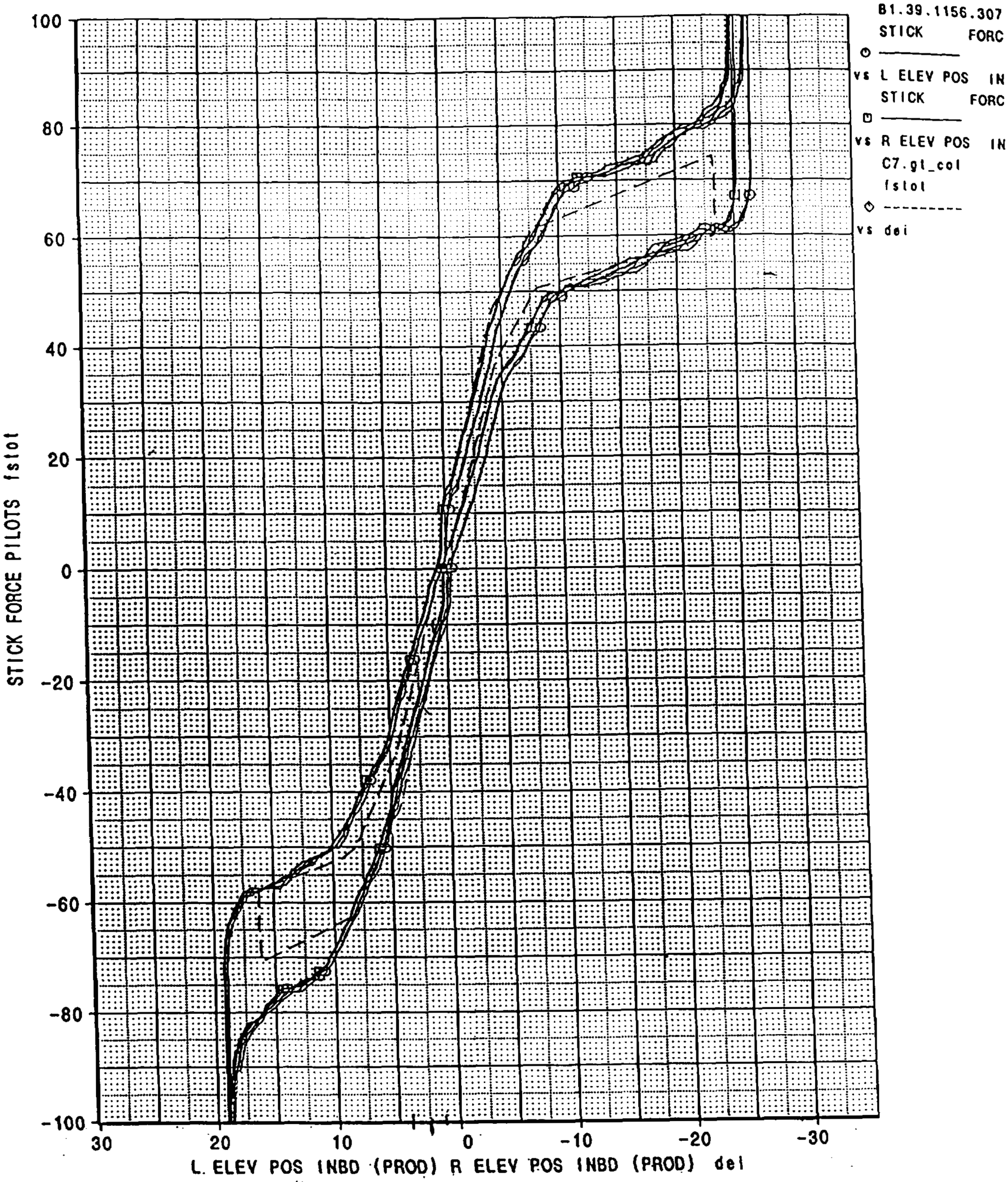


[A]: /project/fltsys/flt_test/data/VQ001/VQ001.000_12.3664.esb
[B]: /acct/pkb1662/d.sim_767/gt_column.esb

CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 306 Slow Captain's Column Sweep with Feel pressure = 400 psi	767-400
CHECK						Fig 3.3
APPD.						
APPD.					BOEING	PAGE 19

09/19/99 21:26:40.0000-21:29:15.0000 VQ001 000-12 767-400 ARENT, LAUREN, E

Biases Removed: Stick Force +0.425 lbs

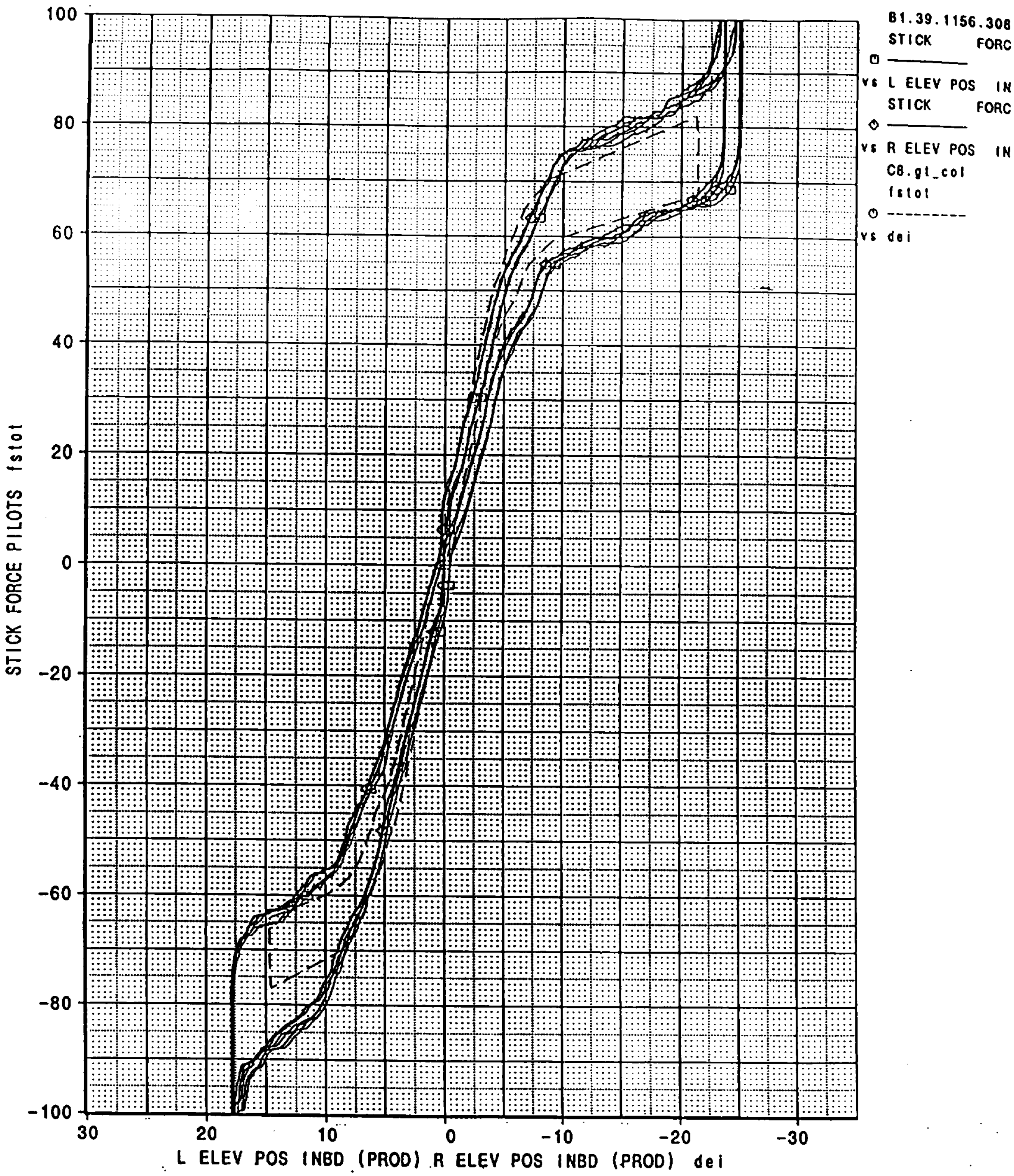


[A]: /project/fltsys/flt_test/data/VQ001/VQ001.000_12.3664.esb

[B]: /acct/pkb1662/d.sim_767/gt_column.esb

CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 307 Slow Captain's Column Sweep with Feel pressure = 600 psi	767-400
CHECK						Fig 3.4
APPD.						
APPD.					BOEING	PAGE 20

Biases Removed: Stick Force +0.425 lbs



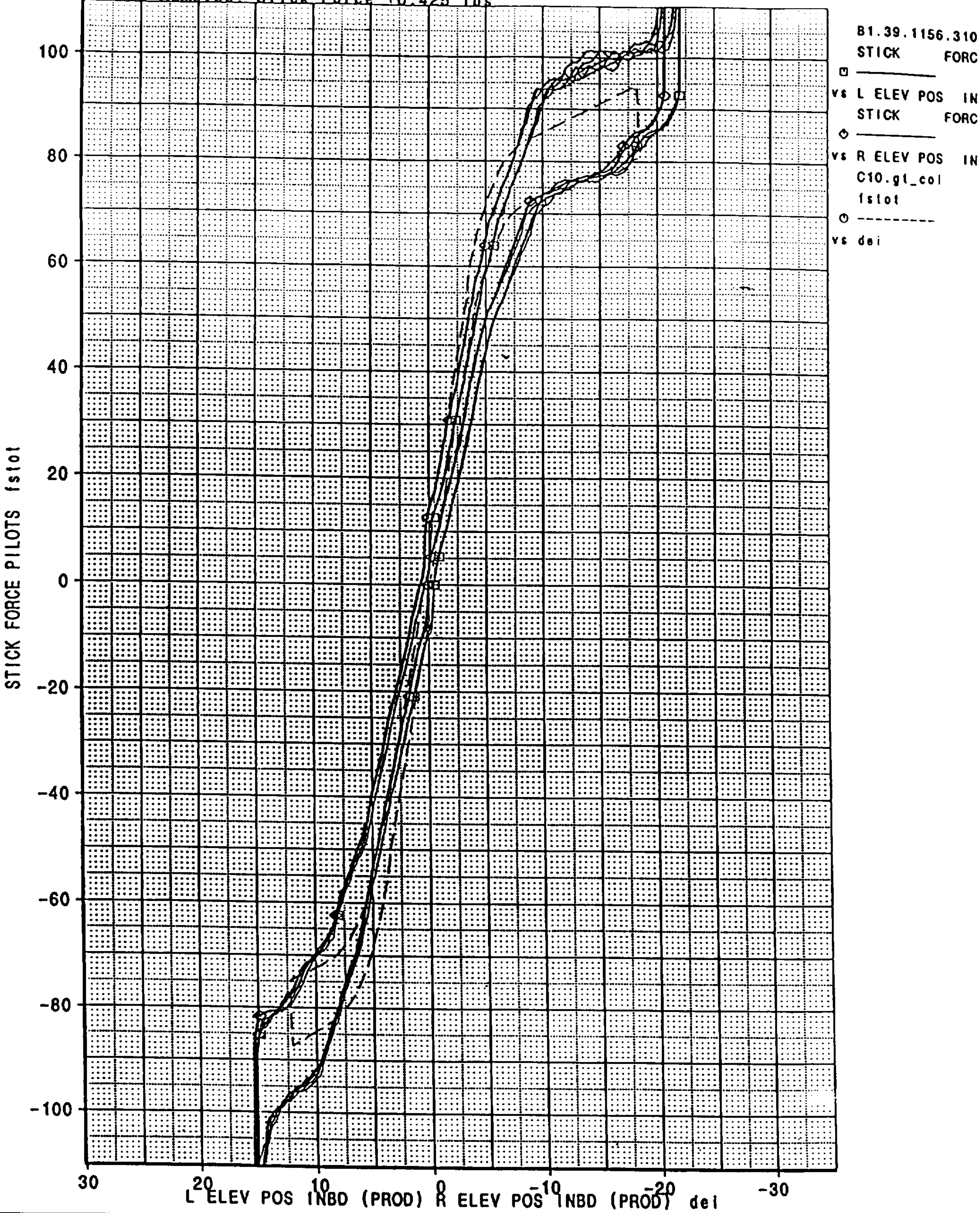
[A]: /project/fltsys/flt_test/data/VQ001/VQ001.000_12.3664.esb

[B]: /acct/pkb1662/d.sim_767/gt_column.esb

CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 308 Slow Captain's Column Sweep with Feel pressure = 700 psi	767-400
CHECK						Fig 3.5
APPD.						
APPD.					BOEING	PAGE 21

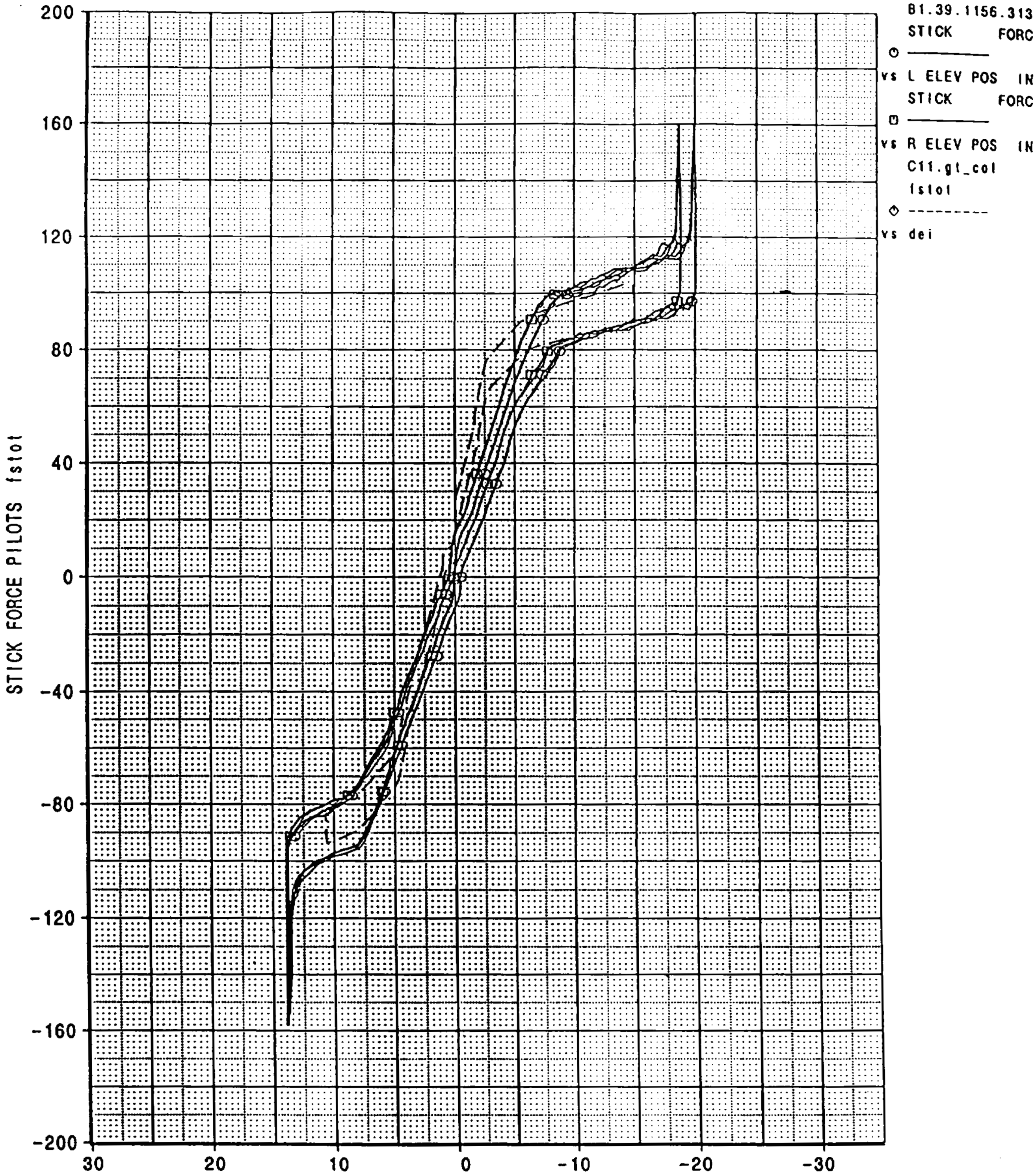
05/13/99 21:40:30.0000 21:43:05.0000 VQ001 000-12 767-400 AHENT, LAUREN, L

Biases Removed: Stick Force +0.425 lbs



CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 310 Slow Captain's Column Sweep with Feel pressure = 900 psi	767-400
CHECK						Fig 3.6
APPD.						PAGE 22
APPD.					BOEING	

Biases Removed: Stick Force +0.425 lbs



L ELEV POS INBD (PROD) R ELEV POS INBD (PROD) dei

CALC	Brian Cook	30Sep99	REVISED	DATE	VQ001 test 000-12, Condition 313 Slow Captain's Column Sweep with Feel pressure = 1100 psi	767-400
CHECK						Fig 3.7
APPD.						
APPD.					BOEING	PAGE 23

Ronald J. Hinderberger
Director
Airplane Safety
Commercial Airplanes Group

The Boeing Company
P.O. Box 3707 MC 67-XK
Seattle, WA 98124-2207

13 December 2000
B-H200-17076-ASI-R1

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

BOEING

Subject: Elevator System Response to Hydraulic Power On – Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Reference: a) Your e-mail to Rick Howes, 06 September 2000, 11:28 a.m.
b) Boeing letter B-H220-17018-ASI, 21 July 2000
c) Your e-mail to Rick Howes, 18 October 2000
d) Boeing letter B-H220-17076-ASI, 16 October 2000

Dear Mr. Warren:

In reference (c), you requested an explanation of what the physical process was that caused the "two-step" movement during the hydraulic dynamic response test conditions during the dual elevator PCA failure ground tests provided in the original letter, reference (d). Our explanation is provided below in this revision.

In reference (a), you requested Boeing to provide data plots that show how the elevator surface positions responded as hydraulics were applied to the elevator system with test conditions that were demonstrated during the 29 March, and 20 April 2000 ground tests. The following information supplements the information provided in reference (b).

In order to simulate the dynamic response of the elevator system to a sudden test condition as described below, hydraulic pressure to the elevators was supplied in a step manner by opening the Left, Right, and Center Flight Control Shutoff Tail Valves. To simulate another condition, the surfaces were manually moved back to the neutral position (in most conditions) with hydraulics turned off, the new fault was inserted, and hydraulic power was again applied to the elevator in a step manner.

The following table lists the test conditions plotted in Figures 1 – 11, as well as corrections made to instrumentation biases on the Captain's and First Officer's column forces.

Figure	Elevator Feel Pressure	Condition (all PCA modifications were performed on the right elevator)	Captain's Column Force Bias (lbs)	First Officer's Column Force Bias (lbs)
1	Base	Inbd PCA Disconnected	7.73	20.18
2	770 psi	Inbd PCA Disconnected	6.86	19.36
3	Base	Inbd & Mid PCA Disconnected	6.60	21.71
4	770 psi	Inbd & Mid PCA Disconnected	6.86	20.33
5	770 psi	All PCAs Connected	6.72	20.65
6	Base	Mid PCA Jammed	-7.20	-8.59
7	770 psi	Mid PCA Jammed	-7.00	-5.77
8	Base	Mid PCA Jammed, Inbd PCA Disconnected	-6.33	-11.01
9	770 psi	Mid PCA Jammed, Inbd PCA Disconnected	-5.98	-13.26
10	Base	Inbd & Mid PCA Jammed	-5.25	-21.43
11	770 psi	Inbd & Mid PCA Jammed	-5.00	-21.40

Boeing follow-up response to reference (c):

The following theory is presented to explain the "two-step" movement. It should be noted that the test conditions in question are beyond the original scope of the ground test. Therefore, the data available for analysis and the number of test conditions that were performed, limit full understanding of the phenomenon.

Two additional parameters were plotted, elevator feel pressure (L&C hydraulic systems) and the calculated "PCA valve commanded position" ("PCA Valve Cmd"). The elevator feel pressure was plotted to examine the hydraulic pressure spool-up rate and timing/sequencing of the opening of the hydraulic tail valve switches. The "PCA Valve Cmd" was calculated and plotted to determine where the non-failed PCA control valve was positioned during the transient hydraulic activity. The dual failure conditions were replotted with the new parameters. The figure numbers correspond to the original plots, and marked as "RevA".

The "PCA Valve Cmd" parameter is the calculated PCA control valve position of the non-failed elevator PCA(s). This calculated position is also valid for the non-failed actuator on the failed surface during the transient state (until the 2nd slope starts).

The following describes the sequence of events of the "two-step" elevator movement during the dual elevator PCA failure ground test:

As the hydraulic power was supplied to the elevator system (hydraulic tail valve switches opened) the failed PCA(s) initially drove the surface in the nose down direction. Because the failed PCA/surface movement back fed the entire elevator system, a nose-down input was commanded to all of the non-failed PCA control valves. The result of the failed and non-failed PCA control valves all being commanded in the nose-down direction was a high rate, nose down elevator movement (first slope). As the elevator surface drove towards its commanded position (the point at which the PCA input pogo force balanced with the feel and centering mechanism), the summing link returned the non-failed PCA control valves to the neutral position as shown by the "PCA Valve Cmd" passing through neutral. The non-failed PCA on the failure side then opposed the two failed PCAs and prevented further elevator movement (slope flattens outs). After the failed PCAs built up enough pressure to override the non-failed PCA (3600 psi), the surface continued to drive to the full nose-down position, but at a slower rate than the initial rate (second slope).

This theory does not explain why the "two-step" movement does not occur during the dual disconnect ground test. There is insufficient data to understand the different characteristics between the disconnect failures and the jam scenario failures. It should be pointed out that the condition shown in Fig 4 RevA would not be expected to exhibit the "two-step" characteristic because the left hydraulic system (pressure to the outboard/non-failed PCA) was turned on after the surface position had already traveled to the full nose down position.

CONCLUSION:

- A theory is presented to explain the reason for the "two step" elevator movement.
- All the jam failure scenario data supports the theory presented.
- With the data available, we can not explain why the test condition plotted on Fig 3 (Rev A) does not exhibit the 2 step characteristic.
- Boeing believes the "two step" characteristic is a "test set-up characteristic" and would not be present if the hydraulic systems were fully powered at the time when the faults were inserted.

Please contact us if you have any questions.

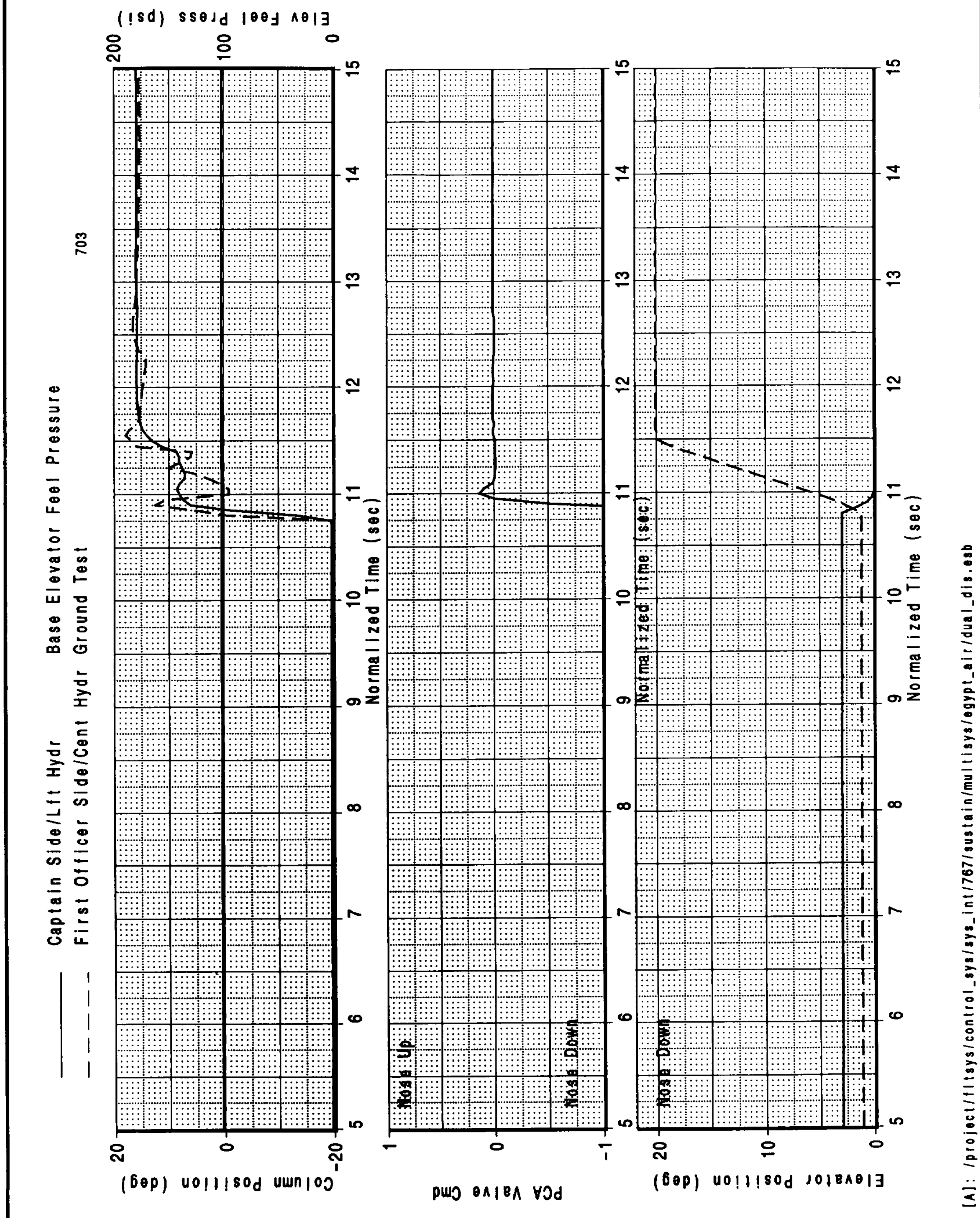
Very truly yours,

[redacted]

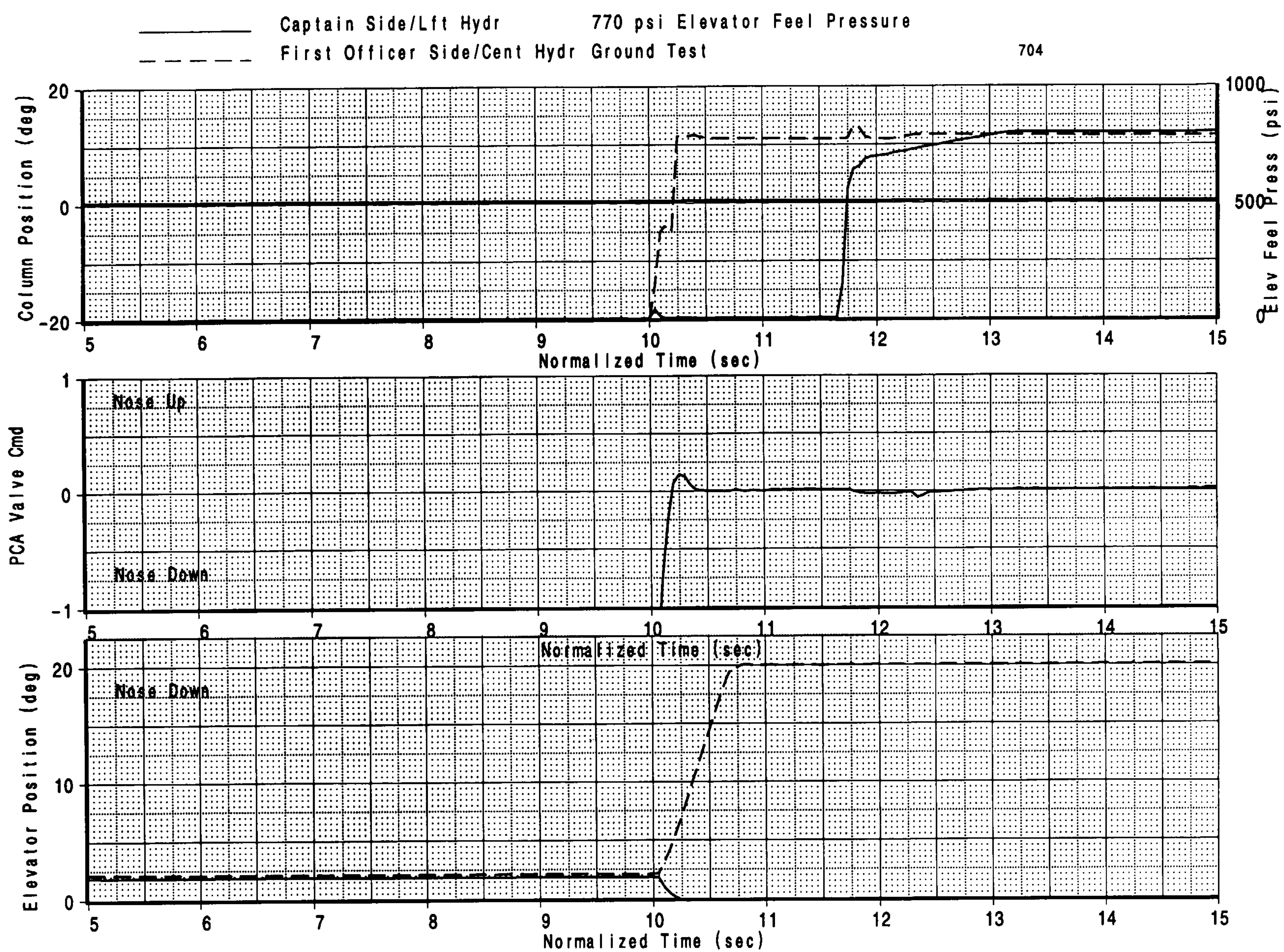
for: Ronald J. Hinderberger
Director, Airplane Safety
Org. B-H200, MC 67-PR
Telex 32-9430, STA DIR AS
[redacted]

- Boeing figures 3 Rev A, 4 Rev A, 8 Rev A, 9 Rev A, 10 Rev A, and 11 Rev A, *Egypt Air Investigation, System Dynamic Response to Hydr Power On*

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



CALC	B.Richardson	1Nov00	REVISED	DATE	Egypt Air Investigation System Dynamic Response to Hydr Power On Inbd & Mid PCU on Rt Elev Disc	767-400ER VQ001
CHECK						BE326-C00-152 FIG 3 RevA
APPD.					BOEING	PAGE
APPD.						



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/dual_dis.esb

CALC	B.Richardson	1Nov00		
CHECK				
APPD.				
APPD.				
			REVISED	DATE

Egypt Air Investigation
System Dynamic Response to Hydr Power On
Inbd & Mid PCU on Rt Elev Disc

767-400ER
VQ001
BE326-C00-152
FIG 4 RevA

PAGE

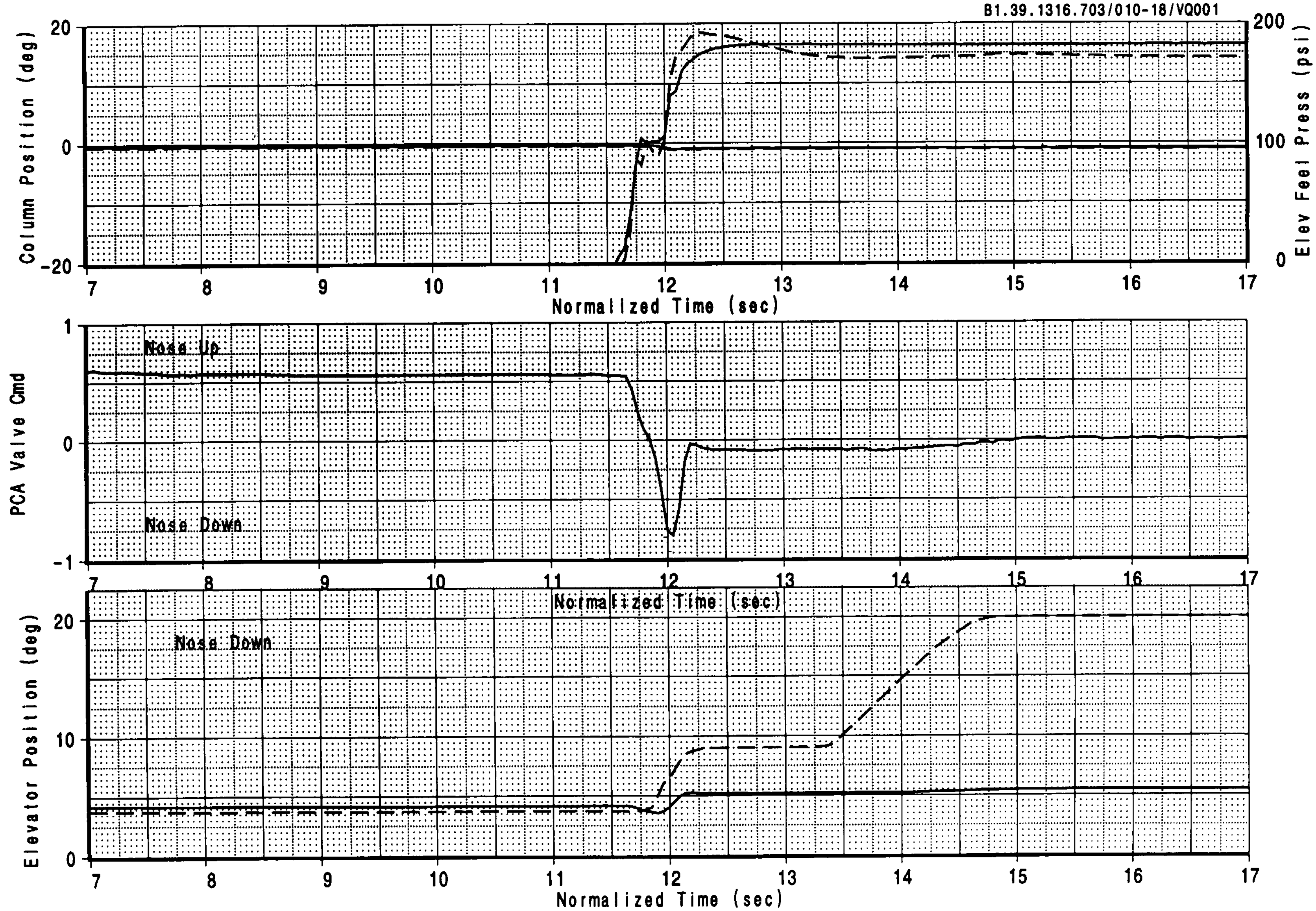
04/20/00 12:07:50.0000-12:08:10.0000 VQ001 010-18 767-400 BUCKLEY, KIMBERL

——— Captain Side/Lft Hydr — Base Elevator Feel Pressure

– – – – First Officer Side/Cent Hydr Ground Test

703

B1.39.1316.703/010-18/VQ001



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/pca_cmd_pos.esb

[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.3806.esb

CALC	B.Richardson	2Nov00
CHECK		
APPD.		
APPD.		
	REVISED	DATE

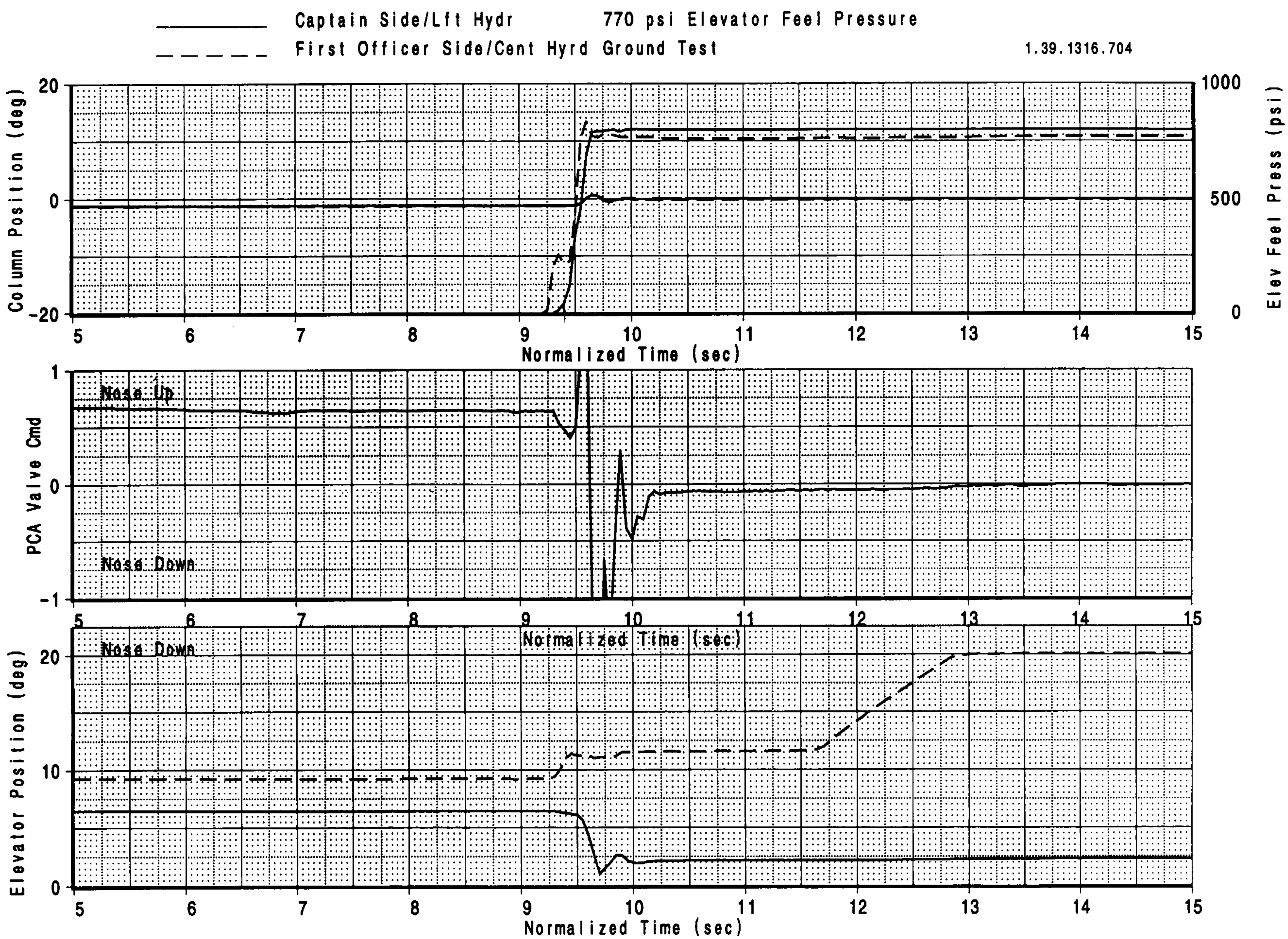
Egypt Air Investigation
System Dynamic Response to Hydr Power On
Mid PCA Rt Elev Jam; Inbd PCA Rt Elev Disc

BOEING

767-400ER
VQ001

BE326-C00-152
FIG 8 RevA

PAGE



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/704_706.esb

CALC	B.Richardson	1Nov00
CHECK		
APPD.		
APPD.		
REVISED	DATE	

BOEING

Egypt Air Investigation
System Dynamic Response to Hydr Power On
Mid PCA Rt Elev Jam; Inbd PCA Rt Elev Disc

767-400ER
VQ001

BE326-C00-152
FIG 9 RevA

PAGE

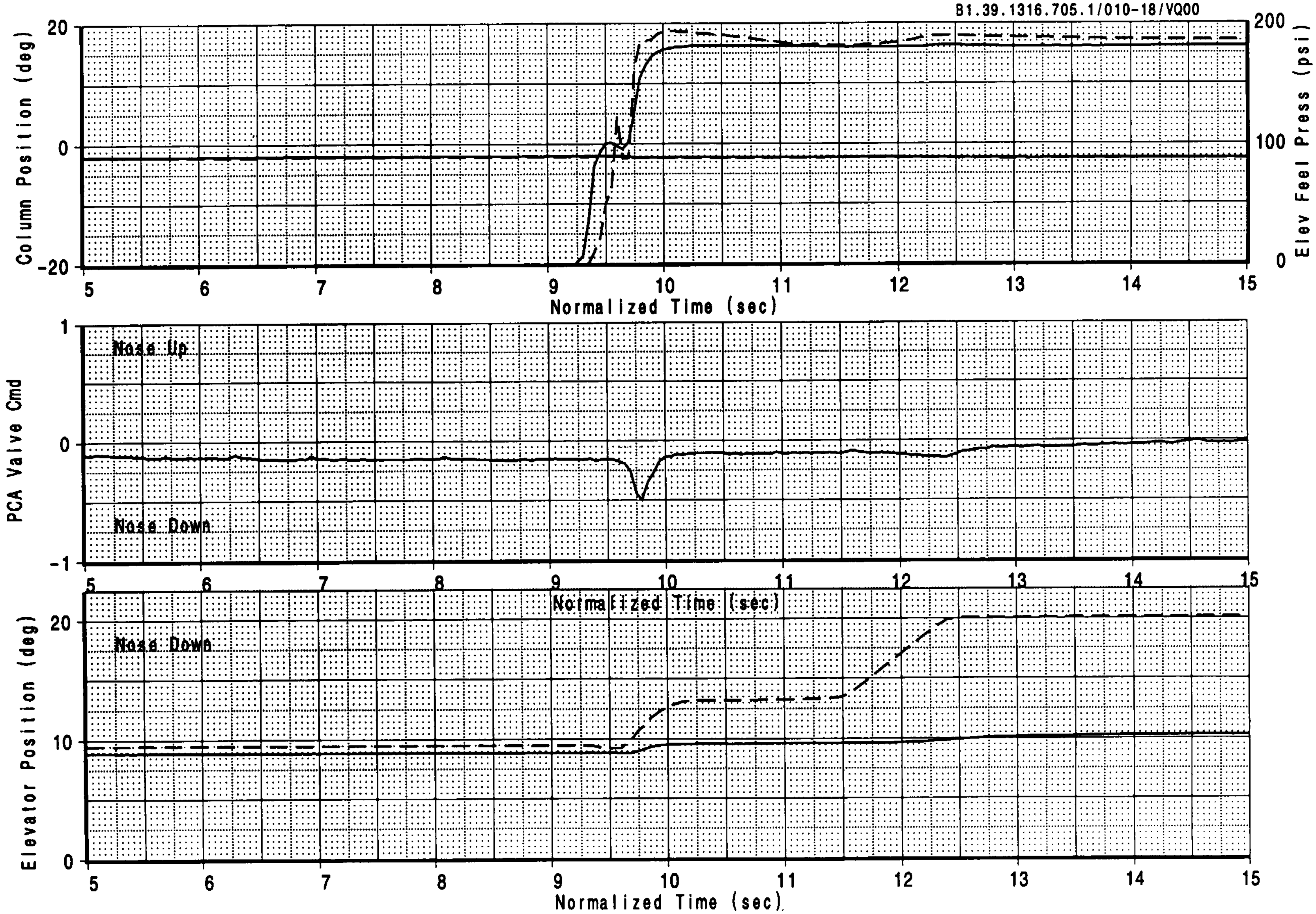
04/20/00 15:20:17.0000-15:20:37.0000 VQ001 010-18 767-400 BUCKLEY, KIMBERL

——— Captain Side/Lft Hydr — Base Elevator Feel Pressure

– – – First Officer Side/Cent Hydr — Ground Test

705.1

B1.39.1316.705.1/010-18/VQ00



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/pca_cmd_pos.esb

[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.3806.esb

CALC	B.Richardson	2Nov00
CHECK		
APPD.		
APPD.		
	REVISED	DATE

BOEING

Egypt Air Investigation
System Dynamic Response to Hydr Power On
Mid & Inbd PCA Rt Elev Jam

767-400ER
VQ001
BE326-C00-152
FIG 10 RevA

PAGE

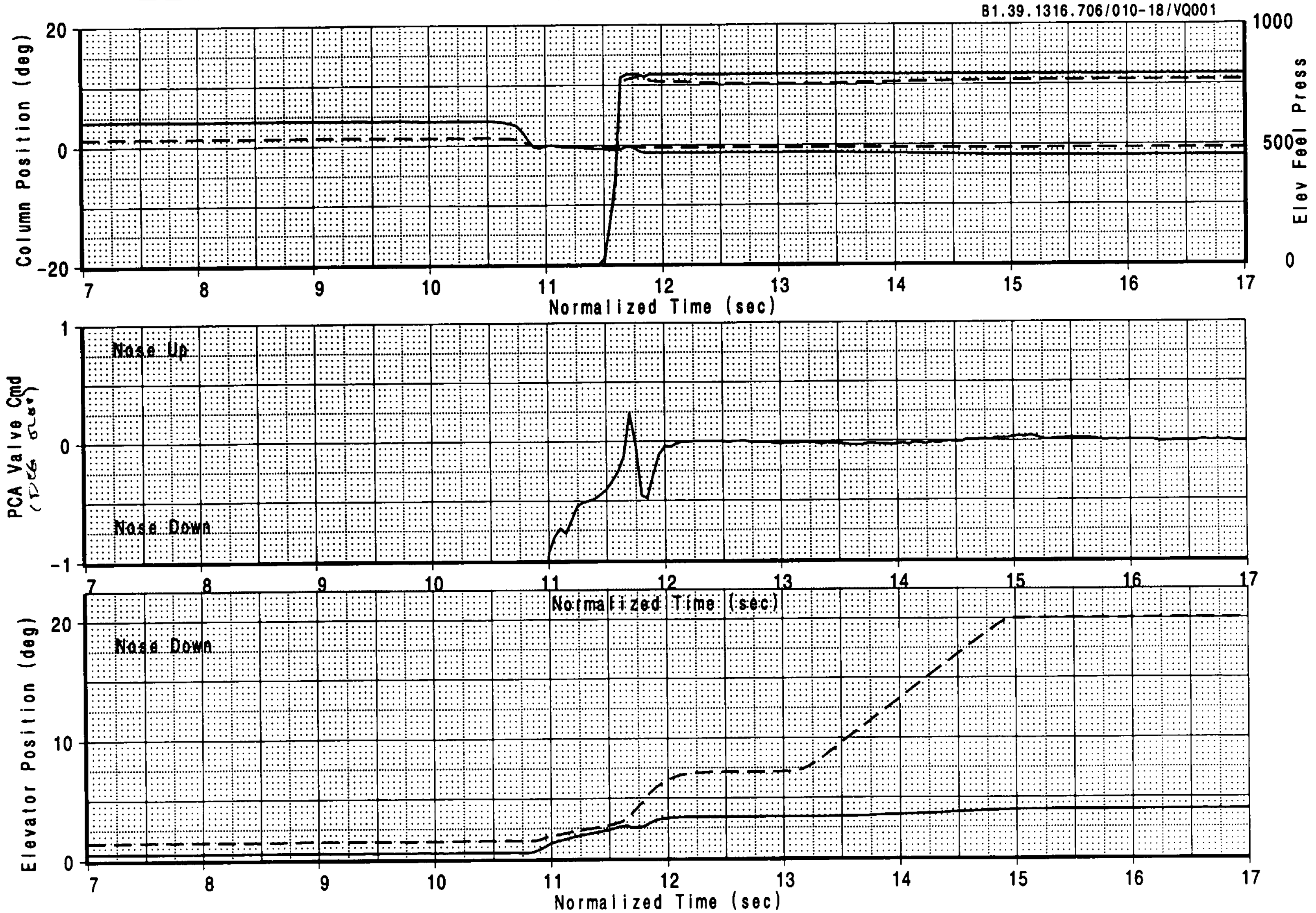
04/20/00 15:56:51.0000-15:57:11.0000 VQ001 010-18 767-400 BUCKLEY, KIMBERL

——— Captain Side/Lft Hydr   770 psi Elevator Feel Pressure

– – – First Officer Side/Cent Hydr Ground Test

706

B1.39.1316.706/010-18/VQ001



[A]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/pca_cmd_pos.esb

[B]: /project/fltsys/control_sys/sys_int/767/sustain/multisys/egypt_air/GT_10_18/VQ001.010_18.3806.esb

CALC	CHECK	APPD.	APPD.
B.Richardson			
300c100			
REVISED			
DATE			

BOEING

Egypt Air Investigation

System Dynamic Response to Hydr Power On

Mid & Inbd PCA Rt Elev Jam

767-400ER

VQ001

BE326-C00-152

FIG 11 RevA

PAGE

The Boeing Company
P.O. Box 3707
Seattle, WA 98124-2207

BOEING

20 March 2001
B-H200-17196-ASI

Mr. Scott Warren (AS-40)
National Transportaion Safety Board
490 L'Enfant Plaza East, SW
Washington, DC 20594-0003

Subject: CG and Elevator Position Data – Egyptair 767-300ER SU-GAP, Accident Off Nantucket, Massachusetts – 31 October, 1999

Reference: (a) Email message from Scott Warren to Simon Lie, 13 March 2001

Dear Mr. Warren:

In the reference email message, you requested some additional data concerning the subject accident. In particular, you asked for fuel burn data showing the change in airplane center of gravity (CG) as fuel is burned as well as Boeing's comments on apparent variations in elevator offset position recorded on the FDR from previous flights. This letter provides our response.

Center of Gravity Change due to Fuel Burn

To calculate the change in center of gravity as fuel is burned, we started with the total fuel load recorded on the FDR just prior to the initial upset. For these conditions (gross weight 388,800 lbs and total fuel 127,200 lbs), Boeing's recommended operating procedure is to have the wing tanks nominally full with the engines supplied from the center tank. When operated according to Boeing's recommended procedure, the change in CG due to fuel burn is shown in Figure 1, CG Change due to Fuel Burn. Starting from the point labeled 388,800 lbs, the airplane gross weight and CG move along the straight line segment until the center tank fuel is exhausted. At that point, the engines begin to burn fuel from the wing tanks, as represented by the kink in the curve and subsequent curved segment. At the point of the initial upset, Figure 1 shows that the trend in CG due to fuel burn alone is rearward.

BOEING

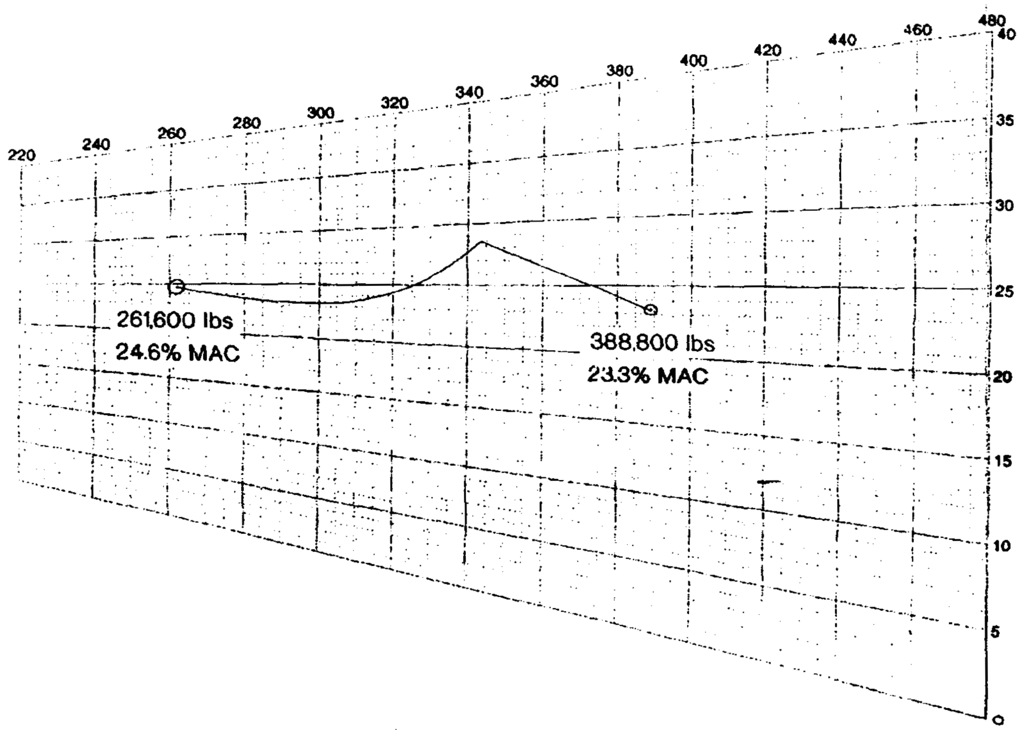


Figure 1, CG Change due to Fuel Burn

Boeing's Comments on Apparent Variations in Elevator Offset

Boeing has reviewed all of the elevator data from the FDR and found that with the exception of the accident dive, the two elevators tracked within about +/- 1 degree or +/- 2% of the full scale travel. Boeing did not find any problems with the operation of the elevator system in the FDR data.

There are many factors that affect the offsets of the 767 elevators. These factors are discussed in the following paragraphs.

The purpose of the elevator control system's temperature compensation rods is to minimize the amount of elevator motion that occurs as a function of temperature. Without temperature compensation rods, the two elevator surfaces move in opposite directions when the temperature changes. Since the temperature compensation rods are open loop compensation and there are tolerances involved in the thermal expansion coefficients of these rods and the system, some elevator offsets will still occur as a function of temperature.

Gearing tolerances of the system's components and routing differences between the left and right elevator control cables will both produce differences in elevator tracking.

The sign of the loads being transmitted through several control system components changes when the elevators are moved in the vicinity of the neutral position. When the sign of the load in any component changes, the resulting backlash and freeplay in the bearings can affect the tracking of the two elevator surfaces.

BOEING

Friction in the elevator control system allows the elevators to take on a range of values at any particular column position. How the friction is distributed within the system at any given time will also affect the elevator positions.

The feel and centering unit connected to the left aft quadrant contains a Y linkage mechanism that produces a variable feel force as a function of hydraulic feel pressure. The feel and centering unit connected to the right aft quadrant has a similar Y linkage mechanism, but it also contains a spring-cam mechanism that produces a fixed feel force. This spring-cam mechanism produces most of the centering detent force and all of the feel unit forces when no hydraulic feel pressure is present. The geometry of the two Y linkage mechanisms is different. The Y linkage mechanisms were designed with two goals in mind. The first goal is to make the sum of the two feel unit forces equal to the desired column force versus deflection characteristics at all feel pressures. Since the desired column force versus deflection curves are smooth, the slope changes on the two Y linkage gains are staggered such that their sum will produce a smoother curve. The second goal is to make the total force from each feel unit about the same which requires making the force gain of the left feel unit's Y linkage mechanism higher in order to make up for the spring-cam mechanism on the right feel unit. Keeping the feel unit forces about the same enables similar operation of the elevator control system from either control column. Since the feel forces produced by the two elevator feel units are a little different and the aft quadrant breakout mechanism which connects the two aft quadrants is compliant, the tracking of the elevators will change as a function of both the elevator feel pressure and applied column force.

The source of the force driving the elevator system has an effect on elevator tracking. The compliance experienced by the system components is a function of whether captain's column, first officer's column, autopilot actuators, or a combination thereof are driving the system.

The rigging of the elevator control system will affect the elevator offsets. The flight control rigging procedures keep the system force fight and tracking differences within a certain range, but they do not completely eliminate them.

The accuracy of the sensors used to measure the elevator positions for the FDR affects the recorded elevator tracking.

The left and right elevator positions are sampled at different times by the FDR. When the elevators are in motion, this difference affects the recorded elevator tracking error.

BOEING

Due to the large number of factors which affect the elevator offsets, it is very difficult to determine the exact source of the motion at any particular point in time except under the most controlled of test conditions. Even if the test conditions are controlled, there will be some variations between one airplane and the next. The behavior of the elevator system recorded on the FDR of EgyptAir 990 is consistent with what Boeing has seen on other normally operating 767 aircraft.

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

Very truly yours,

[redacted]

for Richard S. Breuhaus
Chief Engineer, Air Safety Investigation
Org. B-H200, MC 67-PR
Telex 32-9430, STA DIR AS
[redacted]

cc: Mr. Greg Phillips (AS-10)
National Transportaion Safety Board
490 L'Enfant Plaza East, SW
Washington, DC 20594-0003

Richard S. Breuhaus
Chief Engineer
Air Safety Investigation
Commercial Airplanes

The Boeing Company
P.O. Box 3707 MC 67-TC
Seattle, WA 98124-2207

BOEING

27 June 2001
B-H200-17265-ASI

Mr. Greg Phillips, AS-10
National Transportation Safety Board
490 L'Enfant Plaza East, SW
Washington, DC 20594-0003

Subject: Potential Elevator System Failure Scenarios – EgyptAir 767-300 SU-GAP Accident near Nantucket – 31 October 1999

Reference: a) Telecon with Rick Howes and Rich Breuhaus, 20 June 2001
b) Letter B-H200-16968-ASI-R2 to Scott Warren, 29 Sep 2000, *Split Elevator Failure Scenario – EgyptAir 767-300 SU-GAP Accident near Nantucket – 31 October 1999*

Dear Mr. Phillips:

Further to the reference (a) phone call and per your request, the following describes additional information regarding potential elevator system failures that may be of interest for the subject accident investigation. A similar phone call between Boeing and EgyptAir was held June 25.

Boeing recently met with EgyptAir on May 21-23, 2001, to discuss the subject accident. This meeting was in accord with the customer and manufacturer dialogue established since the NSTB technical review last August. Subsequent to this meeting, Boeing accomplished a qualitative review of the reference (b) scenarios to determine if there were any other potential failures that could produce the elevator behavior associated with the initial pitch-over of the accident event. Emphasis for this review was placed on combinations and/or variances of the original 18 scenarios identified by the Systems Group relative to the initial pitch-over only (approximately the first five to six seconds of the upset), and not the remaining flight profile.

As a result of this review, we have identified two scenarios that we believe warrant additional consideration by the Systems Group. These two scenarios are variations of Scenarios #1 and #6 of reference (b) and are summarized in the following table.

BOEING

Failure Scenario	System Effects	Comparison to FDR Elevator Data
1. Single failed elevator body cable (ref. b)	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.
1A. Single control cable failure combined with a jam of the failed cable (variation of ref.b)	Both elevators would initially move to an offset position related to the position of the cable failure/jam. The pilot on the side of the failure would have elevator control in one direction only and the other pilot would have control in both directions.	Analytical assessment of this failure indicates that it could produce TE down motion on both elevators. Further validation work is required to understand the details of the initial elevator motion and the remaining control from each column.
6. Rate jam in system (valve or valve input linkage jam) on a single PCU (ref. b)	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 pounds force bias would remain for further column inputs	This failure would not have caused initial elevator input.
6A. Single PCU control valve/linkage jam combined with an associated high break-out input pogo (variation of ref. b)	Both elevators would initially move to an offset position corresponding to the break-out characteristics of the pogo (limited by the bellcrank shear-out force). Either pilot would retain control of both elevators but the force bias from the pogo would remain in the system.	The elevator motion following this failure is dependent on the position of the control valve when it jams and on the interaction of the pogo break-out and the system characteristics. Low temperature pogo test data has produced variable pogo characteristics. Additional validation is required to address this further.

At this time we have not established if these scenarios could produce elevator behavior similar to the initial upset profile. Please advise how you wish to proceed in any further evaluation of these scenarios.

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

Very truly yours,

BOEING

[redacted]

for: Richard S. Breuhaus
Chief Engineer, Air Safety Investigation
Org. B-H200, MC 67-PR
Telex 32-9430, STA DIR AS
[redacted]

cc: Mr. Scott Warren, NTSB, AS-40
Captain M. El Missery, Egyptian Delegation, Cairo
Captain S. Kelada, EgyptAir Coordinator, Cairo
Mr. Tony James, FAA, AAI-100