Docket No.: **SA-510**
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NATIONAL TRANSPORTATION SAFETY BOARD

Washington, D.C.

Systems Group Chairman's Factual Report Addendum

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety
Washington, D.C. 20594

January 12, 1995

SYSTEMS GROUP CHAIRMAN'S FACTUAL REPORT ADDENDUM

A. ACCIDENT DCA-94-MA-076

Location: Aliquippa, Pennsylvania
Date: September 8, 1994
Time: 1904 Eastern Daylight Time
Aircraft: Boeing 737-300, N513AU

B. SYSTEMS GROUP

The following group members participated in the examinations

Chairman: Greg Phillips
National Transportation Safety Board
Aviation Engineering Division
Washington, DC

Member: Ken Frey
Federal Aviation Administration
Aircraft Certification Office
Seattle, WA

Member: Dale Hoth
Federal Aviation Administration
Flight Standards District Office
Pittsburgh, PA

Member: Thomas C. Nicastro
USAir-Engineering
Pittsburgh, PA

Member: Jack A. Wurzel
USAir-IAMAW
Pittsburgh, PA

Member: Captain John Cox
Air Line Pilots Association/USAir

Coraopolis, PA

Member: Richard Babunovic (Boeing EQA only)
Boeing Commercial Airplane Group
Seattle, WA

Member: Paul Cline (Boeing EQA only)
Boeing Commercial Airplane Group
Seattle, WA

Member: Rick Krantz
Boeing Commercial Airplane Group
Seattle, WA

Member: Steve Weik
Parker Hannifin
Irvine, CA

Member: John Calvin (Boeing EQA only)
Boeing Commercial Airplane Group
Seattle, WA

C. SUMMARY

On September 8, 1994, at 1904 Eastern Daylight time, USAir flight 427, a Boeing 737-300, N513AU, crashed while maneuvering to land at Pittsburgh International Airport, Pittsburgh, Pennsylvania. The airplane was being operated on an instrument flight rules (IFR) flight plan under the provisions of Title 14, Code of Federal Regulation (CFR), Part 121, on a regularly scheduled flight from Chicago, Illinois, to Pittsburgh. The airplane was destroyed by impact forces and fire near Aliquippa, Pennsylvania. All 132 persons on board were fatally injured.

D. DETAILS OF THE INVESTIGATION

The systems group met at the Parker facilities in Irvine, CA on January 9, 1995, and the Boeing EQA facilities on January 10-12, 1995.

1.0 USAir Flight 427 Servo Valve Testing at Parker Hannifin

On January 9, 1995, the accident airplane's main rudder PCU servo valve (s/n 2956) was tested at Parker Hannifin Control System Division (CSD) in Irvine, CA. The purpose of the testing was to determine the rudder PCU hinge moment capability with the servo valve primary and secondary control slides at opposing positions. The slides were held in opposing positions by inserting spacers machined to duplicate the dimensions of the accident servo valve.

The valve was tested in four positions. They were: the secondary spool jammed at full travel in the extend and retract servo positions and the primary spool jammed at full travel in the extend and retract servo positions.

The servo retract direction pushes the slides into the servo body which results in a PCU piston extend command. Servo cylinders C1, C2, C3, and C4 correspond in PCU terminology to: C2 extend, C1 retract, C4 extend, and C3 retract respectively.

The following data was obtained during the testing and is stated in terms of servo position.

Test condition	(psi) Ps	(psi) C1	(psi) C2	(psi) C3	(psi) C4	Residual
1. Secondary Retract Linkage Stop	3000	1200	1775	1575	1750	-12%
(.0625 shim, .090 primary stroke, simulates secondary jam at retract external servo stops)*1						
2. Secondary Extend Linkage Stop	3000	1975	1300	1550	1700	-9%
(.0616 shim, .090 primary stroke, simulates secondary jam at extend external servo stops)*2						
3. Secondary Retract Internal Stop	3000	550	2700	1250	2550	+58%
(.0843 shim, .068 primary stroke, simulates primary jam at full primary extend stroke)*3						
4. Secondary Extend Internal Stop	3000	2350	1350	2150	400	+46%
(.0757 shim, .076 primary stroke, simulates primary jam at full primary retract stroke)*4						

*1 = ((C1-C2) + (C3-C4)/6000psi)*100) for retract direction only
*2 = ((C2-C1) + (C4-C3)/6000psi)*100) for extend direction only
*3 = ((C1-C2) + (C3-C4)/6000psi)*100) for retract direction only
*4 = ((C2-C1) + (C4-C3)/6000psi)*100) for extend direction only

The "Residual" column indicates the percent of full hinge moment the PCU is capable of providing with the slide condition noted in column "Test Condition". A positive residual pressure indicates that the unjammed slide can null the effect of the jammed slide, and still provide position control of the surface, but at a reduced hinge moment in one direction. A negative residual pressure indicates that the unjammed slide could not completely null the effect of the jammed slide. The test results showed that; for tests 1 and 2, full displacement of the primary slide does not have the capability to overcome the effects of a secondary slide jammed at its linkage stop. Tests 3 and 4 showed that full movement of the secondary slide can overcome the effects of a primary slide stuck at its linkage stop.

A second test was conducted to validate the results of the first test. The data was generated by using Parker-provided modified input link arms. The test results and sign conventions noted in the preceeding paragraph apply to the following data. Tests 1 through 4 (using the shims) duplicates measured valve conditions and is considered the most accurate of the two tests.

Test condition	(psi) Ps	(psi) C1	(psi) C2	(psi) C3	(psi) C4	Residual
5. Secondary Retract Linkage Stop	3000	1200	1775	1575	1750	-12%
(.0625 shim, .090 primary stroke, simulates secondary jam at retract external servo stops)*1						
6. Secondary Extend Linkage Stop	3000	2050	1350	1675	1650	-12%
(.0616 shim, .090 primary stroke, simulates secondary jam at extend external servo stops)*2						
7. Secondary Retract Internal Stop	3000	500	2550	1350	2400	46%
(.0843 shim, .068 primary stroke, simulates primary jam at full primary extend stroke)*3						
8. Secondary Extend Internal Stop	3000	2500	1300	2150	400	53%
(.0757 shim, .076 primary stroke, simulates primary jam at full primary retract stroke)*4						

*1 = ((C1-C2) + (C3-C4)/6000psi)*100) for retract direction only
*2 = ((C2-C1) + (C4-C3)/6000psi)*100) for extend direction only
*3 = ((C1-C2) + (C3-C4)/6000psi)*100) for retract direction only
*4 = ((C2-C1) + (C4-C3)/6000psi)*100) for extend direction only

2.0 Servo Valve High Pressure Test

A test was performed to evaluate the effects of hydraulic inlet pressures higher than the nominal 3000 psi. All recorded forces noted below are the axial forces required to move the spools at the noted pressures. "Initial" is defined as the direction that compresses the detent spring from detent position to full secondary slide overtravel. "Release" is defined as allowing the spring to relax and return to the detent position.

Ps	Primary Extend	Primary Retract	Secondary Extend	Secondary Retract
3000	9 oz	1.38 pounds	11.5 pounds release	9.5 pounds initial
3600	9 oz	1.38 pounds	11.5 pounds release	12.0 pounds initial
			10.0 pounds initial	9.5 pounds release
3850	8 oz	1.38 pounds	11.0 pounds release	11.0 pounds initial
			9.5 pounds initial	9.0 pounds release

3.0 Main Rudder PCU Filter Tests

A bubble point test was performed on the three Purolator filters removed from the accident airplane's rudder PCU at Parker facilities in Irvine, CA on January 9, 1995. Hydraulic system A & B pressure inlet filters met Boeing specification 10-60808-4 and the yaw damper filter met Boeing specification 10-60808-3. The specification requires that the nominal filter rating shall be 10 microns, that is, 98 percent of all particles 10 microns or larger in any single dimension shall be stopped by the filter. The absolute filter rating shall be 25 microns, that is, all particles with any single dimension larger than 25 micron shall be removed. The bubble point test results were:

Filter	Bubble Point Pressure*
Yaw Damper Filter s/n 30498, BAC 10-60808-3	9.2 (25.9 micron absolute)
A System Filter s/n 14443, BAC 10-60808-4	10.5 (22.7 micron absolute)
B System Filter s/n 14319, BAC 10-60808-4	10.7 (22.2 micron absolute)

* Bubble point pressure was converted to microns absolute values (per Purolator Spec Z-708 dated 2/68) by dividing the recorded bubble point pressure by 238.

4.0 Main Rudder PCU Servo Valve Spool Chip Shear Test

On January 10-12, 1995, testing of the main rudder PCU servo valve was conducted at the Boeing Renton EQA lab. The testing was accomplished to examine the effects of particulates placed into the metering ports of the control valve.

Testing was performed using a primary and secondary slide assembly. Chips were placed in the primary metering orifices and were sheared by stroking the primary slide across the metering orifice. Tests were not performed on the secondary metering orifices because the systems group determined that the primary metering orifices are representative of the secondary metering orifices and the materials are the same. The primary and secondary "stacks" are both 52100 through hardened steel (Rc 57-62), and the O.D. of the primary and secondary slides are both Nitralloy 135, nitrided to a case depth of .008-.010 inches (core 160-180 ksi, surface hardness Rc 55-58).

A test fixture was constructed by Boeing. A pneumatic load cylinder was used to apply the load to the centerline of the primary slide. The stroke of the load cylinder was controlled to approximately .060 inch. A 100 lb load cell, ± 1% accuracy, installed between the load cylinder and primary slide was used to record the force during testing. A linear variable differential transducer (LVDT) was used to record the position of the primary slide. The output of the force transducer and LVDT were captured on an oscillographic recorder during the chip shear testing (see attached data sheets). A dial indicator was used to verify that the secondary slide did not slip within the test fixture during testing.

An optical microscope was used to aid in the insertion of the chip into the primary metering The direction of the primary slide was reversed with respect to its normal orientation (i.e, swapped end-for-end).

Parker Hannifin provided the primary and secondary slide assemblies for the tests. The secondary spools were machined, using electrical discharge machining (EDM), to expose the four primary metering ports and facilitate chip insertion.

The tests were conducted by placing the chip into the metering window and applying an axial force to the primary spool. The axial force on the primary slide was limited to 44 lbs. The limit was determined by previous testing at Parker Hannifin to be the maximum force at the centerline of the slides just prior to the external crank contacting the external manifold stops (in the retract direction).

Prior to testing, each primary slide was examined and photographed using a scanning electron microscope (SEM) to document the "before" condition of the slide lands. Photograph was performed at 50X and 150X magnification for each land. Only the 12 O'clock and 6 O'clock positions of each land were documented.

The following documents the findings of the testing (see attached data sheets for more detail):

Test no.	ID, Land, Pos	Chip material	Chip shear load (pounds)
1	220x-3, 8, 12:00	EPR rubber	2.5
2	220x-3, 8, 12:00	Teflon	1.6
3	220x-3, 8, 12:00	302 stainless steel	23.5
4	3630-7, 8, 12:00	Music wire	37.0
5	427x-1, 8, 12:00	2024-T4 aluminum	3.4
6	427x-1, 8, 6:00	2024-T4 aluminum	10.4
7	2534x-4, 6, 12:00	7075-T6511 aluminum	6.8
8	507x-2, 6, 12:00	52100 (Rc 61)	Did not shear*
9	3922-8, 6, 12:00	Al-Ni-Bronze	30.1
10	2722-5, 6, 12:00	400 Stainless Lockwire**	19.9
11	2534x-4, 6, 12:00	Chrome	5.9
12	2534x-4, 2, 12:00	4340 C 180-200	3.6

* The 52100 chip did not shear at the maximum chip shear load (44.1 lbs) for the retract direction of the accident Rudder PCU.

** The .020 inch diameter lockwire was partially work hardened by flattening (to fit in the metering orifice).

5.0 Autopilot Accessory Unit Relay Examination

Relays K2, K6, K11, K12 and K17 were removed from the autopilot accessory unit. Relays K12 and K17 were the only relays examined. The relays were examined in the Boeing EQA lab on January 12, 1995.

Relays K12 and K17 were manufactured by Struthers-Dunn P/N FCA-410-63. The relays were manufactured in the 24 week of 1987. Both relays had been severely damaged. Both relay covers had been crushed and torn open and the electrical contacts had been bent.

Continuity measurements conducted on the K12 relay revealed that the normally closed contacts were open and the normally open contacts had continuity with no coil power applied. Coil power was not applied to the relay because of the damage the relay had sustained. The examination of the relay contacts after the cover had been removed revealed a normal wear pattern on all the contacts except for the D2-D3 contact set. This set of contacts exhibited deposits of a dark material around the contact point. A continuity test determined the deposit was conductive.

Continuity measurements conducted on the K17 relay revealed that the normally closed and open "A" contacts were electrical open. The remaining contacts had continuity with no coil power applied. Coil power was not applied to the relay because of the damage the relay had sustained.

The examination of the relay contacts after the cover had been removed revealed a normal wear pattern on all the contacts except for the C1-C2 contact set. This set of contacts exhibited deposits of a light gray material around the contact point. A continuity test determined the deposit was conductive.

[redacted]

Gregory Phillips
Aerospace Engineer
National Transportation Safety Board

DATA SHEET

TEST DATE: 1/10/95 test #1

VALVE DATA

VALVE S/N: 220X-3

~~PORT~~ LAND IDENTIFIER: 8 12:00

SAMPLE MATERIAL

MATERIAL TYPE: Ethylene Propylene Rubber (O-ring)

MATERIAL SIZE: ~ 90% filled metering window

METHOD OF MEASURE: wedged shaped piece

CHIP SHEAR LOAD: 2.5 # max

DATA SHEET

TEST DATE: 1/10/95 test #2

VALUE DATA

VALVE S/N: 220X -3

~~PORT~~ LAND IDENTIFIER: 8 12:00

SAMPLE MATERIAL

MATERIAL TYPE: Teflon (back-up)

MATERIAL SIZE: ≈ 90% filled metering window

METHOD OF MEASURE: wedge shaped piece

CHIP SHEAR LOAD: 1.6 # max

DATA SHEET

TEST DATE: 1/10/95 test #3

VALVE DATA

VALVE S/N: 220X-3

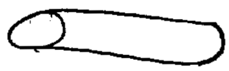
~~PORT~~ LAND IDENTIFIER: B 12:00

SAMPLE MATERIAL

MATERIAL TYPE: 302 stainless

MATERIAL SIZE: .011 DIA WIRE

METHOD OF MEASURE: stock



CHIP SHEAR LOAD: 23.5 # MAX

DATA SHEET

TEST DATE: 1/10/95 test #4

VALVE DATA

VALVE S/N: 3630 - 7

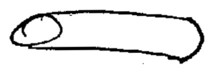
~~[illegible]~~ LAND IDENTIFIER: 8 12:00

SAMPLE MATERIAL

MATERIAL TYPE: MUSIC WIRE

MATERIAL SIZE: .013 DIA

METHOD OF MEASURE: Stock



CHIP SHEAR LOAD: 37 # MAX

DATA SHEET

TEST DATE: 1/11/95 test # 5

VALVE DATA

VALVE S/N: 427 x -1

[redacted] IDENTIFIER: 8 12:00
LAND

SAMPLE MATERIAL

MATERIAL TYPE: 2024 - T4

MATERIAL SIZE: .32L x .049W x .008-.017T

METHOD OF MEASURE: scale, micrometer, photograph

Note: had trouble keeping larger chips in slot - at one point a larger chip reached 6.5 lbs but the chip popped out without shearing

ALSO Note: Preexisting damage @ Land 8 12:00 as evidenced by SEM

CHIP SHEAR LOAD: 3.4 # max

DATA SHEET

TEST DATE: 1/11/95 test #6

VALVE DATA

VALVE S/N: [redacted] 427X-1

[redacted] IDENTIFIER: 8 6:00
LAND

SAMPLE MATERIAL

MATERIAL TYPE: 2024-T4

MATERIAL SIZE: .44 L x .028 W x .015 T

METHOD OF MEASURE: micrometer, scale, photograph

NOTE: chip shaped to fit .028 W x .015 T into slot

CHIP SHEAR LOAD: 10.4 #

DATA SHEET

TEST DATE: 1/11/95 test # 7

VALUE DATA

VALVE S/N: 2534 x - 4

[redacted] LAND IDENTIFIER: #6 12:00

SAMPLE MATERIAL

MATERIAL TYPE: 7075 - T6511

MATERIAL SIZE: .2 L x .032 W x .013-.021 T

METHOD OF MEASURE: micrometer, scale, photo

7.a. sheared 1st time 4.1 #

chip worked it's way partially out

7.b. sheared 2nd time 6.8 #

CHIP SHEAR LOAD: 6.8 # max 7.b.

DATA SHEET

TEST DATE: 1/11/95 test #8

VALVE DATA

VALVE S/N: 507X-2

~~[illegible]~~ LAND IDENTIFIER: 6 12:00

SAMPLE MATERIAL

MATERIAL TYPE: 52100 61 R_c

MATERIAL SIZE: .22L x .032-.058 W x .012-.016T

METHOD OF MEASURE: micrometer, scale, photo

CHIP SHEAR LOAD: 44.1 #

did not shear

DATA SHEET

TEST DATE: 1/12/95 Test #9

VALVE DATA

VALVE S/N: 3922-8

~~PORT~~ LAND IDENTIFIER: #6 @ 12:00

SAMPLE MATERIAL

MATERIAL TYPE: al-Ni-Bronze

MATERIAL SIZE: .14L X .034-.048W X .014T

METHOD OF MEASURE: Micrometer-scale-photo

CHIP SHEAR LOAD: 30.1 #

DATA SHEET

TEST DATE: 1/12/94 test #10

VALVE DATA

VALVE S/N: SLIDE 2722-5 / SLEEVE 633-5 *

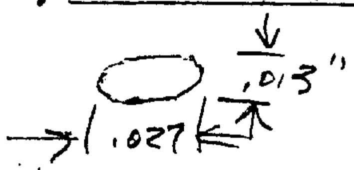
~~[illegible]~~ IDENTIFIER: 6 12:00
LAND

opposite side of sleeve was used relative to previous samples, but slide still @ Land 6 12:00 (mismachined sleeve)

SAMPLE MATERIAL (COND. A)* (MS 20995 NC)

MATERIAL TYPE: 400 STAINLESS LOCKWIRE

MATERIAL SIZE: .020' DIA FLATTENED with hammer*
METHOD OF MEASURE: Stock size, micrometer



.47" long

* partially workhardened

CHIP SHEAR LOAD: 19.9 # max

DATA SHEET

TEST DATE: 1/12/95 test 11

VALVE DATA

VALVE S/N: 2534X-4

~~BORE~~ LAND IDENTIFIER: 6 12:00

SAMPLE MATERIAL

MATERIAL TYPE: Chrome chip

MATERIAL SIZE: .070 L x .047 W x .005 T

METHOD OF MEASURE: micrometer, scale, photo

ARROW head shaped

CHIP SHEAR LOAD: 5.9 ~ digital #

6.4 ~ graph

DATA SHEET

TEST DATE: 1/12/95 test 12

VALVE DATA

VALVE S/N: 2534X-4

~~PORT~~ LAND IDENTIFIER: 2 12:00

SAMPLE MATERIAL

MATERIAL TYPE: 4340 C 180-200

MATERIAL SIZE: .16 L x .016-.046 W x .007 T

METHOD OF MEASURE: micrometer, scale, photo

CHIP SHEAR LOAD: 3.6 # max