NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety
Washington, D.C. 20594
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SYSTEMS GROUP CHAIRMAN'S FACTUAL REPORT OF INVESTIGATION
ADDENDUM
Main Rudder PCU Thermal Testing and Dimensional Examinations

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

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C. **SUMMARY**

On September **8,** 1994, at 1904 Eastern Daylight time, USAir flight 427, a Boeing 737-3B7 (B-737-300), **N5**13AU, 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.

This report presents factual data collected during testing of the main rudder power control unit (PCU).

D. DETAILS OF THE INVESTIGATION

General

The systems group, with the assistance of a group of technical consultants, formulated a test plan to examine the effects of hot hydraulic fluid introduced into a cold Boeing 737 main rudder power control unit (PCU). The testing was conducted in three phases. Phase 1 was conducted at Parker Bertea, Irvine, California and Canyon Engineering, Valencia, California, on August 20-29, 1996. Phase 2 was conducted at Boeing, Seattle, Washington, on October 7-12, 1996. Phase 3 was conducted at Parker Bertea, Irvine, California, on November 20-21, 1996.

Prior to Phase 1 testing, Boeing supplied the systems group with analytical data that indicated that the air temperature in the vertical stabilizer cavity near the PCU would be approximately -27°F at an outside ambient air temperature of -65°F. The data also indicated that, with the hydraulic system pump case drain overheat sensor set at 220°F, and a corresponding hydraulic system reservoir temperature of **180°F** to **207°F**, hydraulic fluid at about 220°F at the pump case drain would cool to approximately 170°F before it reached the main rudder PCU.

Based on this analysis, the systems group set the thermal test target points for a PCU external surface temperature of -27°F and hydraulic fluid temperature at 170°F. The systems group requested flight test verification of the temperature analysis.

At the request of the systems group, Boeing performed two flight tests to collect this data. The first flight was performed on October **4,** 1996. After reviewing the data during Phase 2 testing, the systems group determined that an additional flight test should be performed.

The second flight test was conducted at night on December 6, 1996. The night test was conducted to minimize the effects of solar heating. The flight test was conducted at night for a total of four and a half hours. The airplane cruised at approximately 32,000 feet for two hours, and then descended to 20,000 feet for 1 hour, and landed within 1 additional hour. Data collected during this test are summarized below. Complete data collected during both flights can be found in the Phase **2** data attachment to this report.

	Temperature °F (end of soak)	
Temperature sensor location	35K	20K
A hydraulic system PCU inlet fluid	22	24
A hydraulic system PCU inlet tube	21	23
B hydraulic system PCU inlet tube	34	35
PCU valve housing	35	38
PCU surface (rabbit ears)	15	18
Rudder PCU cavity ambient	-15	0
Standby Rudder PCU cavity ambient	-25	-5
Cavity ambient above stdby PCU	-30	-8
A system engine driven pump (EDP) outlet	58	65
A system ac motor pump (AMP) outlet	53	53
B system EDP outlet	52	53
B system AMP outlet	48	50
Outside air ambient (static)	-58	-35.5
Outside air ambient (total)	-22	-0.4

Boeing could not provide flight test data for a hydraulic system overheat condition. Therefore, a thermal analysis for this condition was performed by a Boeing hydraulics group. **A** thermal model was used to simulate an engine-driven pump (EDP) pressure compensator jammed full open. This resulted in a worst-case hydraulic overheat condition due to throttling 22 GPM flow across the pressure relief valve to reservoir. The rate of change in the fluid temperature at the rudder PCU inlet is a function of the total flow in the aft section of the airplane (section **48).** The higher the flow, the higher the rate of fluid temperature rise. The flow used for the analysis was assumed to be ***0.26*** GPM for the rudder and 0.554 GPM for the elevator. This represents the rudder cycling at +/- 1 degree at **0.3** Hz (the **B-737** Dutch roll frequency). The elevator flow represents the estimated combined steady state flow of the autopilot servo and elevator PCU.

The predicted temperatures for the **A** hydraulic system are shown in Figure **3,** Phase **2** attachments. Figure **4** shows the worst case hydraulic system overheat condition and Phase **2** test conditions D, F, and G

Phase 1 Testing

The Phase 1 test objectives were to:

(1) Re-assemble and re-evaluate the USAir flight 427 accident PCU by re-performing the acceptance test procedure (ATP)
(2) Examine the effects of a cold PCU subjected to hot hydraulic fluid
(3) Examine the effects of air introduced into the hydraulic fluid entering the PCU
(4) Examine the effects of silting on the PCU .

All testing was first performed on a rudder PCU from new production stock (s/n 2203A)[1] to verify the test set-up and methodology. After completion of the initial test series, the accident PCU was tested following the same procedures.

The systems group met at Parker Bertea on August 20 and 21, 1996, to re-assemble the accident PCU and perform an ATP on the accident and production PCUs. The results of the ATP are included in the attachment to this report titled "Phase 1 Data".

Following the re-assembly and testing, the units were taken to Canyon Engineering, Valencia, California on August 22 and 23, 1996 for initial fitting of the production PCU into the Canyon thermal test fixture. The thermal testing commenced on August 26, 1996 and continued through August 28, 1996. On August 29, 1996, both PCUs were taken back to Parker for an additional post-thermal test ATP, visual, and dimensional examination. The results of the ATP are included in Attachment Phase 1 data to this report.

Phase 1-Test facilities and equipment

Phase 1 testing at Canyon Engineering was conducted on a Canyon Engineering-fabricated holding fixture contained in a temperature controlled chamber. The chamber consisted of a commercially available foam "cooler" with openings cut to allow the test fixture and hydraulic lines to pass into the chamber. The cooler was turned upside down with the top or lid of the cooler forming the bottom of the chamber. To gain access to the PCU, the cooler was lifted off the fixture.

The chamber was cooled by introducing gaseous liquid nitrogen through a supply manifold located in the top of the chamber. The manifold consisted of stainless steel tubing with small holes drilled along its length. The supply of nitrogen to the chamber and temperature were controlled by a cryogenic flow control valve that could be set at a given temperature. The control valve automatically opened and closed to control the chamber temperature. Temperatures in the chamber, on the PCU, and in the hydraulic fluid were recorded on a computer data collection system and by manually noting values on digital thermometers.

A pneumatically operated load cylinder was attached to the PCU input arm for manual inputs. The cylinder was actuated by operating a switch box that operated electro-pneumatic

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[1] **S/n 2203A is referred to as "engineering unit" on data sheets. This term was used because the unit was provided to the systems group by Boeing engineering. It had not been modified and was representative of production stock. The term engineering unit has no other meaning.**

control valves that allowed pressure to be applied to the cylinder. Variable orifice control valves were installed for both extend and retract input directions. These valves were' opened and closed by turning the valve to allow air to slowly or quickly leave the input actuator. Prior to beginning testing, several runs were made to adjust the control valves in an effort to create input force levels that would exercise either the primary (only) or primary and secondary servo control valve slides.

A second pneumatic load cylinder was connected to the PCU output. Load was not applied through the cylinder during any of the tests. The load cylinder was installed in case the group wished to conduct testing beyond the original test plan.

Temperature, position, and force data were recorded by a Canyon Engineering-operated computer data recording system and a Boeing-operated data recording system. Both units utilized the same signal source probes. The Boeing data was recorded on a strip-chart recorder. The **Canyon** data was recorded to a computer data file **as** tab delineated text. Data recorded during Phase 1 testing can be found in Phase 1 data attachment to this report. Some Canyon data files were lost during extreme temperature testing of the accident unit, the Boeing data system successfilly recorded all tests.

Phase 1 Tests

Phase 1 testing began when the production unit was installed in a temperature-controlled chamber shown in the Phase 1 attachments. All testing was conducted with hydraulic fluid removed from in-service USAir Boeing **737** aircraft. There were no hydraulic system filters in the test bench.

The thermal tests consisted of three different test conditions.

1. The PCU was first subjected to environmental conditions that simulate normal operating conditions, i.e. normal fluid and PCU temperatures. A silting test was also performed.
2. The PCU was subjected to a thermal shock by introducing hot hydraulic fluid that passed through a length of hydraulic tube in the test chamber and then into the cold PCU,
3. The PCU was subjected to an extreme thermal shock when hot hydraulic fluid was directly introduced into the cold PCU. This special case condition was created by dumping the cool hydraulic fluid from the system lines in the chamber near the PCU prior to the surge of warm hydraulic fluid. Because of inadequate capacity in the cooling setup, it was necessary to depressurize the PCU during the cold soak. This eliminated the warming effect of hydraulic leakage through the PCU.

The effects of cyclic and step input yaw damper operation were also examined in the testing. Also, hydraulic system failures were simulated and the tests were performed with single hydraulic system operations.

Additional tests were performed on the accident PCU where nitrogen (gaseous) was introduced into the PCU to determine how its operation was affected.

Room temperature test-production unit-Test A (test data files-production unit **8/26)**

On August **26,** 1996, the PCU was operated via the input arm to demonstrate normal operation with the yaw damper energized and no yaw damper input command. The PCU was then operated for approximately 50 extend and retract cycles with sufficient force to insure that the secondary valve opened during each cycle. Periodically, the PCU was checked for controllability by stopping the input prior to full extend or retract and noting that the actuator rod positioned itself correctly. The actuator responded normally to all tests. The following data was manually recorded during the tests:

Test A- Production unit-room temperature run, 8/26/96

Time	T1	T2	s/v	ctrl	flow	comments
11:30	81	77	83	81	.1	
shut off gaseous nitrogen						
11:55	79	68	71	68	.1	preliminary run
12:20	95	104	111	103	.32	
12:30	91	95	106	101	.09	
14:55	79	-22			.21/.46	

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flow=return system flow in gallons per minute

The PCU was then operated for approximately 50 extend and retract cycles with sufficient force to insure that only the primary valve opened during each cycle. Periodically, the PCU was checked for controllability by stopping the input prior to full extend or retract and noting that the actuator rod positioned itself correctly.

The input arm to the PCU was then held at the actuator null position. The yaw damper was operated with a ±3° step input signal, and then ±3° 1.0 Hz and 0.3 Hz sinusoidal yaw damper input command signals were applied. The PCU responded normally

Nominal operating conditions tests-production unit (test data files-production unit **8/26)**

Following the initial room temperature tests, on August **26** and **27, 1996,** the yaw damper engage solenoid was energized and the input command signal was set at zero. The test chamber temperature was lowered *to* a target range of no warmer than -27°F and no colder than **-45°F** and held at a constant temperature in that range until the temperature measured on the servo valve stabilized. The chamber temperature was not stabilized during the testing.

The servo valve surface temperature reached **-31°F** at 13:40 on August **26,** but as soon as hydraulic fluid flowed through the PCU, the temperature began to rise (see test B temperature table). The temperature rose to **32°F** during **8** minutes of testing. The following data was manually recorded during the tests:

Test B- Production unit-nominal conditions, 8/26/96

Time	T1	T2	s/v	ctrl	flow	comments
13:40	-36	-26	-31	-40	.39	start flow
13:41	-36	-6	-23	-39		
13:42	-49	13	-14	-41	.39	
13:43	-42	33	-7	-40	.39	
13:44	-72	48	-5	-41		hot fluid connected at 44.5
13:45	-64	88	4	-39	.80	y/d on
13:46	-119	135	10	-39	.39	startedmanual input46.5
13:47	-149	153	20	-39		
13:48	-171	131	32	-36		

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flowreturn system flow in gallons per minute

The **PCU** was manually operated to retract (the input extended toward the PCU rod end) with sufficient force to insure that the secondary valve opened. The input to the PCU was slowly moved to the null position. Then, a rapid input of higher force was applied to check secondary valve operation. The operation was normal.

The PCU temperature was lowered and re-stabilized (8/26-time 16:37) and the test was repeated to full extend and then retract with an input of sufficient force to insure that the secondary valve opened. The input to the PCU was then slowly moved to the null position and a sudden input of higher force was applied to the input to check secondary valve operation. The PCU responded normally. Once again, after cold soaking, and a servo valve external surface temperature of -29°F, the servo temperature quickly rose to 30°F with the introduction of hydraulic fluid. The hydraulic fluid temperature (taken at the inlet to the coiled tubing) after the cold soak was raised to 177°F. The following data was manually recorded during the tests:

Test C- Production unit-nominal conditions, 8/26/96

Time	T1	T2	s/v	ctrl	flow	comments
16:37	-6	-73	-29	-40	0	test run
16:40	-3	-15	-27	-40	.12	started manual input at 40.5
16:42	2	74	-1	-35	2.0	
16:44	8	79	30	-24		

Hydraulic reservoir sump 177 at start, 160 at test completion
T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flowreturn system flow in gallons per minute

Following these tests, the **"A"** hydraulic system pressure was shut off and the test was repeated.

Summary of production unit nominal operating conditions tests results

The PCU responded normally during all tests. No anomalies were noted. The systems group noted that the cold-soaked servo valve temperature rose quickly with the introduction of hydraulic fluid. Testing was further complicated by the inability to maintain consistent temperatures within the test chamber. The use of gaseous liquid nitrogen in the chamber with large holes cut out in the test chamber resulted in the loss of cooling capacity. *Also,* the adjustment and operation of the pneumatic input cylinder was somewhat inexact in the proper application of input forces at controlled rates.

Test plan modification-hydraulic fluid cooling

The original systems group thermal test plan called for allowing the PCU under test to cold *soak* with hydraulic pressure on and the yaw damper engage solenoid energized. These conditions best replicate a "real world' airplane environment. After the initial tests began, the group realized that with the Phase 1 test equipment, it would be impossible to get the **PCU** servo valve external Surface temperature to stabilize at the temperatures set out in the test. The group elected to **modify** the test plan to stop all hydraulic flow through the yaw damper engage solenoid and to immerse **a** section of coiled steel tubing in dry ice and alcohol. The dry ice/alcohol bath provided **additional** pre-cooling to the fluid. There was no temperature control for the ice/alcohol bath. [Note-This test plan modification was done under protest of the Boeing representative who advocated delaying testing until equipment capable of running the test per the original test plan could be obtained.]

All subsequent Phase 1 tests were conducted with these modifications to the original test plan.

Special condition-extreme AT test-production unit-Test D (test data files-wod unit **8/27**)

On August **27, 1996,** the yaw damper engage solenoid was energized and the input command signal set at zero. The test chamber temperature was lowered to a target range of no warmer than **-27°F** and no colder than **-45°F** and held at a constant temperature in that range until the temperature measured on the servo valve stabilized.

The servo valve surface temperature reached **-35°F** at 11**:28** on August **27,** but as soon as hydraulic fluid flowed through the PCU, the temperature began to rise (see test D temperature table). The temperature rose to **62°F** during **8** minutes of testing. The following data was manually recorded during the tests:

Test D- Production unit-special condition, extreme thermal shock, 8/27/96

Time	T1	T2	s/v	ctrl	flow	comments
11:28	-9	95	-35	-40		
11:29	-13	107	-20	-40	.7	start flow
11:30	-14	127	-7	-40		
11:31	-22	144	12	-39	.33	
11:32	-59	162	20	-40	.33	manual cycles
11:33	-29	163	35	-39	.33	manual cycles
11:34	-78	157	44	-39	.70	y/d on
11:35	-102	158	55	-35	.70	
11:36	-122	145	62	-32	.12	y/d off

T1=inlet fluid temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flowreturn system flow **in gallons per minute**

The hydraulic fluid temperature was raised to and stabilized at **90"**-100°F (temperature taken at the inlet to the coiled tubing). After PCU thermal stabilization, the hydraulic fluid temperature was raised to 160°-170°F. The system solenoid was opened to dump the cold hydraulic fluid from the chamber and the hot hydraulic fluid was applied directly to the PCU.

A ±3° sinusoidal yaw damper command at 1.0 Hz was input until the hydraulic fluid cycled through the PCU (as indicated by a servo valve temperature rise). The PCU input was operated using the pneumatic cylinder described on page **4.** The cylinder was operated with sufficient force to insure that the secondary valve opened. Then, the PCU input was moved slowly to the null position. Then, a sudden input of higher force was applied to check secondary valve operation. The PCU responded normally.

The PCU temperature was re-stabilized and the test was repeated to full extend and then retract with an input with sufficient force to insure that the secondary valve opened. The input to the PCU was then moved slowly to the null position and a sudden input of higher force was applied to the input to check secondary valve operation.

Following these tests, the "A' hydraulic system pressure was shut off and the test was repeated.

Summary of production unit special condition-extreme operating conditions tests results

The PCU responded normally during all tests. No anomalies were noted. The systems group again noted that the cold-soaked servo valve temperature rose quickly with the introduction of hydraulic fluid. Previous difficulties with the test equipment lessened somewhat as modifications were made to the nitrogen manifold to saturate the chamber with flow. This resulted in more rapid cooling of the PCU.

Room temperature test-accident unit-Tests **A** and B (test data files-accident unit **8/27]**

On August 27, 1996, the PCU was operated via the input to demonstrate normal operation with the yaw damper energized and no yaw damper input command. The PCU was then operated for approximately 50 extend and retract cycles with sufficient force to insure that the secondary valve opened during each cycle. Periodically the PCU was checked for controllability by stopping the input prior to full extend or retract and noting that the actuator rod positioned itself correctly.

The PCU was then for approximately 50 extend and retract cycles with sufficient force to insure that only the primary valve opened during each cycle. Periodically the PCU was checked for controllability by stopping the input prior to full extend or retract and noting that the actuator rod positioned itself commensurately via the feedback summing linkage.

The PCU was then held at the actuator null position. The yaw damper was operated with a ±3° step input signal, and then 0.3 Hz and 1.0 Hz sinusoidal yaw damper input command signals were applied. Throughout this test, the PCU operated normally with no noticeable significant effects due to silting or fluid particulate contamination.

Nominal operating conditions tests-accident unit test **E** (F,G, and H for hydraulic failures) (test data files-accident unit 8/27>

The yaw damper engage solenoid was energized and the input command signal was set at zero. The test chamber temperature was lowered to a target range of no warmer than -27°F and no colder than -45°F and held at a constant temperature in that range until the temperature measured on the servo valve stabilized. The following data was manually recorded during the tests:

Test E-Accident unit-normal thermal shock, 8/27/96

Time	T1	T2	s/v	ctrl	flow	comments
15:24	-65	-159*	-30	-40	0	
15:26	-52	-16	-20	-40	.38	start y/d at 1 Hz
15:27	-62	40	-15	-39		*start* bypass at 27.5
15:28	-79	96	-3	-40	.78	
15:29	-179*	133	10	-39		*start* manual cycles at 29.3
15:29.5	-208*	148	16	-38		manual slow cycle
15:30	-206*	156	22	-37		

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flowreturn system flow in gallons per minute. [Note* = The very cold chamber temperatures were a result of local impingement of liquid nitrogen on thermocouples and are probably not representative of actual chamber temperatures.]

The hydraulic fluid temperature was raised to and stabilized at 90°-100°F (temperature taken at the inlet to the coiled tubing). After **PCU** thermal stabilization, the hydraulic fluid temperature was raised to 160°-170°F.

A ±3° sinusoidal yaw damper command at 1.0 Hz was input until the hydraulic fluid cycled through the **PCU** (as indicated by a servo valve temperature rise).

The **PCU** was manually operated to retract (extend the input toward the rod end) with sufficient force to insure that the secondary valve opened. The input to the **PCU** was slowly moved to the null position. Then, a rapid input of higher force was applied to check secondary valve operation. The **PCU** responded normally.

The **PCU** temperature was re-stabilized and the test was repeated to full extend and then retract with an input with sufficient force to insure that the secondary valve opened. The input to the **PCU** was slowly moved to the null position and a sudden input of higher force was applied to the input to check secondary valve operation. The **PCU** responded normally.

Following these tests, the "A" (Tests F and ***G)*** and "B" (Test H) hydraulic system pressures were each shut off and the tests were repeated. The following data was manually recorded during the tests:

Test F- Accident unit-normal thermal shock-A system **OFF**, 8/27/96

Time	T1	T2	s/v	ctrl	flow	comments
16:12	-27	-95	-30	-40	0	
16:14	-27	-92	-31	-40	.09	start y/d
16:16	-30	-89	-31	-40	.09	
16:19	-37	-85	-28	-40		
16:19.5	-25	-84	-25	-40		start manual cycles
16:20	-38	-83	-25	-40		

YD electrical connector not connected. Test stopped

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flow=return system flow in gallons per minute

Test G-Accident unit-normal thermal shock-A system **OFF**- 2nd Test, 8/27/96

Time	T1	T2	s/v	ctrl	flow	comments
16:48	-68	-100	-36	-41	0	
16:49	-48	-100	-34	-41	.33	
16:49.5	-37	-100	-32	-89	.5	start y/d-bypass flow
16:50	-49	-100	-29	-40		start manual cycles
16:51	-54	-100	-25	-40		fast cycles
16:52	-74	-100	-22	-40		

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flow=return system flow in gallons per minute

Test H- Accident unit-normal thermal shock-B system **OFF**, 8/27/96

Time	T1	T2	s/v	ctrl	flow	comments
17:14	-85	-95	-48	-40	.08	
17:15	-62	-98	-42	-40		start bypass flow
17:15.5						start manual cycles
17:16	-41	-98	-31	-39		
17:16.5	-55	-98	-20	-39		fast cycles
17:17	-89	-99	-13	-89		
17:17.5						fast manual cycles
17:18	-87	-102	-4	-39		

Note: T2 thermocouple was laying on test fixture during test.

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flow=return system flow in gallons per minute

Effects of air/nitrogen injected into hydraulic system accident unit- Test M (test data files: accident unit **8/28**)

On August **28,** 1996, at about **13**:**20,** prior to conducting the special case-extreme thermal shock test, a test was conducted to examine the effects of injecting nitrogen into the hydraulic fluid upstream from the PCU. To accomplish this, a valve in the system **A** hydraulic line **was** opened and nitrogen was introduced into the line.

The unit was operated for approximately 10 full extend and retract cycles. The controllability of the actuator was periodically checked **by** stopping the input prior to **full** extend or retract and noting that the actuator rod positioned itself correctly.

With the input held at actuator null position, a ±3° **0.3 Hz** sinusoidal yaw damper input command was supplied to the actuator. The PCU operated normally.

The B system hydraulic pressure was shut off while the 0.3 Hz sinusoidal y/d input command was sustained. The PCU response was normal. The actuator did not respond because the y/d system is powered by the B hydraulic system.

The A system hydraulic pressure was then shut off while the 0.3 Hz sinusoidal y/d input command was sustained. The PCU response was normal.

With the input held at the actuator null position, a ±3° stepped input command signal was input to the yaw damper in each direction. The PCU responded normally. Test data is recorded in accident unit files, 8/28/96, 5-1A_A_B, 5-1B_A_B, 5-1C_A_B, 5-1D_A_B, 5-1E_A_B, 6-1A–A–B, 6-1B_A_B, and strip chart reference sheets 470-473 and 476 (see Phase 1 data attachment).

Effects of silting- accident unit- Test N (test data files-accident unit 8/28>

On August 28, 1996, after the nitrogen injection test, the accident PCU was allowed to sit at its neutral position for approximately 1 hour and 12 minutes with hydraulic pressure applied to the unit and no input to the yaw damper (yaw damper input would move the control valve and potentially clear any silt). At about 14:56, the pin connecting the input actuator to the input point was removed. The input arm did not move. Note: a servo valve spring bias normally allows the unrestrained input arm to move towards the retract direction when the input point is not fixed.

A spring scale was connected to the input arm. Pulling on the arm with a force of 1.5 lbs, the arm did not move. Two more attempts were made at 1.75 lbs each to move the arm, it did not. **A** larger spring scale was attached to the arm and at a force of **4** lbs the input arm moved. Test data is recorded in accident unit files, 8/28/96, 7-1A_A_B, 7-1B_A_B, and 7-1C–A–B and strip chart reference sheets 455 and 45 1 (see Phase 1 data attachment).

Special condition- extreme AT test-accident unit-Test I. J. K. and L (test data files-accident unit 8/28)

At about 1700 on August 28, 1996, testing began for the special condition extreme thermal differential test. This test condition represented an unlikely event in normal airplane operations. The PCU was cold-soaked while depressurized and then hot hydraulic fluid was introduced directly into the PCU. This was done by dumping the cold hydraulic fluid in the hydraulic lines in the test chamber prior to circulating the fluid through the PCU. For this condition to exist, hot hydraulic fluid could not lose any of its heat prior to entering the PCU in the empennage of the aircraft. The test was also made more severe by performing the test on each hydraulic system separately to simulate a single system overheat with the other system pressure failed.

The yaw damper engage solenoid was energized and the input command signal was set at zero. The test chamber temperature was lowered to a target range of no warmer than -27°F and no colder than -45°F and held at a constant temperature in that range until the temperature measured on the servo valve stabilized. The following data was manually recorded during the tests:

Test I-Accident unit-extreme thermal shock-A and B systems ON, 8/28/96

Time	T1	T2	s/v	ctrl	flow	comments
17:07.5	-28	-103	-24	-41	0	
17:10	-14	5	-24	-43	1.1	y/d on
17110.2	-10	99	0	-42		slow cycles
17:11	-7	108	21	-40		
17:17	-10	-106	-57	-42		
17:17.5	-80	140	17	-42		fast cycles

Test stopped-potential test equipment failure
T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flow=return system flow in gallons per minute

The hydraulic fluid temperature was raised to and stabilized at 90°-100°F (temperature taken at the **inlet** to the coiled tubing). After **PCU** thermal stabilization, the hydraulic fluid temperature was raised to **160°-170°F**. The system solenoid was opened to dump the cold hydraulic fluid from the lines in the test chamber and the hot hydraulic fluid was applied directly to the PCU.

A ±3° sinusoidal yaw damper command at 1.0 Hz was input until the hydraulic fluid cycled through the **PCU** (as indicated by a servo valve temperature rise). The **PCU** was operated to retract (extend the input toward the rod end) with sufficient force to insure that the secondary valve opened. The input arm-output response was normal for **4** extend-retract cycles. At about **17:11,** at the end of the 4th cycle, the input arm stuck in the full **PCU** extend direction, the **PCU** output matched the input command. The input arm load was sustained at about **40** lbs for approximately **5** seconds. At that time the input arm load dropped to about 0 lbs and the input arm returned to its neutral position and extend-retract cycling returned to normal with the exception of a step plateau noted in each cycle's input arm position motion. The **PCU** output matched the input response. Reference data can be found on strip charts **437-436.** Operator error at the time of this event precluded any recording of electronic data on the Canyon Engineering data system. The operator had been replaced prior to this test and was unfamiliar with the procedure used to save data files. Therefore the data was collected but not recorded.

At the beginning of the test, the servo valve surface temperature was about **-24°F,** at the time of the binding, the servo valve surface temperature was about **21°F**.

Testing was halted to discuss the groups observations. The reason for the binding was unclear to the group and the potential for pneumatic input actuator failure was discussed. The group decided to repeat the test.

At about **17:54,** the **PCU** temperature was re-stabilized (test J) and the test was repeated. A ±3° sinusoidal yaw damper command at **1.0** Hz was input until the hydraulic fluid cycled through the **PCU** (as indicated by a servo valve temperature rise). The **PCU** was operated to retract (extend the input toward the rod end) with sufficient force to insure that the secondary valve opened. The input arm-output response was normal for 1 extend-retract cycle. For the next **2** cycles, the input arm moved slower than normal on the extend command. At the end of the **4th** cycle, the input arm stuck in the full **PCU** extend direction, the **PCU** output matched the input command. The input arm load was sustained at about 120 lbs for approximately 1 second. At that time the input arm load dropped to about 0 lbs and the input arm returned to its neutral position and extend-retract cycling returned to normal. The **PCU** output matched the input response throughout all tests. Reference data can be found on strip charts 429-428. The operator error problems from the previous test were corrected and the data was recorded in the accident unit file, 8/28/96, 4-1B_A_B. The following data was manually recorded during the tests:

Test J-Accident unit-extreme thermal shock-A and B systems ON, 8/28/96

Time	T1	T2	s/v	ctrl	flow	comments
17:54	-48	-152	-21	-44	0	
17:55	-38	-146	-21	-41		y/d on
17:55.2						fast cycles
17:55.5	-48	98	-2	-41		
17:56	-54	165	43	-40		

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flowreturn system flow in gallons per minute

Following these tests, the "B" (Test K) hydraulic system pressure was shut off and the test was repeated. At about **18:40**, the **PCU** temperature was re-stabilized. No yaw damper command was introduced because the yaw damper system had no pressure with the B hydraulic system depressurized. The following data was recorded manually during the test:.

Test K- Accident unit-extreme thermal shock- B system OFF, 8/28/96

Time	T1	T2	s/v	ctrl	flow	comments
18:40.5	-49	-165	-21	-42	0	
18:41.5	-56	-158	-28	-41	0	
18:42						y/d on
18:42.5	-83	62	-20	-43		fast cycles

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flowreturn system flow in gallons per minute

The **PCU** was operated to retract (extend the input toward the rod end) with sufficient force to insure that the secondary valve opened. The input arm-output response was normal for **3** extend-retract cycles. For the next **3** cycles, the input arm moved slower than normal on the retract command. At the end of each of these retract cycles, the force to move the input arm back to neutral rose to about 124 lbs for approximately 1 second. At that time the input arm load dropped and the input arm returned to its neutral position and extend-retract cycling returned to normal. The **PCU** output matched the input response throughout all tests. Reference data can be found on strip charts **426.** The data was recorded in the accident unit file, 8/28/96, **4-1_AON**, MANUAL, and **4-1A-SYS.**

At about 18:55 on August **28,** 1996, the "A" hydraulic system pressure was shut off and the test was repeated (Test L). The following data was manually recorded during the tests:

Test L- Accident unit-extreme thermal shock- A system OFF, 8/28/96

Time	T1	T2	s/v	ctrl	flow	comments
18:55	-54	-112	-25	-41	0	
18:56	-68	-124	-26	-43	.46	y/d on
18156.7	-37	-123	-11	-43		
18157.5	-31	-119	-5	-42		

T1=chamber temp, T2=A system fluid temp, s/v =servo valve surface temp, ctrl=chamber control temp, flow=return system flow in gallons per minute

A ±3° sinusoidal yaw damper command at 1.0 Hz was input until the hydraulic fluid cycled through the PCU (as indicated by a servo valve temperature rise). The PCU was operated to retract (extend the input toward the rod end) with sufficient force to insure that the secondary valve opened. The input arm-output response was normal. The PCU output matched the input response throughout all tests. Reference data can be found on strip charts 424-421. The data was recorded in the accident unit file, 8/28/96, 4-1_BON.

Additional Phase 1 Testing-Parker-Bertea

On August 29, 1996, the accident and production PCUs were taken to Parker-Bertea, Irvine, California for a post-test ATP of each unit. The ATP results were generally acceptable, there were no obvious functional detrimental effects of the thermal testing on either PCU. The ATP test results can be found in the Phase 1 data attachment to this report.

Phase I-Hydraulic Fluid Tests

All thermal testing was conducted with hydraulic fluid removed from in-service aircraft. The fluid was sampled at the beginning of the tests and at the end of testing on each day of test. The first sample was analyzed by HR Textron (Valencia) under the supervision of a Monsanto fluid specialist. All other tests were conducted by Monsanto (the fluid manufacturer) in St. Louis, Missouri. The following table describes the test results.

HR Textron results

	5-15µ	15-25µ	25-50µ	50-100µ	>100µ
Start of test 8/26	32326	2716	323	34	1
End of test 8/26	47096	4467	416	15	2
End of test 8/27	62902	12362	1401	116	4

Monsanto results (average of split run of same sample)

	5-15µ	15-25µ	25-50µ	50-100µ	>100µ
End of test 8/27	829011	25885	1680	56	1
End of test 8/28	921944	18498	907	16	1

On August 29, 1996, prior to ATP testing at Parker, the hydraulic fluid in the USAir 427 and production PCUs was tested. The following results were recorded:

Parker results

Production PCU

	5-15µ	15-25µ	25-50µ	50-100µ	>100µ
Asystem	**190316**	**8737**	**1247**	**12**	0
Bsystem	**221586**	**3199**	**246**	**1**	**0**

USAir 427 PCU

	5-15µ	15-25µ	25-50µ	50-100µ	>100µ
A system	**482116**	**8897**	**1328**	**70**	**6**
B system	**489510**	**7631**	**733**	**5**	0

Phase **2** Tests

Phase 2 testing was conducted at Boeing in Seattle, Washington, on October 7-12, 1996. **As a** result of testing accomplished during Phase **1,** the systems group elected to perform additional tests at Boeing facilities. During Phase 1 testing, the accident PCU appeared to bind during the extreme AT tests after a prolonged cold-soak period. The production PCU did not bind under similar test conditions. The systems group felt that the Canyon Engineering test fixture and equipment may have had an effect on the results of the test.

During Phase 1 testing, temperature control of the hydraulic fluid supplied to the PCU and the free air temperature near the PCU did not replicate the original test plan, therefore the nominal operating conditions and extreme AT tests were re-done with improved temperature control and temperature/data recording ability. **A** programmable temperature controlled cold chamber contained the PCU, test fixture, and hydraulic tubing. Phase 2 testing incorporated 2 independent hydraulic systems along with additional temperature and pressure probes. **A** needle valve was used to heat the fluid and two solenoid valves were used to direct the hot fluid to a PCU single hydraulic inlet or both hydraulic inlets.

Phase 2-Test facilities and equipment

Phase 2 testing was conducted on a Parker Bertea production PCU holding fixture contained in a temperature controlled chamber at the Boeing Integration and Systems simulation laboratory in Seattle, Washington. The chamber consisted of a foam box with openings cut to allow the test fixture and hydraulic lines to pass into the chamber. To gain access to the PCU, the front foam panel was removed from the fixture. **A** viewing window was built into the top of the test chamber.

The chamber was cooled by introducing cold air from a high capacity cooling unit. Temperatures in the chamber, on the PCU, and in the hydraulic fluid were recorded on a computer data collection system.

The hydraulic tube included the following: coiled tubing to represent the airplane **A** and B system hydraulic tubing between the aft bulkhead and the elevator PCU; and the elevator PCU to the rudder PCU. This tubing was contained in the cold chamber. The section of tubing from the hydraulic supply pump to the cold chamber was outside the chamber.

A hydraulic operated load cylinder was attached to the PCU input arm for manual inputs. The cylinder was actuated by operating a control valves that allowed pressure to be applied to the cylinder. Prior to beginning testing, several runs were made to test the system. Because of repeatability concerns, the systems group decided to remove the hydraulic cylinder and actuate the input arm by means of a steel tube connected to the arm that could be hand-operated outside the chamber.

Temperature, position, and force data were recorded by a Boeing-operated computer data recording system. Data recorded during Phase 2 testing can be found in the Phase 2 data attachment to this report. The Boeing data system successfilly recorded all tests.

Phase 2 Testing

Phase 2 testing was conducted using a matrix test plan. **A** matrix was developed based on Phase **1** test results. The following tests were conducted on the production PCU:

1. Condition A-Baseline, room temperature
2. Condition B-Cold soak with ambient hydraulic fluid temperatures
3. Condition C-The PCU was cold soaked at -27°F while only A system was depressurized. Both **A** and B hydraulic fluid was heated to 170" F at the inlet to the cold chamber, then the rudder PCU was cycled by inputting a yaw damper sinusoid command and manually cycling the PCU input rod.
4. Condition D-The PCU was cold soaked at -27°F and only **A** system hydraulic fluid was heated to 170° F at the inlet to the cold chamber.
5. Condition E-The PCU was cold soaked at -27°F while only **A** system was depressurized. Both **A** and B hydraulic fluid was heated to 170" F and introduced directly to the rudder PCU, bypassing the coiled tubing.
6. Condition F-The PCU was cold soaked at -27°F while only **A** system was depressurized. Only A system hydraulic fluid was heated to 170" F and introduced directly to the rudder PCU, bypassing the coiled tubing.
7. Condition G-The PCU was cold soaked at **-40°F** while depressurized. Only **A** hydraulic fluid was heated to 170°F and introduced directly to the PCU bypassing the coiled tubing. This testing was intended to imitate the tests conducted during Phase 1 at Canyon engineering.
8. Condition H-Same as G except chamber cooled to -70°F

Test Matrix-Production Unit

***Definition for all test conditions**: **primary = slow input (only primary** spool **flow passages are opened),** both = **fast input (both primary and secondary flow passages are opened).**

Condition A-Baseline (A= ambient temperature)

	Temp	A	B	y/d inuut	input*	hvd. pressure
1.	A	A	A	± 3°@1Hz	none	all
2.	A	A	A	± 3°@1Hz	primary*	all
3.	A	A	A	± 3°@1Hz	both*	all
4.	A	A	A	+3° step	none	all
5.	A	A	A	-3° step	none	all

Condition B-Cold soak with ambient hydraulic fluid temperatures

	Temp	A	B	yldinuut	input	hvd. uressure
1.	-27°	A	A	± 3°@1Hz	none	all
2.	-27"	A	A	± 3°@1Hz	primary	all
3.	-27°	A	A	± 3°@1Hz	both	all
4.	-27°	A	A	+3° step	none	all
5.	-27°	A	A	-3° step	none	all

Condition C- Cold soak with dual hydraulic fluid overheat temperatures

	Temp	A	B	y/d input	input	hvd. pressure
1.	-27"	170"	170°	± 3°@1Hz	none	all
2.	-27°	170"	170°	± 3°@1Hz	primary	all
3.	-27°	170"	170°	± 3°@1Hz	both	all
4.	-27"	170°	170°	+3° step	none	all
5.	-27"	170'	170°	-3° step	none	all

Condition D: Cold soak with A system only hydraulic fluid overheat temperatures

	Temp	A	B	y/d input	input	hvd. pressure
1.	-27"	170"	60"	± 3° @ 3Hz	none	all
2.	-27'	170"	60"	± 3° @ 1Hz	none	all
3.	-27°	170'	60°	± 3° @ 1Hz	primary	all
4.	-27'	170°	60'	± 3° @ 1Hz	both	all
5.	-27"	170°	60°	± 3° step	none	all
6,	-27°	170'	60°	none	man input	none

Condition E: Repeat condition C with hydraulic fluid introduced directly at PCU

	Temp	A	B	yld input	input	hyd. pressure
1.	-27"	170"	170"	± 3° @ 1 Hz	none	all
2.	-27'	170'	170°	± 3° @ 1 Hz .	primary	all
3.	-27°	170°	170"	± 3° @ 1 Hz	both	all
4.	-27"	170"	170"	± 3° @ 1 Hz	none	all
5.	-27'	170'	170°	stopped	man input	all
6.	-27"	170"	170"	disengaged	both	all
7.	-27"	170°	170'	disengaged	both	none

Condition F: Repeat condition D with hydraulic fluid introduced directly at PCU

	Temp	A	B	y/d input	input	hvd. pressure
1.	-27°	170"	60"	± 3° @ 1 Hz	none	all
2.	-27"	170"	60"	± 3° @ 1 Hz	none	all
3.	-27"	170"	60°	± 3° @ 1 Hz	primary	all
4.	-27°	170"	60°	± 3° @ 1 Hz	both	all
5.	-27"	170"	60"	± 3° @ 1 Hz	none	all
6.	-27"	170°	60"	stopped	man input	all
7.	-27'	170°	60"	none	both	all
8.	-27°	170°	60'	none	both	none

Condition G: Simulation of Phase 1 special condition test. PCU cooled to -40°F, A system (only) overheated, fluid directly applied to PCU

	Temp	A	B	y/d input	input	hvd. pressure
1.	-40°	--	--	off	none	off
2.	-40°	--	--	off	5man inputs	off
3.	-40°	170 o	--	off	5-10man inputs both	A

Condition H: Same as G except chamber cooled to -70°F

	Temp	A	B	yld inuut	input	hvd. uressure
1.	-70°	--	--	off	none	off
2.	-70°	--	--	off	5man inputs	off
3.	-70°	170°	--	off	5-10 man inputs both	A

Test Matrix-Accident Unit

The following tests were conducted on the accident PCU:

1. Condition A-Baseline, room temperature
2. Condition B-Cold soak with ambient hydraulic fluid temperatures
3. Condition C-The PCU was cold soaked at -27°F while only A system was depressurized. Both A and B hydraulic fluid was heated to 170" F at the inlet to the cold chamber, then the rudder PCU was cycled by inputting a yaw damper sinusoid command and manually cycling the PCU input rod.
4. Condition D-The PCU was cold soaked at -27°F and only A system hydraulic fluid was heated to 170° F at the inlet to the cold chamber.
5. Condition E-The PCU was cold soaked at -27°F while only A system was depressurized. Both A and B hydraulic fluid was heated to 170" F and introduced directly to the rudder PCU, bypassing the coiled tubing.
6. Condition F-The PCU was cold soaked at -27°F while only A system was depressurized. Only A system hydraulic fluid was heated to 170" F and introduced directly to the rudder PCU, bypassing the coiled tubing.
7. Condition G-The PCU was cold soaked at -40°F while depressurized. Only **A** hydraulic fluid was heated to 170°F and introduced directly to the PCU bypassing the coiled tubing. This testing was intended to imitate the tests conducted during Phase 1 at Canyon engineering.
8. Condition H-Same as G except chamber cooled to -70°F
9. Condition I-Repeat condition G
10. Condition J-Repeat condition G with chamber at -20°F
11. Condition K-Repeat condition F

Condition A: Baseline-ambient temperatures

	Temp	A	B	y/d input	input*	hyd pressure
1.	A	A	A	±3°@1Hz	none	all
2.	A	A	A	±3°@1Hz	primary*	all
3.	A	A	A	±3°@1Hz	both*	all
4.	A	A	A	+3° step	none	all
5.	A	A	A	-3° step	none	all
6.	A	A	A	none	both	all
7.	A	A	A	disengaged	both	all
8.	A	A	A	disengaged	both	none

*Definition for all test conditions: primary = slow input (only primary spool flow passages are opened), both = fast input (both primary and secondary flow passages are opened).

Condition B: Cold soak with ambient hydraulic fluid temperatures

	Temp	A	B	yldinput	input	hyd pressure
1.	-27°	A	A	± 3°@1Hz	none	all
2.	-27"	A	A	± 3°@1Hz	primary	all
3.	-27°	A	A	± 3°@1Hz	both	all
4.	-27°	A	A	+ 3° step	none	all
5.	-27°	A	A	-3° step	none	all
6.	-27"	A	A	none	both	all
7.	-27"	A	A	disengaged	both	all
8.	-27'	A	A	disengaged	both	none

Condition C: Cold soak with dual hydraulic fluid overheat temperatures

	Temp	A	B	y/d input	input	hyd. pressure
1.	-27"	170"	170"	± 3°@1Hz	none	all
2.	-27°	170"	170°	± 3°@1Hz	primary	all
3.	-27"	170°	170"	± 3°@1Hz	both	all
4.	-27"	170"	170°	+ 3° step	none	all
5.	-27"	170°	170°	-3° step	none	all
6.	-27"	170°	170"	none	both	all
7.	-27"	170°	170"	disengaged	both	all
8.	-27"	170"	170"	dlsengaged	both	none

Condition D: Cold soak with A system only hydraulic fluid overheat temperatures

	Temp	A	B	yldinput	input	hyd. pressure
1.	-27°	170"	60°	± 3° @ 3Hz	none	all
2.	-27"	170°	60°	± 3° @ 1Hz	none	all
3.	-27°	170"	60"	± 3° @ 1Hz	primary	all
4.	-27"	170°	60°	± 3° @ 1Hz	both	all
5.	-27'	170°	60"	± 3° step	none	all
6.	-27"	170"	60"	none	both	all
7.	-27"	170"	60°	disengaged	both	all
8.	-27"	170°	60"	disengaged	both	none

Condition E: Cold soak with hot hydraulic fluid introduced at the PCU, dual hydraulic system overheat

	Temp	A	B	yldinput	input	hvd. pressure
1.	-27°	170	170	± 3° @ 1 Hz	none	all
2.	-27°	170	170	± 3° @ 1 Hz	primary	all
3.	-27"	170	170	± 3° @ 1 Hz	both	all
4.	-27"	170	170	± 3° @ 1 Hz	none	all
5.	-27"	170	170	none	both	all
6.	-27°	170	170	disengaged	both	all
7.	-27°	170	170	disengaged	both	none

Condition F: Special condition-extreme ambient hot fluid introduced at the PCU with only A hydraulic system overheated

	Temp	A	B	y/d input	input	hvd. pressure
1.	-27"	170"	60°	± 3° @ 1 Hz	none	all
2.	-27"	170"	60°	± 3° @ 1 Hz	primary	all
3.	-27°	170°	60"	± 3° @ 1 Hz	both	all
4.	-27"	170"	60°	± 3° @ 1 Hz	none	all
5.	-27"	170"	60"	none	manual input	all
6.	-27"	170"	60°	disengaged	both	all
7.	-27"	170°	60°	disengaged	both	none

Condition G: Simulation of Phase 1 special condition test-PCU cooled to -40°F, A system (only) overheated, fluid directly applied to PCU. Both sides of PCU depressurized during cold soak

	Temp	A	B	y/d input	input	hvd. pressure
1.	-40"	--	--	off	none	Off
2.	-40"	--	--	off	5 maninputs	off
3.	-40°	170"	--	off	5-10man inputs both	A

Observation notes on condition G tests- PCU operator felt reduced rudder response rate (1 time), Operator didn't note bind or reverse; however, data shows binding and momentary valve jam, After hot fluid hit actuator, and after effects of "a" above, subsequent cycles felt normal.

Condition H: Same as Condition G except colder chamber temp

	Temp	A	B	y/d input	input	hvd. vressure
1.	-70°	--	--	off	none	Off
2.	-70°	--	--	off	5 man inputs	off
3.	-70"	170	--	off	5-10man inputs both	A

Observations of condition H-manual input (in both directions) did not cause actuator response (after 2 complete cycles). Operator felt kick-back during rudder right command. First review of data showed no apparent correlation.

Condition I: Redo Condition G

	Temp	A	B	y/d input	input	hyd. pressure
1.	-40°	--	--	off	none	Off
2.	-40"	--	--	off	5 man	Off
3.	-40°	170	--	off	5-10 ▾ ▾ both	A

Observations of condition I-Operator felt no response (one-time) at full left command and pushing right there was no actuator response to input. Actuator OK after 1 event.

Condition J: Same as Condition G except warmer chamber temp

	Temp	A	B	y/d input	input	hvd. pressure
1.	-20°	--	--	off	none	Off
2.	-20"	--	--	off	5 man	Off
3.	-20"	170	--	off	5-10 man both	A

Observations of condition J-After first 2 full cycles, operator felt slightly reduced rate in right rudder direction.

Condition K: Re-do Condition F

	Temp	A	B	y/d input	input	hvd. pressure
1.	-27°	170	60	± 3° @ 1 Hz	none	all
2.	-27°	170	60	± 3° @ 1 Hz	primary	all
3.	-27"	170	60	± 3° @ 1 Hz	both	all
4.	-27°	170	60	± 3° @ step	none	all
5.	-27"	170	60	none	manual input	all
6.	-27"	170	60	dlsengaged	both	all
7.	-27°	170	60	disengaged	both	none

Observations of condition K- Normal operation-nothing abnormal felt during manual inputs.

An initial review of the test data indicated a valve jam (high flow without PCU motion) during some of the test conditions. Further post-test data evaluation indicated that a secondary valve jam and subsequent overtravel of the primary spool allowed the PCU to momentarily reverse direction.

Phase 2-Thermal Shock Test Results-Summary of selected tests

Test condition	Test Unit	Maximum AT (°F)	Valve seizure status
C	427	100	no
D	427	95	no
E	427	130	no
F	427	135	no
G	427	180	seized
C	Production	90	no
D	Production	110	no
E	Production	120	no
F	Production	120	no
G	Production	170	no

Phase 2-Hvdraulic fluid particulate tests

The fluid used for Phase 1 testing was removed from the Canyon Engineering test system and shipped to Boeing for use in Phase 2 testing. The fluid was sampled for particulate contamination at several times during the testing. The fluid was tested at Boeing and at Monsanto the following details the findings of the fluid testing.

Boeing laboratory results

Sample date, ID, time	5-15µ	15-25µ	25-50µ	50-100µ	>100µ
10/7, sys A, post 1B	211478	3660	0416	25	2
10/7, sys B, post 1B	191769	3653	575	40	4
10/10, sys A, 14:00	357653	6778	480	17	0
10/10, sys B, 14:00	266124	2195	85	0	0
10/10, sys A, 18:00	245242	6445	797	24	2
10/10, sys B, 18:00	116873	1429	97	10	2
10/11, sys A, 10:10	343473	6555	494	17	1
10/11, sys B, 10:10	286415	3412	393	50	7
10/11, sys A, 11:30	345994	6290	376	12	2
10/11, sys B, 11:30	271080	2794	174	5	2
10/11, sys A, 18:15	312412	2021	64	3	0
10/11, sys B, 18:15	208173	814	23	2	0
10/12, sys A, 10:40	298595	2030	131	11	2
10/12, sys A, 13:05	280516	1989	184	19	3
10/12, sys B, 13:05	191912	941	23	2	0

Monsanto laboratory results

Sample date, ID, time		15-25µ	25-50µ	50-100µ	>100µ
10/7, sys A, post 1B	50028	2540	404	44	8 .
10/7, sys B, post 1B	66580	4040	860	128	48
10/8, sys A, #7	62556	2190	292	14	4
10/8, sys B, #8	47316	1370	162	2	0
10/9, sys A, #1	121736	4498	366	34	6
10/9, sys B, #2	64618	1970	168	2	0
10/10, sys A, #16, 14:00	93856	3268	416	64	16
10/10, sys B, #17, 14:00	73192	3800	756	68	8
10/10, sys A, #6,18:00	106806	4086	348	6	4
10/10, sys B. #9, 18:00	37108	928	88	4	0
10/11, sys A, #5, 10:10	77604	4056	358	18	0
10/11, sys B, #10, 10:10	60244	2646	462	46	6
10/11, sys A, #3, 11:30	98204	4356	398	42	8
10/11, sys B, #4, 11:30	48096	1536	146	6	4
10/11, sys A, #14, 18:15	136352	3456	308	28	0
10/11, sys B, #13, 18:15	91412	2236	164	40	4
10/12, sys A, #11	103680	3248	342	3	0

Effects of cold temperatures on hydraulic fluid

As a part of Phase **2** testing, the systems group examined the effects of cold temperatures on hydraulic fluid. Two samples of hydraulic fluid were examined; one was removed from the thermal test system (used fluid) and the other was new Skydrol fluid. The fluid was cooled in an environmental chamber. The fluid was visually examined at **-80°F** and -110°F by attempting to pour the fluid from its container. In each case the fluid was thick but poured. **A** light coating of ice crystals were visible on the top of the fluid.

The new fluid was removed from the test chamber and immersed in a bath of liquid nitrogen and cooled to a temperature of **-154°F**. At that temperature, the fluid had the consistency of a gelatinous blob.

Phase 3 Testing

Phase **3** was testing was conducted at Parker Bertea facilities, Irvine, CA on November 20 and **21, 1996.** Three rudder PCUs were examined. The units examined were PCU s/n 1596A (removed &om accident airplane), PCU s/n 2203 (new production unit), PCU s/n 0085A (removed from Eastwind airplane). The testing consisted of first performing ATP's on each unit; then, each unit was tested to determine the distance off neutral that the secondary spool had to be placed to allow rudder actuator reversal. Following the completion of this testing, the servo valve was **removed** from each PCU, disassembled, and examined. Data recorded is included as "Phase 3 attachment" to this report. The servo valve surfaces of the accident PCU were also video **recorded.**

The testing indicated that with an input force applied to the main rudder PCU, it would stall **or** reverse with the secondary slide jammed at the following positions (expressed as % of full secondary slide travel from neutral).

Production	USAir 427	Eastwind
38% extend	12% extend	17% extend
54% retract	41% retract	30% retract

The initial testing was done on the production unit to verify test methodology and procedures. The following notes were taken during that setup:

Production PCU (s/n 2203)
Test 1-Secondaryjammed at neutral, no anomalous operation, Inner hex to outer hex .292 (difficult to establish jam at neutral)
Test 1A-Actuator extended, PCU depressurized, applied extend command, data recorded
Test 1B-Actuator extended, PCU pressurized, applied extend command, data recorded
Test 1C-Actuator retracted, PCU depressurized, applied retract command, data recorded
Test 1D-Actuator retracted, PCU pressurized, applied retract command, data recorded
Test 2-Secondary jammed at 100% extend-inner hex to outer hex .340. Actuator extended, PCU pressurized, applied retract command, data recorded, actuator reversed 1.3 gpm crossflow decreased to .12 gpm. Note: since piston bottomed entire test, reversal was not evident by piston motion, just return flow.

Tabular data is presented in the form:

Measurement: Reading (in inches) of depth gauge from the inner hex on the spool set to the outer hex on the jamming tool. This establishes neutral position and deviation from neutral position.

Percent secondary jam: Measurement of (neutral offset-neutral position)/0.045 (secondary travel) x 100, and direction of secondary travel. ie. (0.783-0.752)/.045=69% retract

Results: observations at that condition.

Measurement	Secondary jam	Result
.3195	61% extend	reversed
.3175	57% extend	reversed
.3050	29% extend	borderline (reversed 1 of 20 X)

Method of establishing jam at neutral and measurement were improved during subsequent tests.

Test 2A (repeat of test 2 with improved measuring)

Measurement	Secondary jam	Result
.783	neutral	
.752	69% extend	reversed (y/d ± 3" hardover-no reversal)
.7635	43% extend	reversed
.766	38% extend	borderline no reverse, PCU stalled
.770	29% extend	no reverse

Test 3

Measurement	Secondary jam	Result
.7645	neutral	
.8115	100+% retract	reversed
,795	67% retract	reversed
Rigged neutral and cycled y/d with square wave input, piston output 3° retract, 2° extend-no reversals occurred		
.789	54% retract	borderline (sometimes reverses)
.787	50% retract	no reverse

USAir 427 PCU (s/n 1596A)

Test procedure:

1) jam actuator at neutral with jamming tool
2) with actuator extended-apply extend command
3) adjust jamming tool, repeat step 2

Test 5

Measurement	Secondary jam	Result
.780	neutral	
,733	100% extend	reversed with no piston motion, crossflow leakage 1.39-.07 gpm
.n/a	69% extend	reversed
applied ±3° square wave with no anomalies-slow in one direction fast in other, no reversal occurred		
.760	44% extend	reversed
.764	36% extend	reversed
,7685	26% extend	reversed
.7745	12.2%extend	stalled, but no reverse

Test 6/6A

Measurement	Secondary jam	Result
.824	98% retract	Test 6, redo test as 6A
.828	100% retract	reversed
applied ±3° square wave with no anomalies noted, no reversal		
.8085	63.3% retract	reversed
.7985	41% retract	didn't reverse-almost stalled

Eastwind PCU (s/n 0085A)

Test procedure

1) jam actuator at neutral with jamming tool
2) with actuator extended-apply extend command
3) adjust jamming tool, repeat step 2 ·

Measurement	Secondary jam	Result
.785	neutral	
.754	69% extend	reversed (y/d ±3° hardover-no reversal)
.772	29% extend	reversed, borderline
.7775	17% extend	reversed once- stalled twice
.770	29% extend	no reverse
.815	67% retract	reversed
.7985	30% retract	no reverse

Phase 3-servo valve dimensional examinations

On November 11, 1996, during Phase 3 testing, the **USAir** 427, Eastwind, and production main rudder PCU servo valve spools and housings were each measured in three different places to determine the minimum diametrical clearance available.

Parker tools (with the noted serial numbers) were used for all measurements: .750 probe- s/n L920, set ring s/n L1974 (except Eastwind was s/n L251), .250 probe- s/n L920, set ring s/n L1963, Microkator s/n L1057.

USAir 427, servo s/n 2956
*= max/min at given position

	input lever end	center	spring end
servo valve body ID	.749820*	.749820*	.749850*
	.749850*	.749850*	.749880*
secondary slide OD	.749690	.749680	.749680
minimum clearance	**.000130**	**.000140**	**.000170**
secondary slide ID	.249760*	.249740*	.249740*
	.249770*	.249750*	.249750*
primary slide OD	.249590	.249600	.249590
minimum clearance	**.000170**	**.000140**	**.000150**

Production unit, servo s/n 4999
* = **max/min at given position**

	input lever end	center	spring end
servo valve body ID	.750125*	.750135*	.750120*
	.750130*	.750140*	.750130*
secondary slide OD	.749930	.749920	.749930*/.749940*
minimum clearance	**.000195**	**.000215**	**.000190**
secondary slide ID	.250450*	.250460*	.250460*
	.250460*	.250465*	.250470*
primary slide OD	.250260	,250260	.250250
minimum clearance	**.000190**	**.000200**	**.000210**

Eastwind unit, servo s/n 2567
*= **max/min at given position**

	input lever end	center	spring end
Servo valve body ID	.760790*	.760780	.760790*
	.760800*	.760800*	
secondary slide OD	.760600	.760610	.760610
minimum clearance	**.000190**	**.000170**	**.000180**
secondary slide ID	.250880*	.250870	,250870
	.250890*		
primary slide OD	.250670*	.250680*	.250670*
	.250680*	.250690*	.250680*
minimum clearance	**.000200**	**.000180**	**.000190**

Changes to rudder PCU servo control valve drawing. 68010

The group reviewed and discussed changes to the Parker servo valve drawing number 68010. The drawing was originally done on June 11, 1965. On March 14, 1989, an engineering order (EO) was released to add 2 flag notes to the drawing. Notes 9 and 10 were added that stated:

9) Lap OD of 83319 secondary slide to achieve a clearance of .000150/.000200 with the IDs of the secondary inserts prior to testing per note 6.
10) Lap OD of 83349 primary slide to achieve a clearance of .000150/.000200 with the IDs of the primary inserts prior to testing per note 6.

The reason for the drawing change was given on the EO as:
To upgrade drawing to BDS2305 and standardize lap assy manufacturing procedures and call outs. To reduce friction prior to first test with no changes to ATP results or item performance and lap assy interchangability.

The effectivity of the change was listed as "***next lot***". The disposition of obsolete parts was listed as "***n/a***". The part numbers were not changed for subsequent parts.

[redacted] JD 4/16/97

Gregory Phillips
Systems Group Chairman
National Transportation Safety Board

Phase 1 Attachments

- Data file information-3 pages
- Canyon Engineering data plots-34 pages
- NTSB thermal test schematic-2 pages
- Test Bench 4 hydraulic schematic and test fixture drawing-2 pages
- Boeing memo B-B600-15676-ASI, June 6, 1996-2 pages
- Boeing fax of PCU cold *soak* test plans-6 pages
- Boeing memo B-B600-15696-ASI, June 25, 1996-2 pages
- Strip chart data from Phase 1 testing-~~22~~ 47 pages
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- Main rudder PCU ATP test data sheets, 8/20/96 and 8/29/96-52 pages
- Items replaced on accident actuator prior to test-6 pages
- Phase 1 Photos

Phase 2 Attachments

- Boeing fax of PCU cold **soak** test plans-8 pages
- October **4**, 1996 thermal test flight data-7 pages
- Boeing memo B-B600-15899-ASI, December 13, 1996-12 pages
- Phase **2** test setup schematics-6 pages
- Phase *2* strip chart data-3 pages
- Phase **2** thermal test data plots-115 pages
- Phase **2** thermal test **strip** chart data-46 pages
- Phase 2 Photos

Phase **3** Attachments

- Phase **3** test data plots-6 pages
- Main rudder PCU ATP data sheets, 11/20/96 and 11/21/96-43 pages