
IV. Rudder System Scenarios

Following a brief overview of the 737 rudder system, this section looks at hypothetical failures that might conceivably induce a 737 rudder to deflect to blowdown. Factual data is then reviewed for evidence that any such event might have occurred, and the section concludes with an examination of the overall service history of the 737.

A. Rudder System Overview

Pilot control of the rudder is provided through the captain's and F/O's rudder pedals. The pedal motion is transmitted by a single cable system to the aft quadrant, and then through linkages to the main and standby PCUs, as shown in Figures 7 and 8. Except for the yaw damper, as discussed below, the rudder surface follows the pedal command. The pedals provide the flight crew with an indication of rudder surface positioning.

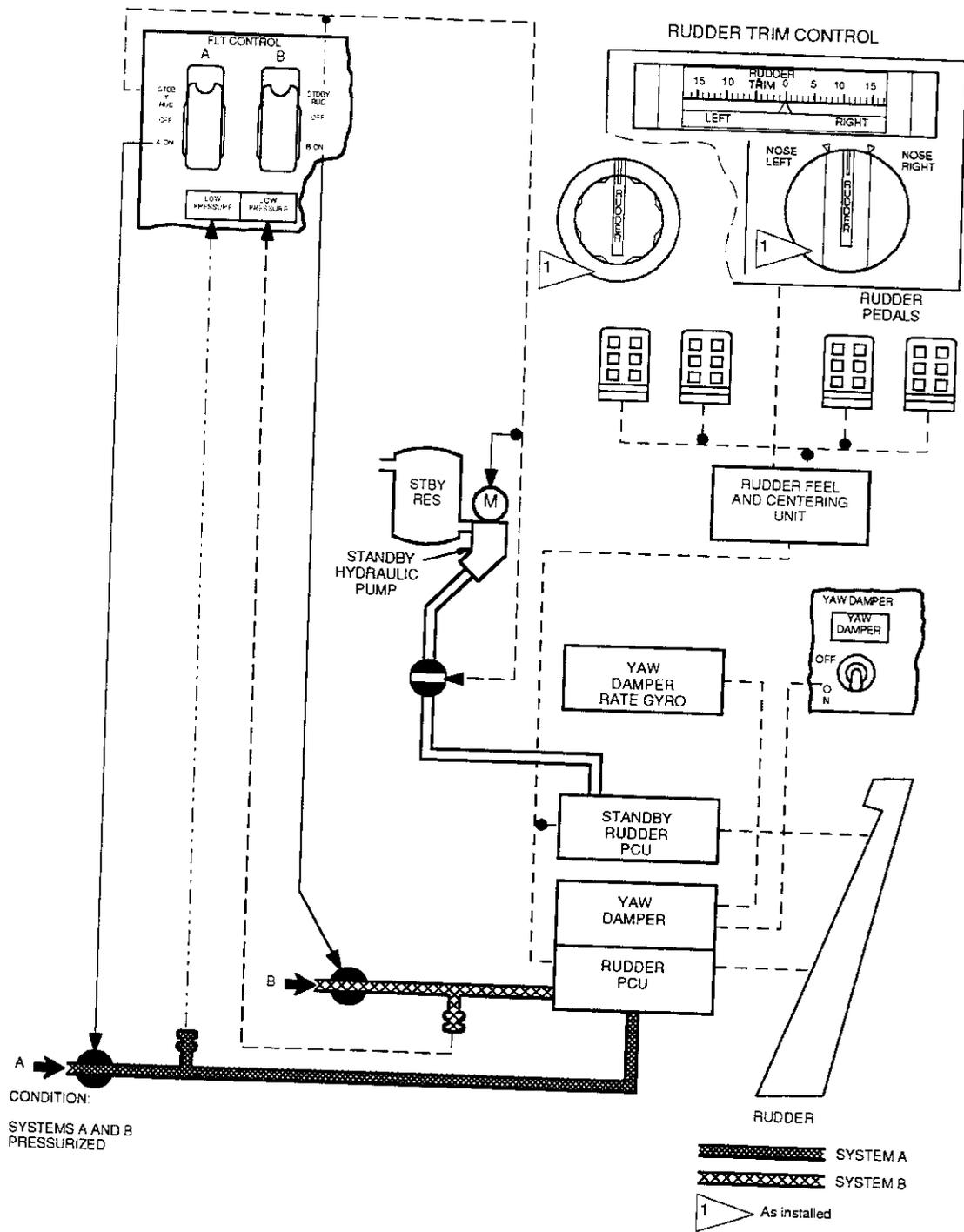


Figure 7: Rudder Control System Schematic

Figure 7 also shows the yaw damper system, which is designed to improve airplane ride quality by minimizing small-amplitude yaw oscillations. The yaw damper electronic module, or coupler, provides an electrical signal to the

yaw damper actuator, which is part of the main rudder PCU. The yaw damper and pilot inputs are summed within the PCU such that yaw damper rudder inputs do not move the pedals.

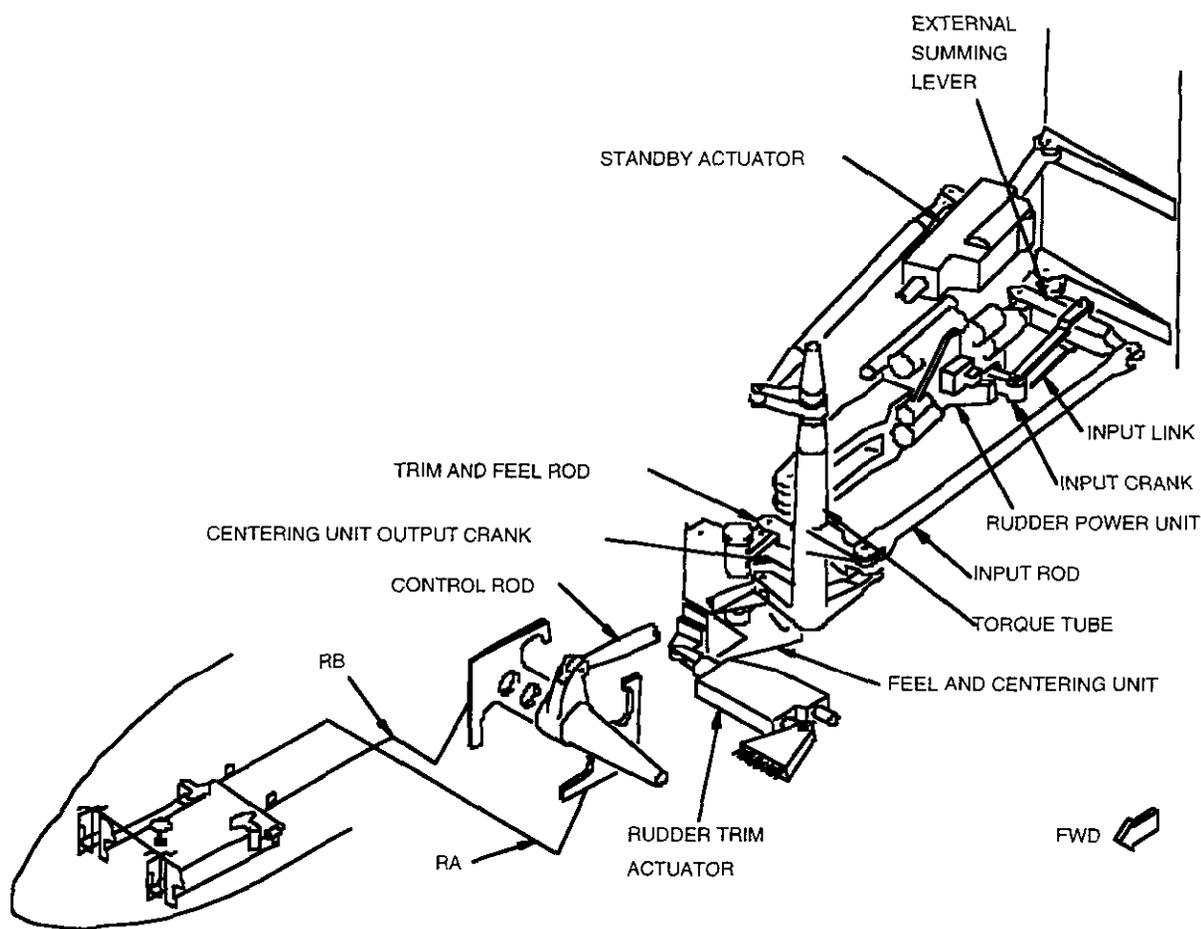


Figure 8: Main and Standby PCU Installation

The rudder feel and centering mechanism attaches to the aft quadrant, and applies a force to the quadrant—and thus to the pedals—that is roughly proportional to the rudder deflection. The pedal force required for full rudder deflection is approximately 70 pounds. Rudder trim allows the pilots to maintain a rudder deflection without having to hold in a pedal deflection. This trim is provided by an electric trim actuator that rotates the feel and centering unit, thereby changing the centered or neutral rudder position.

Aft quadrant rotation is transmitted to the main PCU through a dual-load-path linkage, and to the standby PCU by a single-load-path linkage. During normal operation, the main PCU is powered by the A and B hydraulic systems, and the standby PCU is depressurized. The standby PCU is pressurized by the standby hydraulic system after failure of one or both of the hydraulic systems (A and B). The standby PCU contains a pressure-operated bypass valve that allows it to be backdriven by the main PCU during normal operation.

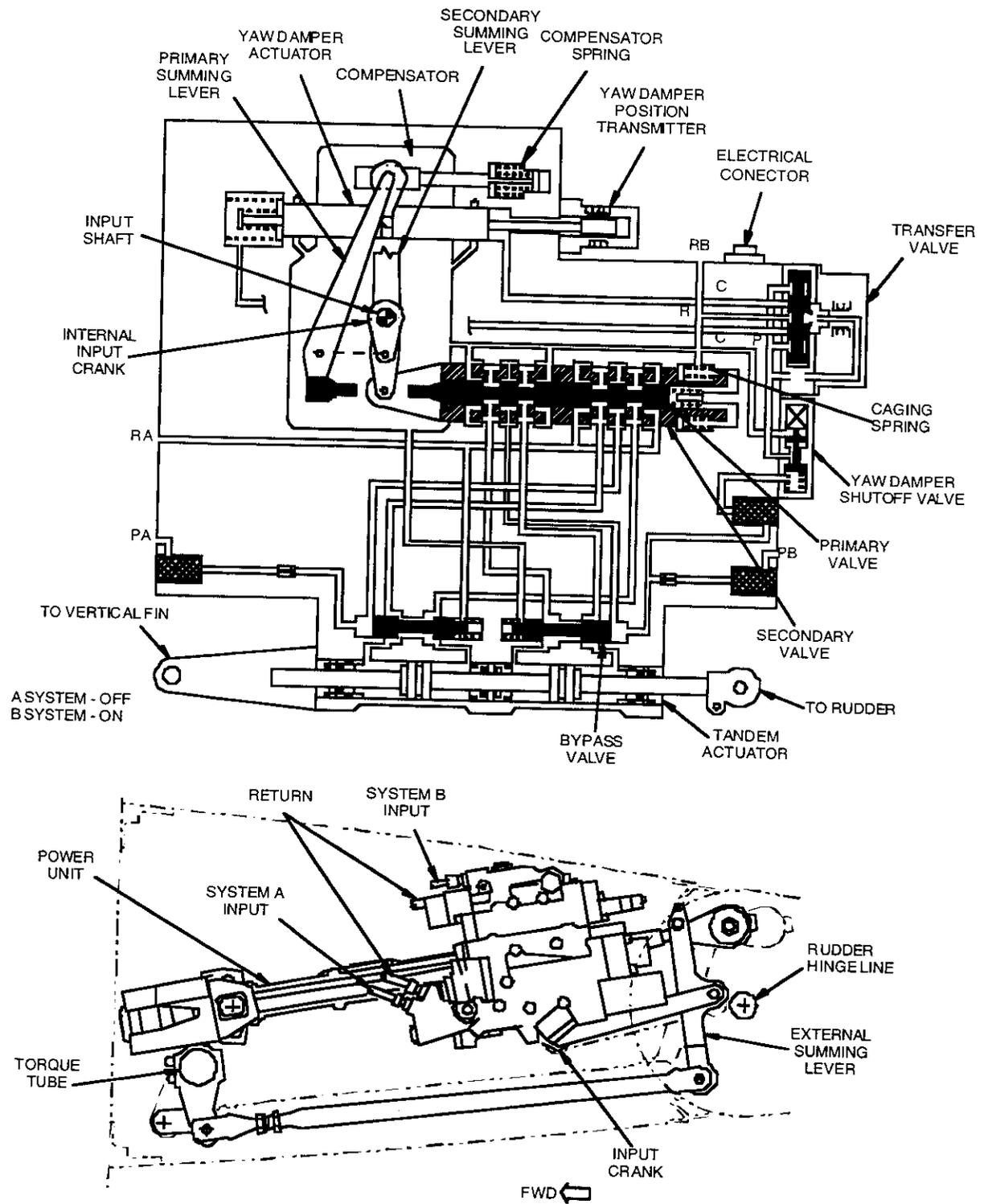


Figure 9: Main PCU Functional Schematic

Figure 9 provides a schematic view of the main PCU. The main control valve is connected through a dual-load-path linkage to both the yaw damper piston and to the pilot input linkage. The linkage sums inputs by the pilots and yaw damper to the control valve. The yaw damper piston is controlled by an electro-hydraulic servo valve that receives an electrical input from the yaw damper coupler. The yaw damper piston in the Flight 427 PCU (as in all 737-300 airplanes) is limited by a mechanical stop that only allows it to command three degrees of rudder.

When the PCU control valve is displaced by either a pilot or yaw damper input, it directs hydraulic flow to one side or the other of the actuator. The actuator then continues to move until the actuator piston rod moves the feedback linkage sufficiently to return the valve to its centered or neutral position.

The main PCU control valve is a dual concentric valve; that is, it contains two concentric slides with each of these slides controlling two hydraulic systems. The inner valve slide is the primary slide and the outer slide is the secondary slide. During normal operation, the primary slide is displaced first, and the secondary slide is displaced only when the primary slide does not provide enough hydraulic flow to keep up with the input command.

The two slides are designed to provide approximately equal flow. Thus, the primary slide can provide a rudder rate of approximately 33 degrees per second (no air load), while the primary and secondary slides acting together can provide a rate of approximately 66 degrees per second. The valve is designed in this way so that if one of the slides jams, the other slide can negate the effect of the jam and, in the worst of cases, allow the air load to force the rudder back to approximately neutral.

The main PCU also has a hydraulic bypass valve for each hydraulic system. Each bypass valve allows hydraulic flow between the two sides of the associated piston. When one side of the PCU is not pressurized, its bypass valve is open and allows essentially unrestricted flow. This allows the PCU to maintain full rate capability after a failure of one hydraulic system. When the PCU is pressurized, the bypass valve is closed and the only flow is

through a fixed orifice included in the valve to assure that the actuator is stable (i.e., that it does not oscillate). This orifice flow does not significantly affect normal operation, but it can have a very significant effect on actuator performance after a valve jam.

B. Rudder Failure Modes

Section II provided the results of the Flight 427 kinematic analyses, which showed that the rudder deflected to its full aerodynamic limit (blowdown). In theory, either a mechanical failure or a pedal input by the flight crew could have caused this deflection to blowdown. Section III outlined the failure modes that can cause the 737 rudder to deflect all the way to blowdown.

There is no known occasion in the service history of the 737 of an in-flight failure that resulted in an uncommanded rudder deflection to its blowdown limit. There are, however, hypothetical malfunctions that can produce this effect. This section describes the various hypothetical failure modes, concentrating on those that can cause a rudder deflection to blowdown matching that indicated by the kinematic analyses. Examination of evidence for or against each of these failure modes will be presented in Section IV-C.

Failure Modes That Do Not Fit the Failure Scenario

There are some theoretical failures that can result in an anomalous rudder deflection or in a rudder offset, but not cause the rudder to deflect all the way to blowdown. For this reason, the following failure modes—which were investigated by the NTSB—were rejected as a possible cause of the Flight 427 rudder deflection: cable failure or jam, cable deflection due to a floor failure, standby PCU input crank binding, and a trim system runaway. The results of these investigations have been documented by the NTSB Systems Group⁹ and will not be further addressed in this submission.

⁹ *Systems Group Chairman's Factual Report of Investigation*, Dec. 21, 1994; Jan. 12, 1995; July 17, 1996; Oct. 24, 1996.

Failure Modes That Can Result in Full Rudder Deflection

This subsection examines the following three hypothetical failure modes, which can result in a full rudder deflection like that in the Flight 427 accident:

- A dual slide jam of the rudder PCU.
- A PCU secondary slide jam with primary slide overtravel.
- A rudder PCU linkage jam.

These three failure modes, including their cockpit effects, are discussed below. The evidence for or against these failure modes will be discussed in Section IV-C.

Dual Slide Jam

A jam of both the primary and secondary slides will result in full rudder deflection if one or both slides are jammed significantly off neutral. If the slides are near neutral, the effect of the PCU bypass valve will greatly reduce the PCU output force capability, and thus the blowdown value will be less than that required to match the kinematic analysis.

Secondary Slide Jam With Primary Slide Overtravel

Normally, if the secondary slide were to jam to the control valve housing, the PCU feedback linkage would move the primary slide in the opposite direction, negating the effect of the secondary slide jam. In this event, a secondary slide jammed fully open would leave the rudder surface very near a faired position (i.e., not deflected).

A new failure effect of a secondary slide jam was discovered during analysis of data from NTSB thermal testing.¹⁰ The effect can occur when the secondary slide is jammed and a forceful rudder pedal command is applied in the direction opposite to the jam. In this case, the internal PCU linkages can be deformed, allowing the primary slide to travel further than normal. The primary slide can actually travel far enough to effectively shut itself off. When the primary slide shuts off, the only remaining command within the PCU is the jammed secondary slide. This PCU command, however, is in the direction opposite to the pilot's

currently applied rudder pedal command. The rudder continues deflecting to blowdown. This scenario is known as "rudder reversal."

NTSB testing of the Flight 427 valve showed that a primary overtravel condition can only occur when the secondary slide is jammed at least 12% open, and a force of at least 190 pounds (60 pounds at the pedal) has been applied to the primary slide. Analysis provided to the NTSB¹¹ shows that the yaw damper in normal operation cannot open the secondary slide. Furthermore, NTSB testing of the Flight 427 actuator demonstrated that, in the event of a secondary slide jam, the yaw damper cannot cause a reversal condition.

The scenario for this failure mode requires the following: A very large or very high rate left rudder deflection must be commanded by the pilot to get the secondary slide sufficiently open. The secondary slide would then jam, followed by a right pedal input sufficient to apply the 190 pounds to the valve without breaking the jam free. If the pilot force is reduced below 190 pounds, the rudder will either center or deflect in the same direction as the rudder command.

A simulation of a secondary slide jam with primary slide overtravel was conducted to determine if that scenario could cause a rudder deflection that would replicate the Flight 427 flight path. This analysis showed that the secondary slide would have to jam while more than 50 percent open for the actuator to have sufficient rate and output force to match the DFDR heading trace. The yaw damper does not have the capability to open the secondary slide that amount. Therefore, for a secondary slide jam to be involved in the Flight 427 accident, the flight crew would have had to initially command a very rapid left rudder deflection.

¹⁰ *System Group Chairman's Factual Report of Investigation*, Jan. 31, 1997.

¹¹ *Simulation and Evaluation, RPCU Valve Slide Jams, USAir 737-300 Accident, N513AR*, Boeing Letter B-6600-16220-ASI, July 27, 1997.

Linkage Jam

If the PCU feedback linkage were to jam so that the main control valve could not close when the rudder reached its commanded position, the rudder could deflect to blowdown. In this scenario, because the slide travel is so small, the jam would have to be extremely rigid. For this reason, and because of NTSB testing discussed in Section IV-C, a linkage jam is not considered a reasonable failure scenario for Flight 427.

Secondary Slide Overstroke

There is one other failure mode that requires the secondary slide to travel to its internal stop. This can occur if the primary slide jams to the secondary slide, or if the summing linkage stop is ineffective. If this occurs and the secondary slide stop is not properly positioned, then the valve can move to a position that results in a flow reversal (commonly known as the "Mack Moore" condition). However, NTSB testing¹² showed that the stops on the Flight 427 valve were properly located, and that a flow reversal due to secondary slide overtravel was not possible.

Cockpit Effects of Failure Scenarios

Each of the above failure scenarios will cause the rudder pedals to be backdriven by the deflection of the rudder. When the rudder hits its blowdown limit (which varies between 14 and 21 degrees for Flight 427), the left pedal will have moved forward approximately 3 inches and the right pedal will have moved aft the same amount. If the pilots then applied a pedal force, the pedals could be moved only a very small amount (as allowed by stretching the control cables). The pedals would not free themselves unless the jam condition spontaneously cleared.

The rudder pedals do not move during normal yaw damper operation. However, if there is a dual valve slide jam or a linkage jam during a yaw damper input, the rudder will backdrive the pedals in the direction of the last yaw damper input. If the jam occurs while the pilot is commanding the rudder, the pedals will continue moving in the same direction as commanded by the pilot when the jam occurred.

For the scenario of a secondary slide jam with primary slide overtravel, the pilot would initially deflect the pedals for left rudder, at which time the valve would jam. When the pilot forcefully countered with right rudder, the pedals would initially deflect for right rudder, then be driven by the PCU back in the left direction as long as the pilot continued to apply a large right rudder pedal force. If the pilot relaxed the force, the rudder would return to neutral.

Rudder System Investigations

All the above rudder system failure modes are extremely unlikely, and there has never been a known case of any of the hypothesized failure scenarios in the history of the 737 fleet. The fact that a failure mode has not been observed during 30 years and more than 80 million flight hours of 737 operation, however, is not a sufficient reason to dismiss such a possibility in the case of Flight 427. The next section will evaluate the evidence that has been accumulated concerning these failure modes during the course of an intense three-year investigation.

In addition to the investigations discussed in the next section, the FAA commissioned a panel of experts to examine all aspects of the 737 lateral and directional flight control systems. This panel determined that the 737 flight control systems meet all applicable certification requirements, and that no specific scenarios could be identified that could explain the accident. The NTSB also commissioned a panel, drawn from government and industry, that reviewed the NTSB investigation of the rudder system, and made suggestions for additional investigations. All these suggestions were pursued and eliminated as possible failure scenarios for the accident.

In spite of nearly three years of investigation, no reasonable mechanism has been discovered for a system failure that could produce a full rudder deflection such as occurred in Flight 427. The lack of evidence for a system malfunction is addressed at greater length in the following section.

¹² System Group Chairman's Factual Report of Investigation, Dec. 21, 1994.

C. Evidence of Hypothetical Scenarios

The following discussion will review the evidence relating to the hypothetical failures discussed in Section IV-B that could cause the rudder to go to blowdown. The discussion will first examine the evidence related to jams within the control valve, and then examine the evidence related to jams of the PCU linkage mechanisms.

Evidence of Hypothetical Control Valve Slide Jams

Of the hypothetical failure modes that are capable of producing rudder deflection to blowdown, two involve a jam of one or both slides of the control valve. The following paragraphs discuss the various mechanisms by which a slide can theoretically become jammed, as well as the evidence that such a jam would create. A comparison is then made with the actual hardware removed from the accident aircraft.

Control Valve Slide Jam Due to a Chip of Foreign Material

If a chip of foreign material were to become lodged in the metering orifice of the control valve, it could theoretically prevent the control valve from closing. However, much like a pair of scissors, the control valve has the ability to shear, or cut, a chip. Also like scissors, the size of material that can be sheared is dependent on the force applied to the slides. In this case, the applied force is not limited by human strength, but rather by the design of the PCU.

The architecture of the PCU's internal linkages limits the chip shearing force to approximately 50 pounds for the primary slide and 190 pounds for the secondary slide. NTSB tests¹³ were conducted to examine the effects of chips placed into the metering orifices of the primary and secondary slides. The force applied to the slides during these tests was limited to the appropriate values.

The secondary slide was able to shear all chips placed into the metering orifice, including a 52100 steel chip that almost completely filled the orifice. 52100 steel is the hardest material (approximately R_c 60 - 65) used in the

manufacture of the PCU, and therefore represents a worst-case chip shear test. Only 140 pounds of force was required to shear this relatively large chip. The primary slide could shear all chips, except for a 52100 steel chip, with 40 pounds or less. Significant damage was created on the land edges of both slides during all of the tests when forces greater than 20 pounds were applied.

It is important to understand that the metering orifices of the control valve are approximately the same width, and only 3 times longer than the period at the end of this sentence (0.015 inches x 0.045 inches). Therefore, even completely filling the metering orifice with a hard steel chip still results in an extremely small amount of material to withstand the available chip shear force. It is therefore impossible for a chip to jam the secondary slide, and nearly impossible for one to jam the primary slide.

The primary and secondary slides removed from the accident PCU were examined by means of visual, microscopic, and scanning electron microscope (SEM) methods. No evidence of a jam due to a chip was found.

Based on the evidence, the primary and secondary slides removed from the accident aircraft were not jammed due to chips within the metering orifices.

Control Valve Slide Jam Due to Corrosion

Corrosion is another method by which the control valve could theoretically become jammed and thus be prevented from closing. Typically, corrosion within a hydraulic component is caused by excessive water content or degradation of the hydraulic fluid's anti-corrosion additive.

The PCU removed from the accident aircraft did not exhibit corrosion on any of its internal parts. Specifically, the primary and secondary slides of the control valve were free of any corrosion products.

Based on the evidence, the primary and secondary slides removed from the accident aircraft were not jammed due to corrosion between the interfacing diameters.

¹³ System Group Chairman's Factual Report Addendums, Jan. 12, 1995, and Apr. 30, 1997.

Control Valve Slide Jam Due to Hydraulic Fluid Particulate Contamination

It has been hypothesized that small particulates within the hydraulic fluid could jam one or both of the control valve slides by creating a contaminant lock condition.

Contaminant lock is when very small particles (less than 5 microns, a micron being 0.000039 inches) suspended in the hydraulic fluid migrate to the clearance between the slides. The theory is that particles collected in the clearance prevent relative movement of the slides.

The contaminant lock theory is based on the fact that when a control valve is in a static condition at hydraulic neutral, only a small amount of flow exists. This small flow is a result of the "trim" of the valve and also the clearance between the slides. Since some of this flow will ultimately pass through the clearance between the slide and sleeve, very small particles will be pushed into the clearance. If enough particles are suspended in the fluid and the valve remains static long enough, the particles will fill the clearance and, in theory, require high forces to cause relative movement of the slides.

NTSB tests¹⁴ were conducted to examine the effects of hydraulic fluid contaminated with particulates. These tests were performed at the same time as the thermal testing recommended by the NTSB's consultant panel. A main rudder PCU was allowed to remain in a static condition for approximately one hour while pressurized with "dirty" hydraulic fluid. The dirty fluid was approximately equivalent to the fluid found in the link cavity of the accident PCU. After remaining static for one hour, the input force of the PCU was measured. The force had increased only slightly to approximately 1.0 pounds (normal is 0.5 pounds).

Additional tests were conducted at Boeing¹⁵ to examine the effects of hydraulic fluid that was heavily contaminated with particulates. The level of contamination was varied during the testing to approximately 50 times the level measured in the accident PCU link cavity. The PCU's inlet filters were removed during the testing to prevent containment of the

particulates. The PCU's inlet filters are nominally rated at 10 microns, which ensures that 98 percent of all particles 10 microns or larger in any single dimension and all particles with any single dimension larger than 25 microns will be removed from the fluid.

Throughout the entire test, the PCU responded correctly to the input commands. At no time was there uncommanded movement of the PCU. The input forces did increase slightly due to particulate matter in the balance grooves of the primary slide. Post-test disassembly of the PCU and the control valve determined that the primary and secondary slides contained hard-packed contaminants in the balance grooves and annular passages. The metering edges of the slides were heavily worn to the point of being fully radiused, and the minor diameter of the slides contained polished craters below the metering edges.

The primary and secondary slides removed from the accident PCU did not contain any particulate matter packed into the balance grooves or annular passages. The metering edges were crisp and sharp, and no polished craters were present below the metering edges.

The tests proved that the main rudder PCU is tolerant of highly particulate contaminated hydraulic fluid even with the PCU's own protective filters removed, and that operation within that environment produces a distinct signature of wear and particulate accumulation on the primary and secondary slides. The primary and secondary slides removed from the accident aircraft did not exhibit any wear or particulate accumulation.

The following can be concluded from the testing and hardware examination:

1. Small particulates migrating to the clearance between the slide and sleeve do not significantly increase the force required to move the slide.
2. Packing the clearance between the slide and sleeve with particulate matter does not jam the slide.
3. Operation of the PCU with hydraulic fluid heavily contaminated with particulates creates a distinct signature of wear and particulate accumulation. This signature was not found on the accident PCU's control valve.

¹⁴ *System Group Chairman's Factual Report Addendum*, Apr. 18, 1997.

¹⁵ *Rudder PCU Particulate Test Report, B-G61R-C95-037*, Mar. 7, 1995.

Based on the evidence, the primary and secondary slides removed from the accident aircraft were not jammed due to hydraulic fluid particulate contamination.

Control Valve Slide Jams Due to Thermal Conditions

The NTSB panel of consultants recommended that testing be conducted to determine if the Flight 427 rudder control valve would seize when subjected to a thermal shock condition. A test program was initiated at Canyon Engineering, a facility associated with one of the consultants, to test the Flight 427 PCU by subjecting it to hypothetical worst case operating conditions. This was to be done by cold-soaking the PCU in the range of -27° to -40°F . The hydraulic system was then to be heated in the range of 160° to 170°F over a five-minute period.

The test setup, however, was unable to keep the PCU sufficiently cold. The test plan was modified to cool the PCU while it was depressurized and apply the hot fluid directly to the PCU inlet. It was recognized that this condition could not occur on an in-service airplane. Under these unrealistic conditions, it was found that the slide would momentarily seize while stroking the input linkage.

Because of the shortcomings of the Canyon test setup, it was decided to rerun the test at the Boeing Airplane Systems Laboratory (ASL). The setup used for this testing allowed the simulation of a variety of potential thermal-shock conditions. The test setup included a large cold chamber that enclosed the PCU, as well as hydraulic tubing that represented the airplane tubing from the aft pressure bulkhead to the PCU. Subsequent to the testing, a flight test was conducted that verified that the temperatures used for the cold chamber were conservative.

The following test conditions were run, during which the Flight 427 PCU operated normally:

1. Ambient fluid and cold chamber temperatures.
2. PCU cold-soaked to -27° and fluid at ambient.
3. PCU cold-soaked to -27° and A and B hydraulic fluid at 170° . Hot fluid introduced at inlet to cold chamber.

4. PCU cold-soaked to -27° , System A at 170° and B at 60° . System A fluid introduced directly into PCU.
5. PCU cold-soaked to -27° with System A depressurized. Both A and B hydraulic systems were heated to 170° with hot fluid introduced directly into the PCU.
6. Same as condition 5 except just System A was heated.

In addition, the following condition was run to repeat the Canyon Engineering test in which the valve seized. In the ASL test, the valve also seized after the Flight 427 PCU was rapidly stroked several times through its maximum displacement.

7. PCU cold-soaked to -40° with System A depressurized. System A heated to 170° and introduced directly into the PCU.

Conditions 1, 2, and 3 represented a worst-case airplane scenario after a hydraulic system overheat failure (there was no indication of such a failure on Flight 427). Conditions 4, 5, and 6 represented a condition more severe than any that could occur on an airplane, because a valve cannot cold-soak to those extremes and then be immediately subjected to hot fluid. These latter test conditions were intended to determine whether the valve had a substantial thermal margin. Condition 7 was designed to replicate the highly unrealistic Canyon test condition that resulted in valve seizure.

The testing demonstrated that the valve could not seize during any airplane operational scenario, and also that it would not seize even for a thermal shock condition that is much more severe than that which might ever be encountered by an airplane in service.

Additional testing and analysis¹⁶ was done by Boeing on control valves with minimum clearances. These tests showed that a minimum-clearance valve did not seize under worst-case test conditions and the highest level of rudder activity that could be encountered in flight.

¹⁶ Boeing letter to the NTSB, B-B600-16147-ASI, May 29, 1997.

Evidence of a Hypothetical Linkage Jam

Another type of hypothetical failure mode capable of producing rudder deflection to blowdown is a jam of the PCU's input linkage mechanism. The jam must be inside the PCU's feedback loop in order to cause a full deflection. Jams outside the PCU's feedback loop will only result in the rudder remaining at the position commanded when the jam occurred. This was confirmed by the NTSB testing of March 1995.¹⁷

NTSB testing identified only one jam location within the PCU's feedback loop capable of producing a rudder deflection to blowdown. Such a result could theoretically occur if there were a jam at the input crank. The jam must either prevent the crank from moving relative to the PCU's manifold, or prevent the crank from rotating relative to the H-link (external link connecting the input crank to the external summing lever). NTSB tests¹⁸ confirmed that no other locations produced anomalous rudder deflections. These NTSB tests included clamping the bearing in the external feedback mechanism, and actually welding the bearing of the primary internal summing lever.

The input crank is located on the bottom of the PCU, preventing foreign objects from falling between the input crank and the manifold. In addition, the PCU's H-link provides a shroud above the input crank and the manifold stop. Inspection of the Flight 427 input crank and manifold stop did not reveal any indications of a jam at this location. Also, the bearings at the crank and H-link interface were not seized at the time the PCU was inspected immediately after the accident.

Summary of Evidence

Hypothetical scenarios exist that would produce a full rudder deflection to blowdown. However, very specific conditions are required for each hypothetical failure scenario. Based on these specifics, it can be determined whether the failure scenario existed during Flight 427 by examining the condition of the main rudder PCU's control valve slides and input linkage mechanism. The examination conducted by the NTSB¹⁹ found no evidence of a control valve slide jam or an input linkage jam during Flight 427.

The table developed in Section III is updated below to include the information obtained from the above tests and examinations.

¹⁷ *System Group Chairman's Factual Report Addendum*, Jul. 17, 1996.

¹⁸ *System Group Chairman's Factual Report Addendum*, Jul. 17, 1996.

¹⁹ *System Group Chairman's Factual Report Addendum*, Dec. 21, 1994.

| Hypothetical Scenario for Full Rudder Deflection | Indications For | Indications Against | Comments |
|---|---|--|----------|
| 1. Dual slide jam | <ul style="list-style-type: none"> Potentially fits a kinematic analysis | <ul style="list-style-type: none"> Secondary slide can shear all chips No evidence of jam due to: <ul style="list-style-type: none"> - Chips - Corrosion - Particulates - Thermal cond. | * |
| 2. Secondary slide jam and primary slide overtravel | <ul style="list-style-type: none"> Potentially fits a kinematic analysis | <ul style="list-style-type: none"> Secondary slide can shear all chips No evidence of jam due to: <ul style="list-style-type: none"> - Chips - Corrosion - Particulates - Thermal cond. | * |
| 3. Input linkage jam | <ul style="list-style-type: none"> Potentially fits a kinematic analysis | <ul style="list-style-type: none"> No evidence of input crank jam Extremely high forces required to jam input mechanism Design geometry protects this area | * |
| 4. Flight crew input, no aircraft malfunction | <ul style="list-style-type: none"> Potentially fits a kinematic analysis | * | * |

*To be filled in further in Sections IV, V, and VI

Table 2: Hypothetical Scenarios Causing Rudder to Go to Blowdown

In summary, the NTSB has thoroughly scrutinized the Flight 427 PCU, which was not significantly damaged in the accident. Immediately following the accident, the PCU was carefully preserved and then examined, X-rayed, photographed, measured, and tested. The PCU operated normally. There was no evidence of binding, sticking, chattering, or a jam. There was no abnormal result of any kind in the functional testing, nor was there any evidence of a jam found when the components of the servo valve were individually inspected.

The NTSB Systems Group in its factual report dated December 21, 1994, summarized the testing conducted on the PCU when it had been preserved in its accident condition. The Systems Group concluded that:

- Testing and examinations conducted on the rudder PCU validated that the unit is capable of performing its intended functions, as specified by Boeing.
- Testing validated that the unit was incapable of uncommanded rudder movement or reversal.

These conclusions are as valid today as they were in December 1994. While the NTSB Systems Group, the NTSB's outside consultants, the FAA, Boeing, and Parker have spent the last three years postulating and evaluating failure modes and effects for the 737 rudder system, the fact remains that the accident PCU has continued to perform in tests exactly as it should in any condition in which it would be used during airline operations.

D. Service History

The 737 has accumulated more than 80 million flight hours of service during its thirty years of commercial operation. During this extensive service history, there has never been a documented case of full uncommanded rudder deflection or rudder reversal in flight.

There have been pilot reports of upsets and uncommanded roll, yaw, and rudder events on 737 airplanes, which have increased in number during the years in which the NTSB has investigated the Flight 427 accident. The increase in the number of reported events coincides with the publicity surrounding this investigation.

A number of comments can be made about these reported upsets. First, the NASA ASRS Multi-Engine Turbojet Uncommanded Upsets Structural Call Back, dated November 8, 1995, contains a compilation of loss-of-control factors in multi-engine turbojet upsets from January 1987 to May 1995. This compilation shows that encounters with wake turbulence are far and away the leading cause of events in which pilots report loss of control. Over twice as many loss-of-control events are attributed to wake turbulence as the next leading cause. As discussed more fully in Section V, 737 pilots, like pilots of all commercial airplanes, have reported large uncommanded roll and yaw upsets that are in fact attributable to wake encounters.

Second, in specific response to recent reports from 737 operators about uncommanded roll, yaw, and rudder events, Boeing assembled a "Roll Team" to make a detailed investigation into each of the reported events (summarized in Appendix C). The Roll Team analyzed the airline reports, the DFDR, and the equipment used in each event. The Roll Team's report concluded that a significant number of the reported upsets occurred as a result of wake turbulence encounters. Other events were caused by unrelated system failures. Still other events seem to have been normal airplane maneuvers that were misunderstood by the crew. All of the reported events were controllable by the flight crews.

Third, as a part of this investigation, the NTSB commissioned a study with a major European operator to monitor its 737s for a period of six months. The goal of the study was to obtain objective in-service data on the 737 that would identify any unusual rudder activity, or aircraft motion that could be attributed to unexpected rudder activity. By downloading the Quick Access Recorders (QAR) of twenty-six 737-400 airplanes, a record of rudder activity was gathered that covered approximately 21,000 flights encompassing more than 24,000 flight hours. In-flight data pertaining to rudder, rudder pedal, and control wheel positions were recorded. Additionally, post-flight monitoring routines were established to evaluate aircraft motion that might be caused by unusual rudder inputs. This mass of data showed that the rudder system operated exactly as expected, with no unexpected rudder activity. There were no rudder system anomalies of any kind.

Although this information does not identify any safety-of-flight rudder problem that can explain the Flight 427 accident, the service history has demonstrated that certain product improvements are appropriate. The improvements that Boeing supports on the rudder system are directed to improving the reliability of the system and eliminating the potential for extremely unlikely failures, none of which was present on Flight 427.

The NTSB, during the course of this investigation, has revisited the March 3, 1991, accident involving UAL Flight 585. The NTSB has also examined a June 9, 1996, event that involved an Eastwind 737-200 airplane. A brief synopsis of the data and analysis surrounding these occurrences follows.

United Flight 585 at Colorado Springs

Flight 585, a 737-200 ADV, crashed while on final approach to Colorado Springs, Colorado, on March 3, 1991. When the accident sequence began, the aircraft was flying at 160 knots just below 7,000 feet (approximately 1,400 feet above ground level), and was in a landing configuration with 30 degrees of flaps and gear down. It appeared to be turning right onto the runway heading when it rolled sharply to the right until inverted, hitting the ground in a near-vertical dive.

Prior to and at the time of the crash of Flight 585, the weather conditions—including wind speed and direction—were conducive to the formation of mountain waves and associated vortices and turbulence. There were numerous reports of severe weather from aircraft flying in the area and observers on the ground, including reports of unusually strong and shifting wind conditions near the time and place of the crash.²⁰ There were reports of rotors (horizontal-axis vortices) in the area.

During the investigation into the Flight 585 crash, the NTSB did not make a definitive probable cause determination. The limited amount of data on the DFDR (just airspeed, altitude, heading, and load factor were recorded) made it difficult to determine the flight path of the aircraft, or the control inputs required to match the DFDR and radar data. The NTSB report on the accident²¹ stated that the two events most likely to have resulted in a sudden uncontrollable lateral upset were either a malfunction of the airplane's lateral or directional control system, or an encounter with an unusually severe atmospheric disturbance.

Studies of the Flight 585 accident were subsequently conducted at Boeing²² using techniques and tools developed during the Flight 427 investigation. These studies showed that:

- The rudder was not involved in the Flight 585 accident.
- A malfunction in the airplane's lateral control system could not have caused the data traces recorded on the DFDR.
- A severe atmospheric disturbance was the most likely cause of the accident.

The results of the Boeing kinematic study of Flight 585 have been shared with the NTSB staff. Details are provided in Appendix C.

Eastwind

The Eastwind aircraft was a 737-200 that experienced a yaw event to the right on June 9, 1996, while on approach to Richmond, Virginia. The aircraft was not damaged during the event, nor was anyone injured. Instrumented flight testing of the Eastwind aircraft after the incident did not produce any anomalous behavior, nor was there any evidence of a rudder jam observed in the post-incident examination.

Examination of the rudder PCU by the NTSB did not reveal any evidence of PCU malfunction, other than a misrigged yaw damper LVDT position sensor. Examination of the control valve at NTSB offices in Washington, DC, on March 12, 1997, did not reveal any evidence of a jam in the primary or secondary control valve slides. Analysis of this event has shown that:

1. The yaw damper position sensor was misrigged, causing a larger-than-normal rudder input due to the yaw damper hardover (i.e., 4.5 deg instead of 3 deg).
2. Bank and heading data from the incident were obtained from gyros that were found in subsequent testing to be producing erroneous data.
3. The crew responded to the upset with near-simultaneous inputs of wheel, throttle, and conceivably rudder. If additional rudder inputs were made, only two degrees of rudder input in the direction of the yaw damper hardover are required to match a derived rudder deflection.
4. The roll angle actually reversed from a right to a left bank during recovery, but both crew members perceived that the aircraft remained in a 25- to 30-degree right bank.

²⁰ More details on the reported weather anomalies in the area of the accident can be found in the document *Boeing Contribution to the USAir Flight 427 Accident Investigation Board*, October 1996.

²¹ *Aircraft Accident Report – United Airlines Flight 585 - Boeing 737-291, N999UA*, NTSB, Dec. 8, 1992.

²² Boeing letter to NTSB, B-B600-16186-ASI, June 23, 1997.

-
5. There is no evidence of any jam in the rudder control valve slides.
 6. NTSB testing demonstrated that the Flight 427 valve could not seize during any operational scenario, and that it would not seize even for a thermal shock condition much more severe than what could have been encountered by an airplane in service. The Eastwind control valve clearances were greater than clearances for the Flight 427 control valve; therefore, neither the Flight 427 control valve nor the Eastwind control valve could seize during any airplane operational scenario.
 7. There is no evidence of a linkage jam in the rudder PCU, and a linkage jam does not match the kinematic analysis.