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B737 Flight Control System
Critical Design Review Report
May 3, 1995

B737 FLIGHT CONTROL SYSTEM CRITICAL DESIGN REVIEW

-REPORT-

MAY 3, 1995

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PROJECT SUMMARY:

Recent accidents have raised questions regarding the operational safety of the B737 flight control system. The FAA initiated an extraordinary effort in an attempt to determine if anything may have been overlooked. A nine-member team composed of engineers and airworthiness inspectors from within the FAA and other government authorities and USA agencies worked for over five months reviewing the flight control system design and service history of all models of the B737. Although some design and maintenance issues have been identified and are reported herein, no safety issue has been found that requires immediate corrective action. The Team has not found any design issue that could lead to a definite cause of the accidents that gave rise to this effort.

1. PROJECT CHARTER:

a. Background and Discussion - As of October 1994, the Boeing 737-100/-200 series airplane has accumulated nearly 43 million flight hours and the -300/-400/-500 series airplane nearly 20 million flight hours. During that time, a total of 55 hull loses have occurred within the whole series of B737 models none of which have yet been attributed to flight control malfunction. This represents one of the best safety records in the fleet of transport category airplanes. However, the USAIR B737 accident near Pittsburgh, and the United B737 accident near Colorado Springs, have raised questions about the flight control system on the B737. Despite repeated reviews and analyses of the design, the question of whether something has been overlooked still persists. In an effort to answer this question, the FAA Transport Airplane Directorate organized a Team to conduct a Critical Design Review (CDR) of the B737 flight control systems. The CDR was conducted independent of the accident investigation of USAir Flight # 427. Appendix 1 contains the complete text of the original charter inaugurated on October 20,1994.

b. Project Objectives - The Team, in coordination with Boeing engineers and other sources of information and guidance, developed an airplane level hazard assessment of the lateral and directional flight control systems. The analysis of the flight control systems was mostly qualitative and was consistent with guidance in Advisory Circular (AC) 25.1309-1A. Single

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failures and malfunctions, both latent and non-latent, and combinations of failures were reviewed initially without regard to their probability of occurrence. The hazard assessment conducted by the CDR Team included flight control system part(s), power supplies, worst-case reaction of the crew to any malfunction, maintenance related issues and airplane model differences. Because the original failure analysis developed by Boeing was qualitative, there were insufficient data to rank the probability of occurrence of the single and multiple failures. Consequently, the focus of the CDR was on the alternative means of flight path control and its preservation in the event of failure(s) or malfunction(s) rather than the elimination of the single or multiple failure event.

2. CDR TEAM MEMBERS: The selection process for the Team members was intended to ensure that selected personnel were expert in their specialties and did not have direct participation in the certification of the B737. It was hoped this approach would afford a fresh look at the B737 flight control design and its continued operational history. Team members outside of the FAA were selected to provide other perspectives on design and operation. The CDR Team was also supported full time by a National Transportation Safety Board (NTSB) aviation safety investigator who was not assigned to any recent B737 accident investigation. This report was reviewed by the investigator and all comments have been incorporated. This involvement by the investigator in no way reflects any official Safety Board position on any matters within this report. Appendix 2 contains the technical biographies of the Team members.

3. B737 AIRPLANE DESCRIPTION: The Boeing Model 737 design was originally conceived in the early 1960s and certified in 1967. The B737 is a conventional, two-engine, jet-powered, large commercial transport. The B737 has a variety of passenger and cargo configurations as provided by different models. A significant model change was introduced with the advent of the B737-300 which incorporated a new engines variant (CFM-56) and updated flight deck displays and automation. The airplane is designed principally for the short and medium range routes. The flight control system is hydraulically powered with manual reversion available for pitch and lateral control. Pilot input to the flight control systems is generally through a cable and pulley arrangement connected to hydraulic power control units that position the flight control surfaces. Appendix 3 contains a more detailed description of the hydraulic control system and the directional, longitudinal, and lateral flight path control systems of the B737.

4. CRITICAL DESIGN REVIEW METHODOLOGY: The CDR Team determined it could not conduct a detailed quantitative analysis within the time frame established in the Charter. It was established that a qualitative effort, as provided by the definition in AC 25.1309-1A, paragraph 8.a., "Functional Hazard Assessment," should be used in considering the available data and resources that could be devoted to the effort. Also, early in the project, the Team decided to focus on the lateral and directional flight control systems. Although the Team received

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familiarization training on the longitudinal flight control system and high lift devices, a design review was not conducted on these systems. The lack of implication of the longitudinal control system as a causal or contributing factor in recent accidents and incidents, indicated that no analysis effort on this system was warranted at this time. (Appendix 4 provides the day-to-day activity of the CDR Team.)

a. Objectives - In an attempt to help maintain focus on the purpose of the review, the Team amplified the original objectives and process as follows:

(1) Identify those failure events, both single and multiple, within certain flight control systems that result in an uncommanded deflection or jam of a flight control surface.

(2) Identify latent failures in each axis of flight control.

(3) Review the service history of the failed or malfunctioning component or subsystem through a review of Airworthiness Directives (AD), Service Bulletins (SB), Service Letters (SL), Service Difficulty Reports (SDR), National Transportation Safety Board (NTSB) recommendations, National Aeronautics and Space Administration (NASA) Aerospace System Reporting System (ASRS) reports, and other reports. (See Section 7: "Service History.")

(4) Identify and review the maintenance or inspection requirements (task and inspection interval), as provided by the manufacturer's Maintenance Planning Document (MPD), Maintenance Review Board (MRB) report, or maintenance manual for each identified component or subsystem with critical failure potential.

b. Determination of Criticality - The determination of the criticality of the failure(s) will be in consideration of:

(1) Functional hazard assessment process (see Section 5).

(2) Current certification regulations, practice, and guidance.

(3) Service history of failed or malfunctioning components (see Section 7).

(4) The simulator exercise conducted in support of this review (see Section 8).

(5) The following assumptions or qualifying statements:

(a) The qualification of "normal flight envelope" or "control position normally encountered" does not necessarily exclude the potential for a flight control surface to jam when at full deflection unless full deflection is only required by flight conditions produced by another improbable failure, e.g., engine failure during a limited time period.

(b) The qualification of "latent failures," as provided by AC 25.1309-1A, paragraph 8.f: "A latent failure is one which is inherently undetected when it occurs. A significant latent failure is one which, in combination with one or more other specific failures or events, would result in a hazardous failure condition."

(c) A failure condition is considered a hazard when continued safe flight and landing are doubtful, based on engineering and operational judgment of the Team.

(d) Continued safe flight and landing include consideration for the flightcrew's workload and the requirement for their prompt and correct response to an upset condition due to a failure.

5. FUNCTIONAL HAZARD ASSESSMENT:

a. Background - Boeing provided the Team with familiarization training and an indepth review and presentation of the certification data developed for the B737 lateral and directional flight controls. The certification data included identification of failures and recommended ameliorating actions. Other documentation provided by Boeing for Team review or reference included the following: Airplane Flight Manual, Operations Manual, Maintenance Planning Document, PCU Overhaul Manual, selected Type Inspection Reports (TIR), and ground-functional flight control mock-up (Ironbird) test reports. Service history information, as defined in Section 4.a. (3) of this report, was collected and sorted, as applicable, to help define failure conditions or scenarios.

b. Discussion - The Boeing certification data was not quantitative, and did not indicate probability of occurrence of failures, except as described in Section 6.b.(3), in the flight control system. Following the review of this analysis, the Team identified a number of potential single and multiple failures, failure scenarios and malfunctions, and latent failures in the flight control system that had the potential to be hazardous, in accordance with Section 4 of this report.

As noted in Section 4.b.(5)(a), the CDR Team considered jams in control position, not just those "normally encountered," in accordance with Amendment 23 to FAR § 25.671 and Appendix 5 pg. A-20. The Team does not agree with the rationale that only control positions associated with "normally encountered" should be considered. There are too many variables (atmospheric conditions pilot technique, airplane condition (trim requirement), air traffic, etc.) to define "normally encountered" other than that it may be less than full deflection. The Team's position is that if a control position is possible, it is there for a purpose, and the pilot can use that control authority. The only exception to this requirement is the case when full control deflection is only required (provided) to counter another improbable failure or event. Probability analysis should not be used to predict pilot action, particularly in worst-case reaction, in accordance with the

Team's charter. (See "Recommendations For FAA Action," Section 15. Recommendation -1, -2).

A plan was established to test a number of the potential failure conditions in the Boeing "M" Cab engineering flight simulator. The "M" Cab was declared by Boeing to be of sufficient fidelity for our purpose. A synopsis of the simulation exercise is contained in Section 8.

c. Assessment Process - The single and latent failures of concern to the Team are contained in Sections 9 and 10. There was insufficient time to determine numerical probability of occurrence for single, multiple and latent failures, therefore the method for resolving the hazard of the failures was qualitative and conducted in accordance with the following:

(1) Failures were segregated by axis.

(2) Failures were then grouped by axis and failure mechanism, i.e., jams, loss of function as a consequence of a break or separation and potential for a pilot to induce a hazardous condition, in response to a failure, such as loss of rudder feel or loss of centering of the pilot's flight control input.

(3) Alternative means of controlling the airplane were identified and analyzed to determine if they were sufficient, available, and could be applied by a pilot of normal skill. Examples would be:

(a) If there is a potential for an uncommanded rudder hardover that cannot be alleviated, is there sufficient control of the aircraft for continued safe flight and landing through the lateral control system?

(b) If the ailerons are hardover because of a jam on the pilot's side (column, cables, aileron quadrant, etc.), is there sufficient lateral control available by the copilot flying the airplane with flight spoilers through the aileron transfer mechanism?

(c) If the pilot were to induce a rudder hardover as a consequence of the loss of feel, is there sufficient indication(s) or sense of pilot control input to regain control of the flight path of the airplane and continue safe flight and landing?

(d). If there is a loss of system function, like a hydraulic system failure, is the standby system readily available and operational?

(4) Having identified failure conditions leading to the use of designed alternative means for flight control, a review was conducted of the service history and maintenance inspection requirements and their frequency. This information was used to support the Team position that there is a potential for occurrence of the identified jams, failures, and malfunctions. The service history was further scrutinized to determine if any changes were desirable, e.g.,

modified inspection tasks and intervals, and whether certain SBs and SLs should be mandated to enhance the safety of the flight control system.

(5) Latent failures that would affect the operation of the alternative flight control system including recommendations to reduce their potential for occurrence were then identified.

6. CERTIFICATION BASIS AND COMPLIANCE:

a. Model B737-100/-200 Series Airplanes -

(1) Airworthiness Requirements. The B737-100 and -200 were type-certificated in December 1967. Their certification basis was FAR Part 25, including Amendments 25-1, 25-2, 25-3, 25-7, 25-8, 25-15, and special conditions that added additional fuel system and inoperative electrical system requirements, which became rules in later amendments to FAR Part 25. In 1979, another special condition was added to provide for an airplane Auto Takeoff Thrust Control System (ATTCS). Two exemptions were granted that concerned maximum takeoff gross weight and location of fire detectors.

(2) Analysis and Testing. In accordance with the certification basis, Boeing performed analysis and testing to demonstrate compliance with the airworthiness requirements of FAR Part 25. The analysis included the generation of failure analysis documents for each flight control system. Testing included ground tests on both a flight controls test bed (Iron Bird) and airplane flight tests. Tests conducted on the ground included proof load, frequency response, and selected control system failure (e.g., aileron body cables). Flight tests included stabilizer jams and trim runaways, failed hydraulic systems, asymmetric leading edge devices, asymmetric trailing edge flaps, jammed flight spoilers, and autopilot/yaw damper hardovers. This list is intended to be illustrative, not all encompassing.

(3) Results. The results of these analyses and tests showed satisfactory compliance with the FAR, and the tests were typical of those conducted to show compliance during the time period this airplane was type certificated.

b. Model B737-300/-400/-500 Series Airplanes -

(1) Airworthiness Requirements. The B737-300/-400/-500 series airplanes were type certificated during the 1984-1990 time period (specifically; November 14, 1984; September 2, 1988; and February 12, 1990, respectively). The certification basis for these aircraft was essentially the same as for the B737-100/-200, without special conditions, which were superseded by later amendments to FAR Part 25. Additionally, some later amendments to FAR Part 25 requirements were imposed upon only structure or components that were unique to the -300/-400/-500 series airplanes, with respect to the existing -200 series airplane. No exemptions

were granted to the -300/-400/-500 series airplanes. However, several equivalent safety findings were made with regard to these airplanes, none of which involved flight controls. Many of the equivalent safety findings for the -400/-500 series airplanes involved flight performance or characteristic requirements that were related to the decision to use the methodologies of a proposed amendment to FAR Part 25. This proposed amendment would allow the stalling speed of the airplane to be the minimum speed at which the wing is capable of producing a normal load factor of 1g rather than the minimum speed observed in the stall maneuver.

(2) Issue Papers. There were a number of FAA issue papers developed during the certification of the B737-300 that addressed concerns currently being raised by the CDR Team. One of these addressed maintenance items resulting from certification activities. This issue was resolved by the determination that no maintenance interval identification was necessary for showing compliance with certification requirements. In contrast, the CDR Team has identified a number of latent failures that require some maintenance/flightcrew action to ensure that a latent failure, combined with any subsequent failure, is not hazardous.

There also were issue papers that dealt with pitch, roll, and yaw-impaired authority; pitch, roll, and yaw control device uncommanded motion; inadvertent extensions/retraction of high-lift devices or spoilers; autopilot hardovers; and non-containment of turbine engine debris that are pertinent to CDR Team investigations and recommendations. All these issues were resolved during the certification of the -300 airplane. However, with the advantage of hindsight, the CDR Team has identified issues that could improve the level of safety. (See "Recommendations For FAA Action," Section 15.).

(3) Analysis and Tests. Boeing performed both tests and analyses to show compliance with the airworthiness requirements of the certification basis for the -300/-400/-500 series airplanes. The certification data were updated and, now, include system safety analyses (numerical probability of failure predictions) for new or modified features in the flight control systems. Some additional ground tests, similar to those conducted on the -200 series airplane, were conducted for the -300/-400/-500 series airplanes.

(4) Results. The results of these analyses and tests showed compliance with the FAR requirements.

7. SERVICE HISTORY: A number of sources were utilized to determine the service history of the identified components and/or subsystem elements of a flight control system under review.

a. Reference Documents - Service Difficulty Reports (SDR), Service Letters (SL), Service Bulletins (SB), Airworthiness Directives (AD), NTSB recommendations, and NASA Aerospace System Reporting System (ASRS) reports were obtained and reviewed. A summary listing of the documents or reports reviewed is included in Appendix 6.

b. Flight Control Components (Wheel Well) - The Team was provided service history information from a number of sources, regarding this subject. Some of the information came from Team observations and personnel interviews conducted at facilities visited (Section 7.c.). This information led to concerns for the vulnerability of critical flight control components in the main wheel well, to damage from environmental debris or failure of a wheel or tire. Boeing identified one incident (ground event) where a piece of epoxy became jammed in the input link to the aileron PCU. This event led to the installation of a protective soft cover. Another incident occurred with a T-43 (B737 military version) when a wheel failure ruptured hydraulic components. In February of 1995, an incident occurred with a B737 -200 when system "A" lost hydraulic quantity during an approach due to a failure of a hydraulic pressure line in the main wheel well. It appears the mechanism for the failure was the accumulation of debris under a clamp which then abraded the line. Also, during one of the Team visits to a repair facility, an airplane was in for a "D" check, and one aileron PCU had enough accumulation of dirt in the area of the input linkage to the PCU to possibly limit linkage travel to less then the designed stop.

Boeing removed the protective screens in the wheel well (Reference SB's 737-52-1091 dated June 22,1989, 737-52-1088, dated April 19, 1985, and 737-52-1081, dated January 29, 1982). Boeing conducted extensive tire burst tests by simulating the gas pressure release from a worn tread (flat or bald spot) rupture with an air cannon. These tests showed that the screens could be eliminated if protection from the gas blast was provided for specific components. SB 52-1091 details the changes required for screen removal as a result of these tests. No consideration was given to tire explosion because nitrogen, rather than air, had been mandated by regulation as the pressurizing gas. Also, no consideration was given to wheel failure because of the later, more stringent wheel requirements contained in TSO-C26c. Tread burst (gas release) was the only mode of failure considered because a historical search revealed no other failure modes for a non-rotating wheel/bias-ply tire in the wheel well. Thrown tread was shown to occur with the wheel rotating outside the well (before automatic braking that occurs as part of the retraction cycle).

Not withstanding the preceding considerations, the Team believes that the vulnerable location of vital flight controls components and the hydraulic fluid reservoirs for all three hydraulic systems in the wheel well is a design concern. (See "Recommendations for FAA Action" Section 15. Recommendation -10, -11).

c. Manufacturer and Repair Facility Visit - The Team visited various facilities and informally inspected the new and used condition of the systems and components that provide flight control. Trip reports on these visits are contained in Appendix 7. Only significant observations are included here.

(1) **Tramco Inc.** The Team members visited Tramco, Inc., an overhaul facility located in Everett, Washington, on December 7, 1994. Tramco is a FAR Part 145 Repair Station that conducts regularly scheduled heavy maintenance checks on the B737 and other large transport category aircraft. The purpose of the visit was to look at inservice components, to observe the condition of the parts and to familiarize the Team members with the actual aircraft

hardware. This trip prompted a number of additional questions for Boeing regarding the repair and maintenance of PCUs.

Observations

(a) In accordance with Parts 121 and 145, the repair station only performs the maintenance requested by the aircraft operator, in accordance with their approved maintenance program. For this particular "D" check, the task cards did not require access to all parts of the airplane of particular interest to the Team, e.g., components under the cockpit floor, etc., which had latent or single failure potential.

(b) The Team obtained valuable hands-on experience with aircraft components, both on and off the airplane, particularly aileron and standby rudder PCUs in the overhaul shop.

(c) TRAMCO uses Fortner Engineering repaired or overhauled "lap assemblies" (servo and bypass valves) for aileron and rudder PCUs almost exclusively in the hydraulic component overhaul shop.

(2) **Parker Hannifin Corporation Control Systems Division.** A Team representative visited Parker Hannifin in Irvine, California, on December 16, 1994, to discuss various aspects of the B737 rudder PCU. The purpose of the visit was to better understand design details of the PCU, and to obtain more information about the service experience of the units.

Observations

(a) Valve-chip shearing forces (as low as 37 pounds for inservice units) on this actuator seem to be marginal.

(b) There is no adequate means for testing the dual spool servo valve for proper operation on the airplane.

(c) The dual spool servo valve is a complex assembly and is a critical component of the rudder and aileron power control units and, therefore, critical to flight safety. Any facility authorized by the FAA to perform repair and maintenance or manufacture this component must assure the FAA of having the necessary equipment, personnel and data (design, manufacture, qualification and acceptance test procedures), including access to the latest revisions to the data provided by the OEM. (See "Recommendations for FAA Action" Section 15. Recommendations -20, -21, -22).

(3) **Douglas Aircraft Company.** Several members of the CDR Team visited Douglas Aircraft Company (DAC) in Long Beach, California, on December 21, 1994. The purpose of the visit was to enhance the Team's knowledge of flight control design philosophies of other aircraft manufacturers, in an effort to compare these with the design principles used in the B737.

Observations

(a) The earlier DAC airplanes employ direct cable-driven surface tabs as the primary control mechanism for many of the flight control systems.

(b) The airplanes that have a hydraulically powered rudder have built-in hardover protection with the use of split surfaces, or manual reversion via hydraulic power shut-off lever. Earlier airplanes use deflection limiting devices with airspeed inputs. Later airplanes use aerodynamic (blowdown) limiting.

(c) After breakout, the resulting prolonged forces required to control the airplane after a jam in the lateral control system are significantly lower than those of the B737.

(d) The DAC minimum chip-shearing capability for hydraulic servo valves (100 pounds) is significantly higher than that of the B737 rudder PCU servo valve (minimum 37 pounds inservice, and 39 pounds design).

(e) DAC has more restrictive contaminated hydraulic fluid inspection requirements than those of the B737.

(f) DAC performs flight tests of "rudder kicks" to determine structural strength issues; flight tests of rudder hardovers to determine lateral versus directional authority are not performed.

(g) DAC employs a safety, reliability, and ergonomics group to perform hazard analysis on newer airplane models.

(h) DAC's Failure Modes and Effects Analysis (FMEA) process is comprehensive and crosses engineering and operational disciplines.

(i) In the DAC FMEA process for analyzing latent failures, DAC takes credit for the inspection interval of the identified failure, but does not make this inspection a Certification Maintenance Requirement.

(4) **Fortner Engineering and Manufacturing, Inc.** On December 20, 1994, several CDR Team members, together with Los Angeles ACO and MIDO personnel, met with Bob, Bill, and Jim Fortner, principals in Fortner, at the FAA Los Angeles Aircraft Certification Office (LAACO). The Fortner firm is an authorized Repair Station under FAR Part 145 and repairs and overhauls aircraft hydraulic components of all types for primarily airline and other aircraft operator customers. They repair and/or overhaul B737 power control units (PCUs) on aileron/elevators, and rudder Main Power Control Units and standby PCUs. Another visit with Fortner was conducted on February 16,1995 at their facility in Glendale, Ca. Further details on Fortner's fabrication of the dual-spool valve were obtained.

Observations -

(a) Fortner uses FAA-approved data (under SFAR 36 authorization) for overhaul and repair of Boeing hydraulic components, but neither this data nor their activities are coordinated with, or authorized by, Boeing.

(b) Fortner stated it has been overhauling hydraulic components since the 1950s and enjoys the confidence of many airline companies.

(5) **Honeywell/Sperry.** A Team representative visited Honeywell/Sperry in Phoenix, Arizona, on December 16, 1994. The purpose of that trip was to review the Honeywell/Sperry Yaw Damper design (Boeing Model No. 10-60447-18) used on Boeing Model 737-300/-400/-500 airplanes, and to identify any issues associated with the design that may compromise safety.

Observations

(a) A 12-month accumulation of 200 failed Yaw Damper units was reviewed by the group, in an effort to identify failure trends. Of the 200 failed units reviewed, 130 were due to rate gyro failures, and all of those were caused by damage to the rate gyro rotor bearings. Of the remaining 70 failures, 42 were confirmed as "No Fault Found," and the remaining 28 failures were considered "typical" (i.e., failed components, cold solder joints, etc.). The review suggests that the reason for the excessive frequency of rate gyro failures is due to a Boeing engine change. Boeing requested that Honeywell approve the existing Yaw Damper in the new vibration environment. That new vibration environment was a direct result of the engine change, which is the principal difference between the model -200 and the -300 aircraft. Honeywell has an action item to review those failures with Boeing.

(b) There are a number of failure modes that could cause the Yaw Damper to command a rudder deflection to the limit of the Yaw Damper authority:

(i) electrical shorts or ground,

(ii) open feedback circuits and

(iii) a condition involving an intermittent connection to the transfer valve and an integration circuit in the coupler where the Yaw Damper could command the rudder to deflect 3^{o} for up to 120 seconds. Honeywell was not aware of this condition. Further investigation is being initiated by Honeywell. (See "Recommendations for FAA Action" Section 15. Recommendation -14).

8. BOEING "M" CAB SIMULATOR EXERCISE CONDUCTED BY THE CDR TEAM:

The CDR Team conducted a simulator exercise in the Boeing "M" CAB simulator configured as a B737-300 on November 17, 1994. The purpose of these tests was to determine the degree of hazard associated with a number of control system malfunctions. These malfunctions were selected without regard for their probability of occurrence or the FAR requirements. A report documenting the results of these tests is presented as Appendix 5.

a. Failure Scenarios Investigated -

(1) Rudder/aileron trim runaways opposed by the autopilot.

(2) Lateral versus directional control power including rudder "hardovers."

(3) Flight with zero or one-half aileron/rudder feel force.

(4) Control through the aileron transfer mechanism with ailerons jammed at one-half to full deflection.

(5) Flight with one or two flight spoilers stuck up on the same side.

(6) Flight with the #2 slat retracted and flaps extended to 1, 5, 15, 25, and 40. This was then combined with a maximum flap asymmetry between flaps 15 and 25.

b. Results -

(1) Rudder/Aileron Trim Runaways. If the autopilot was disconnected "hands off" after a full displacement trim input, the aircraft rolled rapidly (13 to 22 degrees/sec at lower speeds and 30 to 44 degrees/sec at higher speeds). Prompt pilot reaction was required to prevent excessive (>60°) bank angles from developing.

(2) Lateral Versus Directional Control Power Including Rudder "Hardovers." These tests basically confirmed Boeing's contention that lateral control has more roll authority than does the dihedral effect from full rudder inputs for flight conditions tested except the flaps 1, 190 KIAS condition. For this condition lateral control also predominated, but recovery from a rudder "hardover" was slow and required precise pilot control of resulting pitch/airspeed. Prompt pilot response was required to prevent entering the inverted flight regime at high altitude/speed.

(3) Flight With Zero Or One-Half Aileron/Rudder Feel Force. Failure of one spring (1/2 feel) in the feel and centering mechanism in either axis was judged to be difficult for a pilot to recognize in flight and potentially latent. Zero feel in the lateral axis was recognizable and control was not a problem. Zero rudder feel was recognizable and controllable but difficult due to lack of rudder centering. Pilot inputs resulted in conditions similar to partial or full rudder hardovers.

(4) Control With Spoilers Only After A Simulated Pilot's Side Body Cable Jam. With both ailerons jammed at the displacements tested, (10 to 20 degrees) flight with pilot input through the aileron transfer mechanism was extremely difficult due to the high forces necessary. Control of the aircraft could be regained, but long term flight to a successful landing was questionable, due to pilot effort required and the onset of pilot fatigue. (See "Recommendations for FAA Action" Section 15. Recommendation -8).

(5) Flight With One Or Two Spoiler Panels Stuck Up On The Same Side. Roll control in these flight conditions was generally not a problem. The additional pilot workload factor was the loss of performance due to increased drag, and the loss of lift once the malfunction was countered with opposite wheel. The landing configuration (two spoilers stuck up) malfunction was flown to a landing and resulted in a hard landing.

(6) Flight With The No. 2 Slat Retracted And Flaps Extended, Including Asymmetric Flaps. None of these malfunctions presented a control problem until the angle of attack was increased to near stall. Then a sharp roll-off in the direction of the retracted slat

occurred almost coincident with stick shaker activation. A normal stall recovery regained aircraft control.

9. SINGLE FAILURES (TABLES 1 AND 2): Subsequent to the review of the certification data and the simulator exercise, the Team identified a number of failure conditions (non-latent) in the lateral and directional axes that were of particular concern. The failure conditions identified herein include the worst case consequence of the failure, any "associated" service history and recommended actions. The failure conditions identified in Tables 1 and 2 were not designed to be self-explanatory. No attempt was made in this report to explain the system details sufficiently so that the reader can fully understand the failure condition. The certification data provided to the Team by Boeing provides the details of each failure condition. Schematics for the aileron and rudder control system are provided on pages 15 and 18 of this Section.

The "associated" service history shown in Tables 1 and 2 under the column labeled "ADs, SBs, SLs, ASRSs, NTSB REC., SDRs" includes all the references that the Team felt indicated that this type of failure could occur or had occurred. Some of the referenced documents are not directly related to the failure indicated in that row of the table. For example, if the failure is a cable break or jam, documents referring to a cable break or jam on a B737 may be included even though the cable involved is different from the cable for which the row item was created.

Many of the failures identified in Tables 1 and 2 may have a very low probability of occurrence. Further analysis will be necessary to determine their probability. However, because the CDR Team considered them to be not extremely improbable, they are presented as examples of failure conditions that require the use of the alternate means of controlling the aircraft in order to not be a hazardous condition as defined in Section 4.b.(5) of this report.

The tables are considered sufficient to indicate the potential for breaks, jams or malfunction. The objective of this section is to stress the importance of the alternate means of maintaining flight path control, to identify design or maintenance considerations to ensure availability and suitability of those alternate means, and to reduce the probability of the initiating failure.

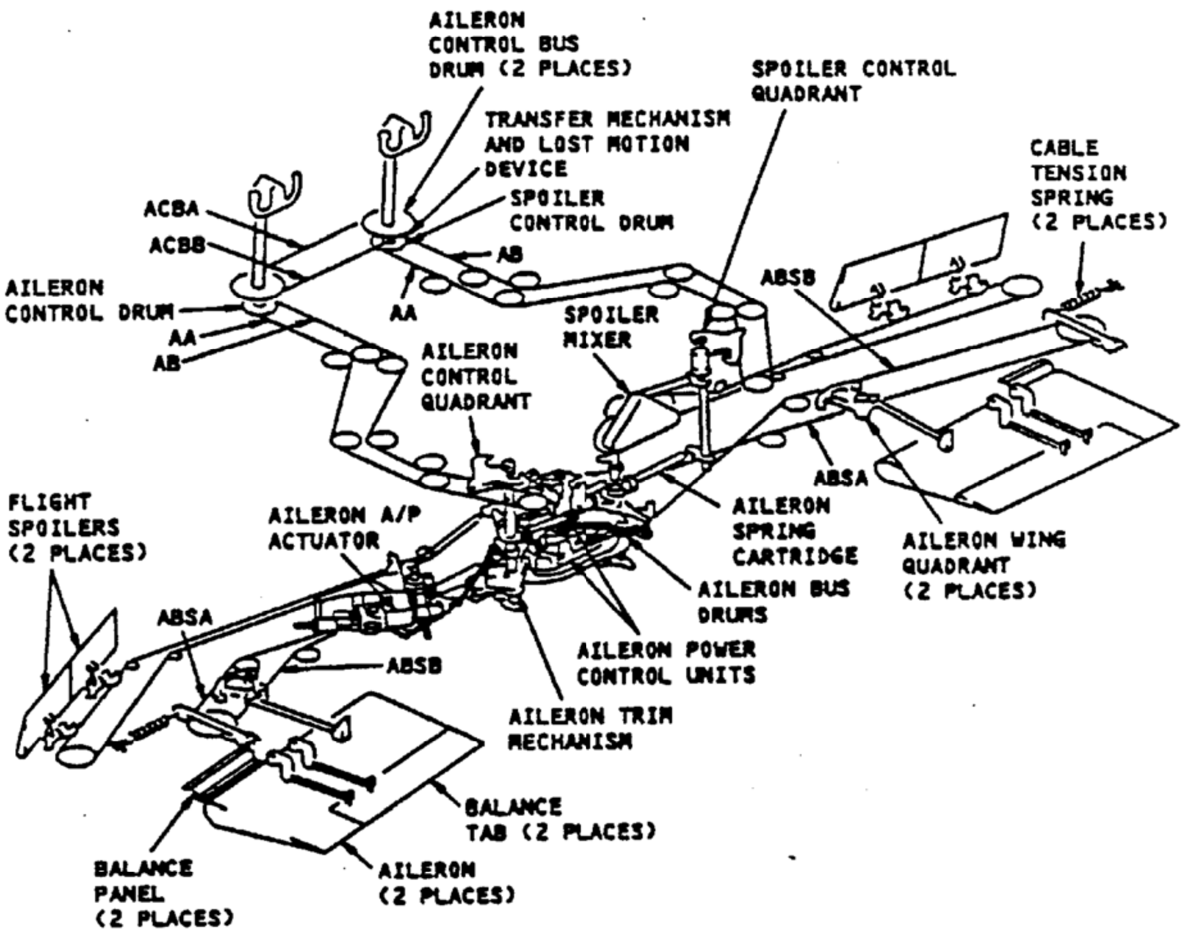
a. Single Failures, Aileron - The failure mechanisms identified in Table 1 suggest there are a number of ways for a failure to result in a sustained aileron hardover. The significance of the aileron failure conditions resulting in a jam of the aileron is the importance of the alternate means for controlling the airplane. The designed alternative means is the aileron transfer mechanism.

As was experienced in the "M" Cab exercise, flight path control through the aileron transfer mechanism may be very difficult due to the high wheel forces. It is believed that if a full aileron hardover was to be countered for any reasonable length of time, continued safe flight and landing in a B737 would be very difficult. (See "Recommendations For FAA Action," Section 15. Recommendation -8).

Failure conditions associated with the flight spoilers are also identified in Table 1. One or two panel failures (up) in the flight spoiler system did not produce a significant roll control problem as long as the rest of the lateral control system was operative. The significance of this failure is the performance loss with four panels up after balancing wheel input has been made in order to maintain wings level. Pilot awareness of the significant loss in performance is necessary to assure continued safe flight and landing.

Also considered in Table 1, Item 5, were the speed brake/spoiler failure modes that could result in one or more spoilers up for takeoff (Ref. NTSB A93-133/134/135). The CDR Team believes that pilot training and/or Airplane Flight Manual or Operations Manual should emphasize the necessity for determining spoiler position and not just speed brake handle position prior to takeoff. (See "Recommendations For FAA Action," Section 15. Recommendation -19).

AILERON CONTROL SYSTEM



b. Single Failures, Rudder - The consequence of the failure mechanisms identified in Table 2 are recognizable by the flightcrew. The failures suggest there are a number of ways where loss of rudder control and potential for a sustained rudder hardover may occur. More importantly, when considering some undetected (latent) failures like Table 4, Items 1 or 2C in the directional control system, in combination with some of the single failures identified in Table 2, the potential for a sustained jam of the rudder at full deflection, as limited by blowdown, is increased. The Team has determined the requirement for full rudder is within the scope of normal operation. Since full rudder hardovers and/or jams are possible, the alternate means for control, the lateral control system, must be fully available and powerful enough to rapidly counter the rudder and prevent entrance into a hazardous flight condition.

The requirement for full rudder may subsequently be shown to be limited, for example, to a specific phase of flight and time interval such as an engine failure on takeoff which has been shown to be an improbable event. If no other requirement for full rudder exists in the other phases of flight, then the Team would accept that the capability of the lateral control system to counter a <u>pilot-induced</u> full deflection jam could be shown at some lesser deflection not associated with an improbable failure condition. The requirement would still remain to show that an <u>uncommanded</u> hardover could be countered with lateral control unless this event can be shown to be extremely improbable in accordance with Section 15. Recommendation -9.

The failure condition identified in Table 2, Item 3, has not been fully defined. The yaw damper mod piston and pilot input summing linkage are a vital part of the main rudder power control unit. The interaction of the yaw damper and pilot input through the mod piston and the summing linkage with the dual spool servo valve is complex. It is this linkage that limits the force that the pilot can apply to shear an obstruction in the servo valve. Whether there is a failure mode of this input/summing mechanism that could result in a yaw damper authority of greater than 3^{o} or could result in a servo valve open condition that produces a rudder hardover was not clearly established to the satisfaction of the team. (See "Recommendations for FAA Action" Section 15. Recommendation -12, -13).

Failures identified in Items 7A and 7B of Table 2 are not of themselves "hazardous." However:

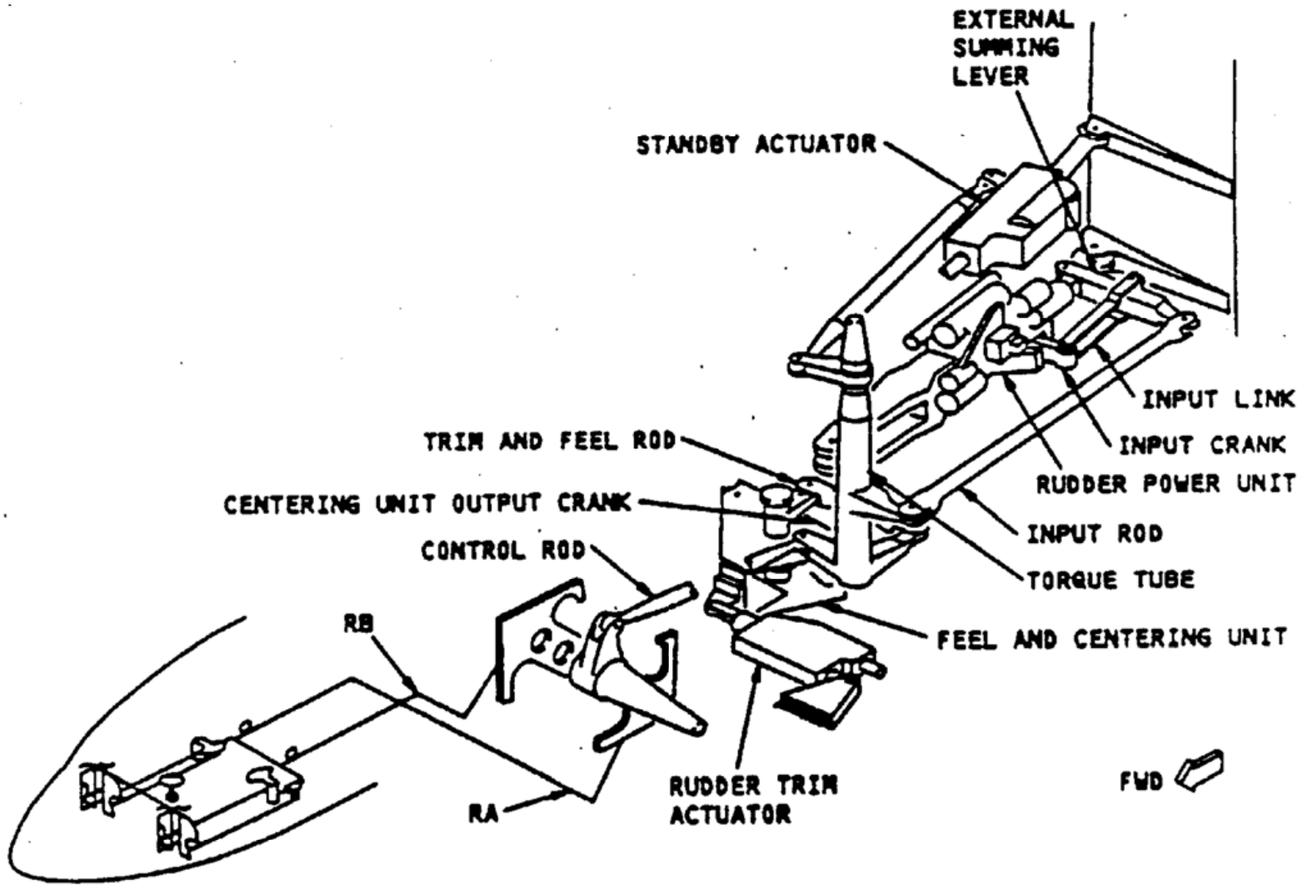
(1) They may initiate a more hazardous event, either flight controls or flightcrew related.

(2) They tend to mask and/or confuse other flight control anomalies that may be precursors or provide evidence of more hazardous failures.

Failures identified in Items 8 and 9 of Table 2 can be confusing to the flightcrew and could result in inappropriate flightcrew response. This is because the crew's primary indicator of rudder position is rudder pedal position, and these two failures cause displaced pedals and inoperative pedals. Flightcrew training in the recognition and proper response to these failures is recommended to assure continued safe flight and landing. (See "Recommendations For FAA Action," Section 15. Recommendation -19).

The rotary valve input on the rudder standby actuator (Table 2, Item 6) produced by Dowty is fitted with a journal bearing arrangement. The rotary input crank material is heat treated to 440°C and a hardness R_c 55-59. This crank rotates in a stainless steel housing heat treated to R_c 35-37. This combination of materials and limited clearance, operating without lubrication, or with only Skydrol lubrication after a recent modification, continues to result in minor galling of the two members, therefore the potential for jamming of the input to the rudder has not been totally eliminated. (See "Recommendations For FAA Action," Section 15. Recommendation - 15).

RUDDER CONTROL SYSTEM



B737 SINGLE FAILURES - LATERAL - AILERONS and/or SPOILERS DEFLECTED (see NOTE) TABLE 1

ITEM #	COMPONENT PART NAME	FAILURE CONDITION	FAILURE CONSEQUENCE(S)	ADs, SBs, SLs, ASRSs, NTSB REC., SDRs	RECOMMENDATION(S) or COMMENTS
1	Any Component Between Columns And Rear Spar Aileron Quadrant or Spoiler Quadrant	Any Component Jams During a Large Control Wheel Input	Flight Control Through Transfer Mechanism Difficult Because Of High Wheel Forces	AD=93-01-27, SB=27-1033, -1154, -1125, -1164 SDR= 88051600032	Reduce Transfer Mechanism Force Required. Ref. Sect. 15. Rec. -8, -19
2	Any Component From Quadrant To The Feel And Centering Unit	Jams	In Worst Case, Ailerons Could Jam at Full Deflection	AD=88-07-04, SL= 27-57,-16: SB 27-1134, -1155 SDR= 91012500143	Determine if Protection for Flight Control Components in Wheel Well is Required. Ref. Sect. 15 Rec. -10
3A	Aileron PCU Input Link	Jams	Ailerons Could Go to Full Deflection	Soft Cover Installed SB = 52-1091	Evaluate Jam Potential and Eliminate as Required- Ref. Item 2 Above
3B	Aileron PCU Spool Valve	Both Spools Jam (dual failure)- Potential Cause Filter Burst	AileronCould Go to Full Deflection if Jams are not Cleared	SB = 29-1062, SL = 27-30, -71a SDR = 5 On PCU - Leaks, Heavy Forces	Incorp SB 29-1062 Ref. Sect 15. Rec. -4
4	Spoiler Mixer	Internal Components Become Jammed	Reduced Lateral Control - High Control Force And High Drag	None	None
5	Spoiler System	Cables Break	Loss of Performance On Takeoff	AD = 93-01-27, SB = 27-1164, - 1125, -1018, NTSB Rec. #A93-133,134,135 = Charlotte Incident SDR = Several Found, 8905300315 - One Involved Cable Misrouting; Others Involved Cable Breaks	Develop training to ensure flightcrew awareness of failure condition. Ref. Sect. 15. Rec. -19
6	Aileron Autopilot Engage Mechanism (-200 Only)	Cam-Out Mechanism Fails	a. Autopilot Hardover Results In Full Deflection Of Aileron (dual failure) b. Aileron Jam	SL = 27-4	Develop training to ensure flightcrew awareness of failure condition. Ref. Sect. 15. Rec. -19
7	Aileron Cables	Cables Break Or Jam	Single Aileron Hardover	NTSB Rec. A94-064,065,066	More Thorough Inspection Per NTSB A94-065 Ref. Item 2 Above Ref. Sect 15.Rec. -23, -24

NOTE: Failure Consequences, column 4, are for worst case condition and are not necessarily uncontrollable and may be extremely improbable. Identified references in column 5 may not directly relate to the specific failure but are included because of similarity of components, materials, etc. The failure condition, column 3, is as defined by the Boeing certification data provided to the CDR Team.

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B737 SINGLE FAILURES - DIRECTIONAL - RUDDER DEFLECTED (see NOTE) TABLE 2

ITEM #	COMPONENT PART NAME	FAILURE CONDITION	FAILURE CONSEQUENCE(S)	ADs, SBs, SLs, ASRSs, NTSB REC., SDRs	RECOMMENDATION(S) AND/OR COMMENTS
1A	Comp From Pedals To Torque Tube AFT	Component Or Cable Breaks Or Disconnect	Loss Of Rudder Function When Needed	None	None
1B	Comp From Pedals To Torque Tube	Component Jams, Rudder Remains in Last Commanded Position	Pilot-Induced Rudder Offset At Full Deflection If Commanded	AD = 93-01-27, SB = 27-1125, -1154, -1164, -1075	Comply With Service Bulletins. Ref.-Sect. 11.
2	Rudder MPCU Input/Feedback Linkage Jams	Linkage Becomes Jammed In Other Than Neutral Position	Uncommanded Rudder Deflection	SB = 27-1064	Train Flightcrews for Upset Maneuvers. Ref.-Sect.15. Rec. -19
3	Yaw Damper Internal Sum Linkage	Jam in Servo Valve Open Position	Uncommanded Rudder Deflection >3 Degrees		Conduct Rudder PCU Tests to Determine Jamming Potential Ref. Sect. 15. Rec. -12, -13
4	Rudder Torque Tube	Torque Tube Jams, Rudder Remains in Last Commanded Position	Pilot-Induced Rudder Offset At Full Deflection If Commanded.	SL = 27-57, -16	None
5	Rudder MPCU Servo Valve	Jams With Improper Tolerances or Both Spools Jam	Uncommanded Rudder Displacement	AD = 80-07-02, 94-01-07; SL 27-83, -82b, -091, -SB = 29-1062; SL 27-71A, NTSB - A-92/118/120/121	Increase Chip Shear Force Sect. 15. Rec. -4
6	Standby Rudder System	Input Linkage Or Valve Becomes Jammed	Uncommanded Rudder Deflection (But May Be Recoverable Via Feel/Centering Unit And Pilot)	SL= 29-8, NTSB = A-91-077	Redesign Input Crank Bearing Sect. 15. Rec. -15
7A	Yaw Damper Coupler, Including Rate Gyro	Electrical Anomalies or Rate Gyro Failures	Uncommanded 3 degree Rudder Deflection (Steady or Oscillatory)	ASRS = 3 Reports Of Yaw Damper Anomalies, SDR = 25 Reports - About 50 % Due To Yaw Damper Coupler	Reduce Failure Rate Ref. Sect. 7.c.(5) and 15. Rec. -14
7B	Yaw Damper Transfer Valve, LVDT and Solenoid Valve	Electrical / Hydraulic Anomalies	Uncommanded 3 degree Rudder Deflection (Steady or Oscillatory)	ASRS = 3 Reports Of Yaw Damper Anomalies, SDR = 12 reports, Improved version solenoid valve applicable to rud PCU Spec No. 10-60881-8, -13	Reduce Failure Rate Ref. Sect. 7.c.(5) and 15. Rec. -14
8	Rudder Bus Bar	Rudder Bus Bar Breaks Or Becomes Separated	Failure Could Produce Confusing Rudder Pedal Indications Leading To Pilot-Induced Unwanted Rudder Deflection	None	Flightcrew Awareness. Ref. Sect. 15. Rec. -19
9	Rudder Cables	Cables Severed Due to Rotor Burst	Loss Of Rudder Function When Needed	None	Team Believes Single Cables Do Not Minimize Hazard of Rotor Burst. Ref.Sect.15. Rec. -3

NOTE: Failure Consequences column 4, are for worst case condition and are not necessarily uncontrollable and may be extremely improbable. Identified references in column 5 may not directly relate to the specific failure but are included because of similarity of components, materials, etc. The failure condition, column 3, is as defined by the Boeing certification data provided to the CDR Team.

10. LATENT FAILURES (TABLES 3 AND 4): The CDR Team identified a number of latent failure conditions for both the lateral and directional axes. The failure conditions identified in Tables 3 and 4 were not designed to be self-explanatory. No attempt is made in this report to explain the system details sufficiently for the reader to fully understand the failure condition. The certification data provided to the Team by Boeing provides the details of each failure condition. The tables are only provided to indicate those latent failures considered.

a. Lateral/Directional System Latent Failures - The failure conditions identified herein include worst case consequence of the failure, any "associated" service history, and recommended actions.

The "associated" service history shown in Tables 1 and 2 under the column labeled "ADs, SBs, SLs, ASRSs, NTSB REC., SDRs" includes all the references that the Team felt indicated that this type of failure could occur or had occurred. Some of the referenced documents are not directly related to the failure indicated in that row of the table. For example, if the failure is a cable break or jam, documents referring to a cable break or jam on a B737 may be included even though the cable involved is different from the cable for which the row item was created.

The Team was not able to identify any latent failures that would result in a direct hazard. The latent failures, when combined with the next worst failure in the component or related system, did result in a hazardous condition as defined in Section 4.b.(5). Because of the potential for hazardous condition, the Team believed that it was necessary to establish a means to determine if the latent failure had occurred. The Team reviewed the MPD, MRB, and some operator programs for the kinds of inspection tasks and intervals recommended regarding this determination. It appears no standard was applied when the frequency of inspection was determined for the identified failed components. In some cases there is no inspection task, or the task is not sufficient to reveal the latent failure. (See "Maintenance Issues," Section 11.)

b. Latent Failures in Control Valves - The Team has some general concerns regarding the design of the aileron and rudder PCUs, specifically, the use of the dual spool servo valves, bypass valve function, and potentials for jamming as a latent condition of the PCU.

As qualified by Boeing, the rudder PCU dual concentric valve (Table 4, Item 2C) was intended to prevent unacceptable rudder deflection after a single slide jam. In the worst case single jam, the dual concentric valve will counteract the jammed open slide and allow aerodynamic loads to trail the rudder in a minimally deflected position. In the best case single jam, the dual concentric design provides full rudder capability available at 1/2 the maximum rate. The dual concentric arrangement does play a vital part in maintaining flight safety. (See "Recommendations For FAA Action," Section 15. Recommendation -20, -21, -22). Consequently, the crew should be assured that they have a properly operating valve assembly. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17).

In addition, the requirement to periodically cycle the standby rudder actuator with the standby hydraulic system activated should be reviewed. Considering the importance of the standby system, in particular the standby rudder PCU, periodic cycling of the system is necessary to ensure proper operation of the actuator, to flush any contaminants (chemical or particulates) from the actuator, to prevent corrosion and binding, and to lubricate the seals. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17, -18).

LATENT FAILURES- LATERAL - AILERONS and/or SPOILERS DEFLECTED (see NOTE) TABLE 3

ITEM #	COMPONENT PART NAME	FAILURE CONDITION	FAILURE CONSEQUENCE(S)AFTER SECOND FAILURE	ADs, SBs, SLs, ASRSs, NTSB REC., SDRs	CURRENT MAINT. ACTIONS	RECOMMENDATION(S) AND REFERENCES
1	Aileron Transfer Mechanism	Mechanism Jams	If There Is A Jam On The Pilot's Side And The Transfer Mechanism Also Jams, Lateral Control Of Airplane Is Lost.	SB 27-1033	Measure Forces At Control Wheel; 7C	Incr. Inspection Frequency . Ref. Sec. 15.Rec. -16, -17, -18
2	Spring Cartridge	Jams	If There Is A Jam On The Pilot's Side And The Spring Cartridge Is AlsoJammed, Lateral Control Is Lost.	None	Function Check; 7C	Incr. Inspection Frequency . Ref. Sect. 15 Rec. -16, -17, -18
3	Spoiler Cables and Actuating Mechanism	Cables or Actuator Fail	Would Not Have Spoilers Available For Lateral Control When Needed After Another Failure.	SB 27-1112, SL 29-37, SDR 91011100096, 40091700300, 89052200019	Visual Inspection At 1A	Ref. Sect. 15. Rec. -16, -17,
4	Ratio Changer Input Rod	Rod Fails Or Jams	When Combined With A Jam On Pilot's Side, Copilot Cannot Move The Spoilers - Lateral Control Is Lost.	None	Visual Inspection And Lube At 1C	Ref. Sect. 15. Rec. -16, -17
5	Aileron Force Limiter	Force Limiter Fails	When Combined With Aileron Autopilot Hardover Could Become A Full Aileron Deflection Hardover.	SL 27-46 SDR= 87652900028	None	Develop Inspection Task and Interval. Ref. Sect. 15. Rec. -16, -17
6A	Aileron PCU By-Pass Valve	Spring Fails Valve Jams	If Valve Fails In Press.-On Condition, Manual Reversion Control Force Incr. Press. Off Failure Results in Loss of Function of One Actuator.	AD 80-07-02, SL 29-46, -5, -37,-SB 29-1062	Gross Leakage Check At 3C.	Leakage Check May Not be Adequate. Ref. Sect. 15. Rec. -16, -17
6B	Aileron PCU Actuator	Blocked Valve Orifice	Reduced PCU Rate Capability	SL 27-30, -71A	Gross Leakage Check At 3C.	Leakage Check May Not be Adequate. Ref. Sect. 15. Rec. -16, -17
6C	Spool Valve	Spool Jams	A Single Spool Jam Is Latent; The Next Jam Could Cause An Uncommanded Aileron Deflection.	SL 27-30, -71A	Gross Leakage Check At 3C.	Leakage Check May Not be Adequate. Ref. Sect. 15.Rec. -16, -17
7	Aileron Feel & Centering Unit	Spring Fails	If The Second Spring Fails, Zero Feel Forces Could Cause A Pilot-Induced Upset. Broken Spring (Non latent) Could Also Jam The Unit.	SB 27-1134, -1155	1C	Ref. Sect. 15. Rec. -16, -17

NOTE: Identified latent failures have no hazardous effect unless combined with a second failure condition. Identified references in column 5 may not directly relate to the specific failure but are included because of similarity of components, materials, etc.

B737 LATENT FAILURES - DIRECTIONAL - RUDDER DEFLECTED (see NOTE) TABLE 4

ITEM #	COMPONENT PART NAME	FAILURE CONDITION	FAILURE CONSEQUENCE(S) AFTER SECOND FAILURE	ADs, SBs, SLs, ASRSs, NTSB REC., SDRs	CURRENT MAINT. ACTIONS	RECOMMENDATION(S) AND REFERENCES
1	Feel And Centering Unit	Spring Fails	If Second Feel Spring Fails Pilot May Induce Large Rudder Deflection Due To No Feel and Centering	SLs = 27-57 And 27-24 Some SDRs Indicate That Some Pilots Identify This Failure.	1C - Visual Inspect	Implement Training To Expose Pilots to Consequence of Failure Ref. Sect. 15 Rec. -19
2A	PCU - Bypass Valves	Valve Jams	If Fail When Deactive Then No Force From Its Hyd. System.	AD = 94-01-07 (SL = 27-91, 27-82, 27-83)	Gross Leakage Check at 3C	Component Leakage Check (requires bottoming actuator) Ref. Sect.15. Rec. -16, -17
2B	PCU - Tandem Actuator	Blocked Press. Path On One Sys.	Lose Effort Of Related Hyd Sys.	SB 27-1060,	Gross Leakage Check at 3C	Check actuator function independent with A & B Hyd. Sys. Ref.Sect.15. Rec. -16, -17
2C	PCU - Spool Valves	Single Spool Jam Or Secondary Slide Overtravel	Next Spool Jam Or Out Of Tolerance Spool Produces Unwanted Rudder Deflection	AD = 94-01-07 (SL = 27-91, 27-82, 27-83)	Gross Leakage Check at 3C	Component Leak Check Ref. Sect.15. Rec. -16, -17 Develop check for single jam.
3A	Stdby Rudder PCU	Bypass Valve Fail In Bypass, Servo Valve Jammed, Linkage Disconnect	No Stdby Rudder Available	AD = 80-07-02, SL = 29-8, NTSB = A91-77	1C - Operational Check	Increase Check Frequency Ref. Sect. 15. Rec. -16, -17. -18
3B	Stdby Rudder Shutoff Valve Including Auto Stdby Function	Shutoff Valve Fails	Fail on: Next Failure Pump On, Result In Greater Rudder Deflection Capability When In Blow Down Region. Fail-Off: No Stdby When Required	SL = 29-8	1C - Operational Check	Increase Check Frequency Ref. Sect. 15. Rec. -16, -17
3C	Stdby System Pump	Pump Fails	No Stdby Rudder Available	SL = 29-8	1C - Operational Check	Increase Check Frequency, Ref. Sect. 15. Rec. -16, -17

NOTE: Identified latent failures have no hazardous effect unless combined with a second failure condition. Identified references in column 5 may not directly relate to the specific failure but are included because of similarity of components, materials, etc.

11. MAINTENANCE:

a. Maintenance Review Board and Maintenance Planning Document - The Team reviewed the inspection intervals and related maintenance tasks for each identified latent failure mode. The Maintenance Review Board Report (MRB) approved by the FAA and the Maintenance Planning Document (MPD) developed by Boeing, were used as the primary references in the review. These documents are used by operators and the FAA in development and approval of an initial maintenance program. The Team also met with the FAA MRB Chairman to discuss the history of the B737 MRB.

The MRB outlines the initial minimum maintenance and inspection requirements established jointly by the manufacturer, operators, and the FAA. The MRB document was originally released in 1967 and revised in 1971. The MRB document was revised again in 1983, concurrent with the introduction of the B737-300, but no changes were made to equipment common to the B737-100/-200. The current Revision 5 was released in December 1993.

The MPD supports the MRB and provides the manufacturer's maintenance recommendations. There are two versions of the 737 MPD to address the -100/-200 models and the derivative -300/-400/-500 models, respectively. The Boeing document identification and revision status are D6-17594, Rev. P, for the -100/-200, and D6-38278, Rev. R, for the derivative models. The -100/-200 models MPD is no longer amended.

The original MRB and MPD did not use any formal analysis for the development of the inspection intervals, processes, or tasks. There are two formal methods in use today which were developed by the Airline Transport Association (ATA) and the FAA referred to as Maintenance Steering Group (MSG) logic 2 and 3. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17, -18).

When applied to a particular aircraft type, the MSG-2 logic results in a list of "maintenance significant items." Each of these items is assigned one or more of the three processes defined below:

(1) On-Condition (OC) is a preventative process that requires a component or part to be periodically inspected or checked against some standard to ensure that it can remain in service.

(2) Hard Time (HT) is a preventative process that requires a component or part be removed from service for overhaul or disposal.

(3) Condition Monitoring (CM) is not a preventative process and allows for failures to occur. It relies upon analysis of operating experience and failure trends to identify corrective action that would preclude continued unsatisfactory performance of a system or part. This process can only be applied to those items which have no direct adverse affect on safety and have no hidden functions (when malfunctions would not be evident to the flightcrew).

MSG-3 logic results in a maintenance program consisting of tasks under specific headings. It does not use any of the MSG-2 processes (OC, HT, or CM). Boeing conducted an independent analysis using MSG-2 to support the introduction of Condition Monitoring in Rev. B (1975) to the MPD. Later revisions to the MPD that incorporated the -300/-400/-500 models utilized both the MSG-2 and MSG-3 procedures. MSG-2 analysis was used for components or systems peculiar to the B737-300/-400/-500 and MSG-3 analysis was used for the engines and new structures.

The MRB Report is not revised every time the MPD is revised. In fact, the MRB has not been revised for those items that are common to all B737 models since the 1971 revision. The later revisions that incorporated the -300/-400/-500 models only incorporated those MPD tasks and intervals that were developed under MSG-2 and MSG-3 for those components, systems, engines, and structures which are peculiar to the derivative models with respect to the -100/-200. Therefore, the MRB is out of date regarding many, if not most, of the components on the B737. New operators normally request that they be permitted to use some fairly recent version of the MPD that is compatible with the modification status of their aircraft as a starting point for their maintenance program rather than using the MRB.

Inspection intervals used in the MRB and MPD are commonly referred to as "letter checks" and they correspond to aircraft utilization in either hours or cycles. The current intervals are 200 hours for A checks and 3200 hours for C checks. Originally, B and D checks were also specified, but these checks and their tasks are now included as multiples of the A and C intervals. For example, D checks are now identified with 7C intervals which corresponds to 22,400 hours as opposed to 9000 hours when the MRB was originally approved. See "Recommendations For FAA Action," Section 15. Recommendation -16, -17 regarding the concern for escalating inspection intervals in consideration of the criticality of the latent failure.

b. Maintenance Issues Pertaining to Latent Failures- The following tables identify the latent failures and related MPD maintenance tasks with inspection intervals. Also included is the maintenance action for each failure. MRB items are not shown because they do not address all components of the current aircraft and are frequently out-of-date, as explained above.

DIRECTIONAL LATENT FAILURES - MAINTENANCE ACTIONS/FREQUENCY

FAILURE	MPD FREQ.	MPD TASK	MAINTENANCE ACTIONS/COMMENTS
Feel And Centering Unit	1C	B27-21-00A4	Visually Inspect For Condition And Security. / May Not Be Latent Because 1/2 Pedal Force May Be Detected.
Rudder PCU (Includes Spool Valve, Actuator, And By-Pass Valve)	3C	B29-00-006A	Some Failure Modes Are Not Detectable By The Internal Leakage Test. / May Not Detect High Internal Leakage Because Test Does Not Isolate Components. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17).
Standby PCU	3C	B29-00-006A	Internal Leakage Test Of Hydraulic Systems. / Would Detect High Internal Leakage Because Test Does Isolate Components.
Standby Rudder System (Including Pump And Valve)	1C	B27-21-84-2A	Operational Check Of The System. / This Includes Moving The Rudder.

LATERAL LATENT FAILURES - MAINTENANCE ACTIONS/FREQUENCY

FAILURE	MPD FREQ	MPD TASK	MAINTENANCE ACTIONS/COMMENTS
Aileron Transfer Mech.	7C	B27-11-05B	Functional Check ./ Measure Forces at Control Wheel.
Aileron Spring Cartridge	1C And 7C	B27-00-00-D B27-11-05B	Visually Inspect For Conditions and Security. / Functioned In Conjunction With Aileron Transfer Mechanism
Aileron Feel And Centering Unit	1C	B27-00-00-D	Visual Inspection For Condition And Security. / May Not Be Latent Because 1/2 Forces At Control Wheel May Be Detected.
Aileron Bus Drive Cables (Right Hand Body)	3C	B20-20-31	Inspect For Condition. Clean And Lube. / May Not Be Latent Because Wheel Offset May Be Detected By Flightcrew.
Aileron PCU	3C	B29-00-00-6A	Internal Leakage Test of Hydraulic Systems. / Some Failure Modes Not Detectable By Internal Leakage Test. May Not Detect High Internal Leakage Because Test Does Not Isolate Components. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17).
Spoiler Cables and Actuators	1A	B27-60-00A B53-14-00-A	Visually Inspect Spoilers And Actuating Mechanism At Wing Location and Check Wheel Well For Condition And Security Including Cables. / None.
Ratio Changer Input Rod	1D	B27-00-00D	Visually Inspect For Condition And Security. / None.
Aileron Force Limiter	None	None	None. / Possible Failure Modes Could Allow An Autopilot Hardover To Be A Full Deflection Hardover. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17).

c. Discussion of Table Items -

(1) Some of the task intervals are excessive, particularly in the hidden function alternate systems such as the standby rudder, aileron transfer mechanism, and aileron spring cartridge. The relationship between task intervals and exposure to latent failures is unclear.

(2) Although the MRB and MPD do specify tasks that could identify latent failures, nothing prevents task interval escalation or possible deletion by operators based on their particular experience, reliability, and local FAA approval.

(3) The MRB originally Hard-Timed the PCUs at 12,000 hours and subsequently allowed "On-Condition." The MRB (Rev. 2, 1971) specifically made reference to the accomplishment of an internal leakage flow check. It also made reference to the component leakage rate which is no longer accomplished, as the MPD task is now a gross internal leakage test. The gross internal leakage test would not detect all latent failure modes within the PCU and, in some cases, may not detect excessive leakage rates. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17, -18).

d. United States Air Force (USAF) Maintenance Philosophy - Maintenance practices in the USAF are driven by regulation. Each Major Command (MAJCOM) is responsible for setting up a maintenance program which meets the minimum requirements. A typical maintenance organization includes: Quality Assurance, Safety, Maintenance Operations Center, Flight Line Maintenance, Inspection Section, Field Maintenance (e.g., airframe, powerplant, hydraulic and electric shops, etc.) and Avionics/Instrument sections.

Phase inspections are equivalent to a C check and Programmed Depot Maintenance to a D check. Special inspections are typically driven by Time Compliance Technical Orders (TCTO) and can be one time or repetitive in nature. Air Force aircraft that are common to commercial operators, comply with FAA A.D.'s through the TCTO program. Compliance with Service Bulletins is driven by the Quality Assurance office at the unit level.

Following a review of the USAF T-43 maintenance program and practice, it was established that flight controls are given particular attention daily by accomplishing complete flight control and standby system checks with a ground observer present. This practice is also true for all transports operated by USAF.

12. HYDRAULIC FLUID CONTAMINATION: The Boeing material specification that defines the hydraulic fluid used in the B737 hydraulic power control systems is BMS 3-11. The currently recommended formulation of this fluid is Type IV Class 1 or 2 (SAE particulate contamination method NAS 1638 - fourteen classifications starting with 00 as the least contaminated). The Type IV fluid contains additives to prevent the erosion of hydraulic valving components that was evident in fluids of the earlier specification. This fluid is currently used in all the Boeing commercial aircraft as well as in commercial aircraft of other manufacturers.

a. Hydraulic Fluid Manufacturers - Manufacturers of hydraulic fluids are Monsanto (Skydrol LD-4 and Skydrol 500B4) and Chevron (Hyjet IV A Plus). Significant performance degradation and component damage can occur if the hydraulic fluid chemical properties are not maintained. The hydraulics section of the Maintenance Manual provides inservice limits of the chemical properties. Boeing does not require/recommend control of the particulate matter in the aircraft inservice hydraulic systems, but limits particulates through filtration. Boeing does ensure that the particulate count in the hydraulic systems of newly delivered aircraft meets the cleanliness requirement of NAS 1638 Class 9. Douglas Aircraft controls all in-house aircraft hydraulic fluid system to a particulate level of Class 8.

b. Filters Size - The hydraulic systems and components in the B737 contain a suitable number of filters. They are located and sized to ensure particulate control. The pressure and return filters are equipped with elements rated at 15 micron absolute. The return filters are equipped with differential pressure indicators to provide visual indication of impending filter by-pass. The case drain line filters are rated as 25 micron absolute. The ground servicing module on the airplane is equipped with a 15 micron filter to ensure filtered fluid when the systems are serviced by a ground cart. A 3.0 micron filter is included in the reservoir fill circuit. In addition, a 15 micron filter is included in the power transfer unit.

c. Filter Replacement - Boeing has established the following replacement intervals for the filter elements:

A & B Hyd. Systems	Interval	Standby Hyd. System	Interval
EMP & EDP Pressure Filters	1C	Pressure Filter	1C
Return Filters	8A	Case Drain Filter	1C
EMP Case Drain Filters	3A		
EDP Case Drain Filters	8A		
Gnd Service Filters	2C		

Power Transfer Unit Filter	1C
Reservoir Fill Filter	1C

The individual power control units are also provided with particle filtration at the pressure inlet with additional filtering provided for the fluid supplied to the yaw damper or auto pilot electro-hydraulic servo valves. Filter ratings vary depending on the particular unit and application. The filter units are customarily cleaned and replaced at component overhaul.

d. Fluid Sampling - Boeing does not have a general fluid sampling schedule but recommends that the operator and the fluid manufacturer determine fluid sampling intervals. Boeing's position is that the airlines and fluid manufacturers are in the best position to determine the fluid sampling intervals for a particular operator, given the operating environment. Both Monsanto and Chevron offer no-charge fluid analysis to the airlines. In contrast, Douglas Aircraft recommends specific hydraulic fluid sampling intervals for their aircraft. Douglas Aircraft maintenance manual limitations for particulates are per NAS 1638 Class 9. See "Recommendations For FAA Action," Section 15. Recommendation -4, regarding standardization of hydraulic fluid sampling and contamination levels.

e. Fluid Recycling - Boeing Service Letter 737-SL-29-50, dated January 10, 1991, discusses and authorizes a "Pall Land and Marine" purifier to recycle the BM 3-11 hydraulic fluid to remove water, air, and chlorinated solvents. It uses a vacuum and moderate heating, and will not degrade or remove the special additives in Type IV fluid formulations.

13. AUTOPILOT: The B737 autopilot examination was limited in scope to the lateral and yaw axes. The pitch axis was not considered, as explained in Section 4.

A brief review of the autopilots used on the various B737 models was conducted. Particular attention was given to failure modes. The roll and yaw autopilot authority is limited by the primary flight control system, and all autopilot "hardover" failures are contained by the limiting devices in the primary flight control system. The Team has concluded that an autopilot malfunction is not a hazardous occurrence, and could not be a primary cause for loss of control of the aircraft without a failure of the mechanical/hydraulic limiting devices. Two of these limiting devices have been identified by the Team as having potential failure modes that could be "hazardous" and are discussed as follows:

a. Aileron Force Limiter - The aileron force limiter (Ref. Table 3, Item 6) is required to function to limit the severity of an autopilot malfunction that results in a "hardover" signal to the aileron PCU transfer valve (-100/-200) or one of the two autopilot actuators (-300/-400/-500). This limiter is a mechanical device, at the base of the pilot's control column, that ramps up an additional force opposing autopilot control input that feeds back to the control wheel. On the -100/-200, this device limits lateral control input from the autopilot to either 17° or 24° of control wheel rotation, depending on whether the aircraft is Civil Aviation Authority (Great Britain) certified or FAA certified, respectively. On the -300/-400/-500, a similar device has a dual mode capability that is switched electrically by the flap position. This limits the autopilot authority to 17° of wheel, flaps up, and 25° of wheel, flaps down.

Boeing performed a failure analysis of the force limiter for the -300 certification which showed a probability of failure of the force limiter that would allow greater than 17°/25° authority of 2.0×10^{-6}. When combined with the probability of a hardover command occurring, which was estimated to be 5.4×10^{-5} and a detection probability of 0.5, this produced a probability of 5.4×10^{-11} that a single channel roll hardover with excessive authority would occur. While this probability is very remote, it is dependent on the function of many components in the force limiter. As shown in the Lateral Latent Failures Table in Section 11, the aileron force limiter presently has no required or recommended maintenance inspections or tasks. The Team believes that inspection tasks and intervals should be established for vital components whose latent failure could have hazardous consequences, even though a failure analysis has shown a numerical probability of failure that allows the component to go uninspected for the life of the airplane or until an "on-condition" overhaul. (See "Recommendations For FAA Action," Section 15. Recommendation -16, -17, -18), regarding inspection intervals and tasks for identified latent failures.)

b. Autopilot Force Limiter - The autopilot force limiter functions to limit the autopilot authority through a "cam-out" mechanism that disengages the autopilot servo(s) input on the -300/-400/-500, and releases the main servo valve so that it cancels the transfer valve (autopilot) input on the -100/-200. This same mechanism allows the pilot to overpower the autopilot. Protection from jamming of this "cam-out" device is provided by a shear-out device on the -300/-400/-500. No such protection is provided on the -100/-200.

Failure of this engage/cam-out device in the aileron PCUs on the -100/-200 to release or disengage could result in either an autopilot induced full deflection hardover (with a hardover electrical signal) or inability of the pilot to make control wheel inputs to the PCU. The pilot could alleviate a "hardover" by disengaging the autopilot with the control wheel disconnect switch. However, he still would be unable to make control wheel inputs to the PCUs (they would be locked in the neutral position). The crew's alternatives would be to control the airplane from the copilot's wheel via spoilers through the transfer mechanism, or to turn off both "A" and "B" hydraulics and utilize manual reversion. If no autopilot electrical anomaly (e.g., hardover) had occurred and only the engage/cam-out device had failed to disengage, the airplane could be flown utilizing the autopilot.

Because of the crew choices and possible confusing nature of this failure scenario, the Team believes it is a crew training issue. (See "Recommendations For FAA Action," Section 15. Recommendation -19). Also, this is one example of a frequently occurring issue in the original Boeing certification data where an action item resulting from the analysis was not carried through to either the Airplane Flight Manual (AFM) or the Operations Manual. Consequently, the flightcrew is not informed of all of the factors necessary to make the best decisions necessary to continue safe flight and landing. (See "Recommendations For FAA Action," Section 15. Recommendation -5, -6, -7).

14. ICING: Loss of control of the aircraft due to airframe ice contamination was not investigated by the CDR Team. The reports of all the accidents or incidents that precipitated the review did not indicate that icing conditions were prevalent or suspected of being involved. The Team did identify and evaluate several incidents of freezing of the control mechanisms (i.e., trim, feel, and centering) or complete aileron system. The trim (Ref. App. 4, .SB 27-1053, SL 27-16 and 27-48) and feel and centering units (Ref. SL 27-24 and 27-57) freezing incidents were relatively minor. The incident when there was a complete freezing of the aileron system was due to the accumulation of rain while the airplane was on ground. The rain then froze as the airplane climbed to altitude. When the aircraft returned to warmer temperatures the situation was alleviated. None of the incidents reviewed by the Team involved icing while airborne.

15. RECOMMENDATIONS FOR FAA ACTION: As a result of having conducted the B737 flight control system critical design review, the Team believes there are a number of Action items that should be addressed by the Seattle Aircraft Certification Office (SACO), the Transport Airplane Directorate Standards Staff (TSS), Aircraft Engineering Division (AIR-100) or Flight Standards Service (AFS) as may be appropriate to any particular or all models of the B737. Prior to the completion of any plans for implementation of these recommendations, the CDR Team will assist the affected FAA offices regarding any required clarification of the intent behind each recommendation. Also, the CDR Team will review specific actions undertaken in response to these recommendations to ensure that they are what was intended and that final action satisfies the recommendations. The recommendations and FAA action include regulatory interpretive material, certification processes, design features, and continued operational safety issues.

REGULATORY INTERPRETIVE MATERIAL

FAR § 25.671 refers to "normal flight envelope," "exceptional piloting skill and strength," and "control position normally encountered" regarding jams in a flight control surface. The CDR Team believes the interpretations that have been applied in the past, regarding amount of flight control input to be considered in showing compliance with the referenced regulations, may not be sufficient. Section 5.b. discusses the rationale for the following recommendation:

Team recommends that TSS:

RECOMMENDATION -1

develop national policy and or rule making as necessary and applicable to transport category airplanes that defines "normal," with respect to jams. This definition should include consideration of a jam of a control surface at any position up to its full deflection as limited by design, and

RECOMMENDATION -2

develop national policy requiring that, when alternate means for flying an airplane are employed, those means shall not require exceptional pilot skill and strength and that the pilot can endure the forces for a sufficient period of time to ensure a safe landing.

Because both primary and standby elements of the directional control system are exercised through only one set of cables, the only alternate means for rudder control after a cable failure is rudder trim. Assuming a rotor burst severs the rudder cables during a critical phase of flight, the Team believes rudder trim is not a suitable alternative for directional control after such an event. Also the Team believes, based on its engineering judgment, that a single set of cables does not constitute minimization of the hazard after a rotor burst in accordance with FAR § 25.903 Amendment 25-73. It is understood that the certification basis of the B737-100/-200 did not include this requirement because it did not exist at the time. The B737-300/-400/-500 did show compliance to the referenced rule, but used earlier policy that allowed a probabilistic analysis including event exposure time.

The CDR Team recommends that TSS:

RECOMMENDATION -3

formally establish the transport category airplane requirement for redundancy in the directional control system to maintain control in the event of a rotor burst for the most critical phase of flight. Determine whether or not this requirement should be applied to new type certificate applications, derivative applications or aircraft in production.

The sensitivity of hydraulic components (including actuators and their controlling elements) to chemical or particulate contamination has not been fully established. Section 12 provides the rationale for the following recommendation:

The CDR Team recommends that TSS:

RECOMMENDATION -4

develop national policy for transport category airplanes requiring the determination of critical hydraulic flight control system and component sensitivity (jam potential and actuator performance) to contamination, requirements for sampling hydraulic fluid, and requirements for actuator components to eliminate or pass (shear) particulate contamination.

CERTIFICATION PROCESS

Following the review of the certification data for the B737 flight control system, the Team determined that there needs to be a review of the failure analysis action items (flightcrew actions that should be taken in response to a failure or failure scenario). Some action items are impractical, and the methods for their implementation are unclear. One of the reasons for accepting some failure analysis is that there is an action item that alleviates the hazard of the failure. Section 13.b. provides an example of this issue and discusses the rationale for the following recommendation:

The CDR Team recommends that TSS:

RECOMMENDATION -5

develop and provide additional guidance in AC 1309-1A confirming that transport category airplane failure analysis action items are required flightcrew procedures in response to the failure condition,

RECOMMENDATION -6

require the action items be practical and

RECOMMENDATION -7

establish process in cooperation with AFS to require flightcrew action items be implemented or require revision of failure analysis to not require action item.

DESIGN ISSUES

The Team found through familiarization with design, review of the certification data, and the experience in the "M" Cab simulator exercise that, in the event of a full aileron jam, the aileron transfer mechanism force level, as would be exhibited in the airplane, substantially exceeds the temporary and prolonged force limits of FAR § 25.143. Consequently, there is no assurance of continued safe flight and landing in the event of an aileron jam when deflected at greater than neutral. Section 5.b. discusses the basis for assuming the jam of the aileron at its full deflection in support of the following recommendation:

Team recommends that SACO:

RECOMMENDATION -8

review the adequacy of the B737 aileron transfer mechanism throughout the airplane operating envelope in the event of a sustained jam of the ailerons up to their limit deflection. Pilot skill and strength requirements should be consistent with the results of RECOMMENDATION -2. Control margins from this condition should be sufficient to allow continued safe flight and landing, including necessary maneuvers such as a crosswind landing or go-around.

As presented in Section 9 and 10, there are potential single failures and combinations of latent and single failures that can cause a hardover or jam of the rudder at its limit deflection. The alternate means of directional control in the event of these failures is the lateral control system.

CDR Team recommends that SACO:

RECOMMENDATION -9

ensure that the capability of the B737 lateral control system to provide adequate directional control is clearly demonstrated throughout the airplane operating envelope after these failures, unless they are shown to be extremely improbable by the most rigorous methodology available.

NOTE: The failure analysis criteria presented in the June, 1994, Criteria Document for Failure Assessment of Thrust Reversers on the Existing Turbojet Fleet is one example of "rigorous" probability analysis methodology, particularly regarding latent failures.

There are a number of vital, lateral control system components, including major elements of the two main hydraulic systems and the standby hydraulic system, in the main wheel well. Although there have been tests showing limited or no damage to vital components as a result of tire burst, there appears to be no attempt to protect these components from environmental debris. The wheel failure event identified in Section 7.b. was a wheel based on TSO-C26, prior to revision C. A subsequent TSO revision, TSO-C26 Rev. C, results in a wheel of higher integrity. Section 7.b. provides further rationale for the following recommendation:

The CDR Team recommends that SACO:

RECOMMENDATION -10 **determine the requirement for and the feasibility of incorporating additional means to protect these components in the main wheel well of the B737 from the effects of environmental debris and**

RECOMMENDATION -11 **ensure the incorporation of wheels based on TSO-C26 Rev. C or later revision.**

The yaw damper mod piston and internal summing linkage is a vital part of the control of the main rudder PCU servo valve. By design, the internal summing linkage is redundant and combines the mod piston motion with the follow-up linkage motion so that rudder displacement produced is limited to three degrees. However, failure modes in these elements that would cause the main servo valve to be held open would result in a rudder hardover. The CDR Team believes that all the failure modes of this mechanism have not been fully examined. Section 9 provides further discussion of this subject.

The CDR Team recommends that SACO:

RECOMMENDATION -12 **require failure analysis of the B737 yaw damper identified components and any relevant tests be conducted to identify all failure modes, malfunctions and potential jam conditions of these vital elements and**

RECOMMENDATION -13 **require corrective action(s) for those failure modes or malfunctions not shown to be extremely improbable.**

Yaw damper malfunctions have an unsatisfactory rate of occurrences (failures occurring in the transfer valve, linear variable differential transformer, yaw damper coupler, etc.). Section 7 (Honeywell visit) and Section 9, paragraph b. and Table 2, provide information on number and kinds of failures of the yaw damper and concern regarding its reliability.

The CDR Team recommends that SACO:

RECOMMENDATION -14 **require appropriate action be taken to reduce the number of B737 yaw damper failure occurrences to an acceptable level.**

The standby rudder rotary input crank has experienced galling of the journal bearing. An attempt was made to eliminate the condition but it continues to persist although to a lesser degree. The standby rudder PCU input linkage and/or internal components have been identified as potential initiating causes for an uncommanded rudder deflection. Section 9. provides further information regarding concern for this issue.

The CDR Team recommends that SACO:

RECOMMENDATION -15 **require appropriate action be taken to correct the referenced galling condition of the standby rudder on the B737.**

CONTINUED OPERATIONAL SAFETY ISSUES

The Team believes that continued operational safety is an important extension of the certification process. Within the scope of operational safety, there are a number of considerations, i.e., adequacy of the maintenance tasks and associated intervals, incorporation of relevant Service Bulletins and Service Letters and the sufficiency of the training and awareness of the flightcrews regarding need for prompt and correct response to failures and flight path upset conditions.

As a condition for the continued suitability of the flight control system and its alternate flight control capabilities, certain inspection and checking requirements should be reviewed, revised, and controlled to ensure the integrity of the flight control system. Sections 11. and 13.a. provide the rationale for the following recommendation:

The CDR Team recommends that SACO, in conjunction with AFS:

RECOMMENDATION -16

review and revise, as appropriate, the B737 inspection tasks associated with the latent failures identified in Tables 3 and 4 in Section 10. in accordance with MSG-3 and

RECOMMENDATION -17

require the identified latent failures have fixed interval inspection frequencies as provided by AC's 25.1309-1A and 25-19. Consideration should be given to interval ranges flexible enough to allow normal inspection schedules.

The latent failures identified in Tables 3 and 4 in Section 10 were reviewed regarding suitability of inspection tasks and intervals. Some of the items, because of their criticality, were evaluated by the Team in some detail and were determined, by analysis, to have excessive inspection intervals as provided by the current MPD and/or inadequate required inspection tasks.

The CDR Team recommends that SACO, in conjunction with AFS:

RECOMMENDATION -18

revise the B737 MRB/MPD inspection task description and interval for the following latent failures-

LATENT FAILURE	RECOMMENDED INSPECTION INTERVAL	TASKS
AILERON TRANSFER MECHANISM	≤1C	OPERATIONAL CHECK
	≤ 3C	MEASURE FORCES AT WHEEL
AILERON SPRING CARTRIDGE	≤1C	OPERATIONAL CHECK CONDUCTED WITH THE TRANSFER MECHANISM INSPECTION
STANDBY HYDRAULIC SYSTEM INCLUDING RUDDER FUNCTION	≤1A	OPERATIONAL CHECK

The "M" CAB flight simulator exercises identified that prompt pilot recognition and correct response were essential to successful recovery from several flight control malfunctions. Section 8, Appendix 3 of this document, and NTSB recommendation A-73-073/074 in Appendix 8, provide further rationale for the following recommendation:

The CDR Team recommends AFS, in coordination with SACO:

RECOMMENDATION -19

revise B737 flightcrew training programs to ensure the use of the proper procedures for recovery from flight path upsets and flightcrew awareness regarding the loss of airplane performance due to a flight control system malfunctions. Consideration should be given to flightcrew action items as a consequence of the failure analysis developed for the relevant flight control system and the failure conditions/malfunctions examined in Appendix 5. (This may require Airplane Flight Manual or Operations Manual revision.)

The Team has developed an understanding of those flight control system components that are critical to proper function of the system. As identified in Sections 9 and 10 and NTSB Rec. Nos. A-92-118/-120/-121, it is essential that the PCUs and their internal components used in the flight control system perform per the design requirement. In addition the Team believes that proper maintenance, overhaul, repair and return to service of the PCUs and its components are critical to maintaining a high level of reliability which is essential for the continued operational safety of the B737 flight control system.

The CDR Team recommends that AIR-100 in conjunction with AFS:

RECOMMENDATION -20

require that only PC or PMA approved replacement parts be used when overhauling primary elements in the flight control system (hydraulic servos and bypass valves) of the B737 airplanes. Ensure replacement parts, as provided by a non-Original Equipment Manufacturer (OEM) or fabricated under SFAR 36 authority, that are used when overhauling primary elements in the flight control system have had their designs approved and processed through the ACO that originally approved the OEM parts. This means that the replacement part will have undergone qualification in terms of design (material, heat treat, dimensions, tolerances, geometric controls, etc.), analysis, and tests (qualification and acceptance) equivalent to the OEM certified part. An analysis is necessary to verify that the replacement part will mate properly with the next assembly under all design tolerance conditions.

RECOMMENDATION -21

require any issuance of PMA for primary flight control servo and by-pass valves be concurred with by the Aircraft Certification Office which certified the original parts or assembly.

The CDR Team recommends that AFS in conjunction with SACO:

RECOMMENDATION -22

form a team composed of a systems engineer, manufacturing inspector and an airworthiness maintenance inspector, to assess the repair procedures, process and tooling used in every repair station approved by the FAA to overhaul B737 PCUs and its components. In addition this team should also reassess all B737 PCU PMAs and SFAR 36 data (design, manufacturing and fabrication) approvals for adequacy in consideration of Recommendations -20 and -21.

A review of the service history regarding aileron and rudder cable failures or incidents where the cables were found to be frayed or damaged, indicates that some corrective action should be initiated. NTSB Rec. A-94-064/-065/-066, Boeing In-Service Activities Report # 88-06 and 17 SDRs identified a number of occurrences where cables have failed or were replaced because of corrosion, wear, chaffing or twisting. The FAA is currently reviewing all cases of cable failure for selected airplanes including the B737. The CDR Team has also identified in Table 1 and 2 those cases where there was concern regarding the continuing integrity of a flight control cable.

The CDR Team recommends SACO in coordination with AFS:

RECOMMENDATION -23

evaluate the adequacy of the B737 maintenance manual actions addressing flight control cable inspection, rigging procedures and replacement criteria and

RECOMMENDATION -24

require control cable service life limits unless acceptable inspection and/or test procedures are developed and utilized that can determine the continuing serviceability of the control cables.

In the process of defining failures in the lateral and directional flight control system, a number of Service Bulletins (SBs) and Service Letters (SLs) were reviewed (Appendix 4). Tables 1 through 4 of Sections 9 and 10 reference SBs and SLs related to the failure conditions. In particular, some were determined as pertinent to continued operational safety. The CDR Team believes the following selected SBs and SLs are relevant and consistent with the preceding recommendations. It is understood that in a number of cases these SBs and SLs may have been already incorporated at the option of the operator. It is believed that a greater degree of assurance is necessary regarding their incorporation.

The CDR Team recommends SACO:

RECOMMENDATION -25

determine the degree of incorporation of the following list of Service Bulletins (includes In-Service Activities Report) in the B737 fleet and, in consideration of the recommendations in Section 15, reassess their safety impact and, as appropriate, require their incorporation on applicable Models of the B737.

BULLETIN #	TITLE	DATE
B737-27-1060	Rudder Pressure Reducer and Relief Valve Inspection/Removal	3 Oct. 1972
B737-27-1033	Improvement of Lateral Control Transfer Mechanism	13 Feb. 1970
B737-27-1081	Inspection of Ground Spoiler Shutoff Valve Control Cable Assembly	10 Dec. 1976
B737-27-1125	Flight Controls, Cable Guard Modification (Pitch)	8 Mar. 1985
B737-27-1134	Flight Controls, Aileron Centering and Trim Mechanism Modification	11 Jul. 1986
B737-27-1152	Flight Controls, Aileron Trim Bracket Replacement	12 May 1988, Rev 2, 22 Dec. 1988.
B737-27-1154	Flight Controls, Aileron Pulley Bracket Inspection/Replacement	25 Aug. 1988
B737-27-1155	Flight Controls, Aileron Centering Spring and Trim Mechanism Modification	26 Oct. 1989
B737-29-1062	Hydraulic Power, Main and Auxiliary, Standby and Ground Service Pressure Filter Modification	14 Feb. 1991

B737 IN-SERVICE ACTIVITIES REPORT

Report No. 95-04-2725-10	Rudder Power Control Unit (PCU) Yaw Damper Solenoid Valve configuration for use on Rudder PCU Spec. No. 10-60881-8,-13	24 Feb. 1995

The CDR Team recommends SACO in conjunction with AFS:

RECOMMENDATION -26 **determine the degree of incorporation of the following list of Service Letters in the B737 fleet and, in consideration of the recommendations in Section 15., reassess their safety impact and, as appropriate, require their incorporation on applicable Models of the B737.**

LETTER #	TITLE	DATE
737-SL-27-16	Rudder Trim Control Actuator Lubrication	25 Aug. 1980
B737-SL-27-24	Rudder Centering Unit Lubrication	28 Jun. 1983
B737-SL-27-30	Aileron/Elevator and Rudder Power Control Unit Cylinder Bore Rework	1 Apr. 1985
B737-SL-27-57	Rudder Feel and Centering Unit Lubrication	5 Dec. 1989
B737-SL-27-71-A	Aileron/Elevator PCU Flow Restrictor Filter Screen Contamination	19 Jun. 1992

The Team has able identified a number of recommendations that it believes will improve the overall reliability and enhance the safety of the B737 flight control systems. It was unable, though to conclusively link failure mode of the flight control system to available accident investigation data from either the B737 Colorado Springs or Pittsburgh accidents. The Team feels that the investigation as to the cause of both of these accidents should continue. Through the critical design review effort, the FAA took a fresh look at the B737 flight control design and certification and believes there is merit in taking a similar fresh look at all of the data gathered on both accidents. Combining a fresh look at the accident along with the data learned from the CDR, could shed new light on the cause of these accidents.

The FAA should:

RECOMMENDATION -27 **request the NTSB form a special accident investigation team to begin a new combined investigation of both the B737 Colorado Springs and the Pittsburgh accidents. The accident investigation team should include an FAA representative from the CDR team and the NTSB aviation safety investigator that worked with the CDR team. This will ensure that all of the data from the CDR is available for review by the accident investigation team. It is further recommended that NTSB personnel on the team not be from the original accident investigation teams and that the NTSB include at least two accident investigators (one each - airplane systems and flight operation) from another competent aviation authority of the world who has experience with B737 airplane.**

Boeing 737 Flight Control System Critical Design Review Team Charter

Background and Discussion

The USAIR 737 accident near Pittsburgh and the United 737 accident near Colorado Springs have raised questions about the flight control system on the B737. Despite repeated reviews and analysis of the design, the question of whether something has been overlooked still persists. In an effort to answer this question, the FAA Transport Airplane Directorate is organizing a Critical Design Review (CDR) of the Boeing 737 flight control systems. The Team conducting this review will consist of members from FAA offices not intimately involved with the B737, the National Transportation Safety Board and other government organizations and airworthiness authorities. The Team will examine the assumptions of previous reviews and develop new analysis as needed to thoroughly examine all aspects of the control systems as described in the Team Objectives below. The overall Team objective is to confirm the continued operational safety of the Boeing 737 or, if deficiencies are found in the design of the B737, make recommendations on the course of action that will correct those deficiencies.

Team Objectives

1. The Team, in coordination with Boeing engineers and other sources of information and guidance, will develop an airplane level hazard analysis of the flight control systems of the 737 airplane. Further, the analysis should identify all catastrophic and major hazard events, considering Advisory Circular (AC) 1309-1A, which could occur as a result of failure or malfunction of any single, or combination of, 737 flight control system part(s), sensor(s), power supplies or related crew display(s). In developing this analysis, the Team should assume the worst case reaction of the crew to any malfunction. It should specifically identify all possible events that

could lead to an uncommanded flight path upset due to flight controls like a rudder hardover. This analysis should account for and include the differences between the various 737 models and likely maintenance-induced failures such as, corrosion, improper connection of mechanical linkages, etc.

2. Using the analysis from objective 1, the Team, in coordination with Boeing engineers, will identify every set of three or less failures or malfunctions which would result in one of the events identified in objective 1. The Team will qualitatively rank the probability of each set of failures or malfunctions developed. The ranking should be rank ordered starting with single failures.

3. The Team will develop a list of recommended 737 systems design changes. The Team will also recommend the method by which these changes should be implemented, i.e., Airworthiness Directive action, service bulletin, future manufactured airplanes, etc.

Team Products

The Team will produce a report which includes a section for each objective in this charter. The report should document the Team's activities, the assumptions used by the Team in accomplishing each objective and a description of the results of the Team's work under each objective. The report should be such that a reader of the report can gain a basic understanding of the workings and operation of 737 flight control systems. The Team will also prepare an executive briefing package which will contain an Executive Summary and slides (hard copies), which describe the Team's methodology, results, conclusions and recommendations. The report will be submitted to the Manager, Transport Airplane Directorate. This will include a short briefing.

Other Factors/Considerations

The Team will meet at the Boeing facilities in the Puget Sound (Seattle/Renton) area. Boeing has agreed to provide office space and engineering resources for the Team.

The Team will arrange their own schedules for the effort, i.e., returning to their homes on weekends, etc.

The Team has complete flexibility in how they approach the task, provided the objectives are met.

Team Members

Member's Name	Organization	Telephone
1. Michael Zielinski	FAA - Team Leader	206 227-2279
2. Tom Donnelly	FAA	817-222-5188
3. Ron Filler	FAA	817-222-5132
4. Danko Kramar*	FAA	516-791-6428
5. Peter McDermott	USAF	303-340-9641
6. Tom Liepins	Transport Canada	604-666-6122
7. Christina Dawson	FAA - Flight Standards	206-227-2819
8. Representative	NTSB	

* Werner Koch of the FAA replaced Danko Kramar mid-way through the CDR effort.

Schedule

The Team is empowered to establish their own schedule for completing the task and advising the Manager, Transport Airplane Directorate, of their proposed schedule. Periodic progress reports will be provided on a bi-weekly basis.

Approved by:

_____(signed October 20, 1994)_____________________________

Ronald T. Wojnar, Manager, FAA Transport Airplane Directorate

CDR TEAM BIOGRAPHIES

Christina L Dawson has been employed as an Aviation Safety Inspector for the FAA Seattle Flight Standards District Office since 1984. Her responsibilities include the certification and surveillance of FAR Part 65 Airmen, Part 145 Repair Stations and Part 135/121 Air Carriers. Ms. Dawson is also responsible for maintenance program approvals and surveillance for a wide variety of aircraft including DC-3s, CV-340/400s, F-27s, BAe-146, B-727, B-737 and DC-9s. She is currently assigned as Principal Avionics Inspector to Alaska Airlines, a FAR Part 121 Air Carrier operating a fleet of B737-200/400 aircraft and DC-9-82/83 aircraft.

Prior to being employed by the FAA, Ms. Dawson was employed as an engineering planner and lead engineer with TRAMCO, Inc., a FAR Part 145 Repair Station. She is a graduate of South Seattle Community College, and holds degrees in Associate of Arts and Associate of Applied Science Aeronautical Technology.

Thomas S. Donnelly has held the position of Aircraft Certification Engineer with the FAA Aircraft Certification Office in Ft. Worth, Texas, since 1988. During this time, he has served a Team member of projects involving Traffic Alert and Collision Avoidance Systems, Predictive Windshear Warning System, Chinese Bilateral Approval of the Y-12 airplane, and VHF Navigation and Communications. Prior to his employment with the FAA, Mr. Donnelly was an independent engineering consultant and was involved with the design of autopilots and yaw dampers, the investigation of Grumman A-6 accidents resulting from latent failures, the flight readiness review of the Grumman X-29 digital flight control system, and analysis of affects of Electromagnetic Pulse (EMP) and High Intensity Radio Magnetic Fields (HIRF) on flight controls.

Mr. Donnelly was also employed as a systems design engineer on the F-117 stealth fighter for Lockheed for three years, and served as a Chief Systems Engineer for the Grumman American Aviation company for ten years. He is a certificated single and multiengine pilot with over 5,000 hours of flight time logged. Mr. Donnelly is a graduate of Tri State University, Indiana, with a Bachelor of Science degree in Electrical Engineering.

Ronald L. Filler has been employed as Flight Test Pilot for the FAA since 1983. From 1983 until 1985, he was involved in flight tests and systems aspects of the MD-83 and installation of the Honeywell Performance Management System on the B737 and B727 aircraft at the Long Beach Aircraft Certification Office. In 1985, Mr. Filler moved to the Ft. Worth ACO where he was assigned as the project pilot on a DC-8-71/73 autopilot certification program and a B727/RR re-engining program. He also specified the criteria for a new Stall Avoidance System (SAS) for the Fairchild Metro airplane, and participated in an aircraft accident investigation of a Fairchild Metro in 1988. He is currently responsible for the various models of the Fairchild Metro at the Ft. Worth ACO.

Previous to his employment with the FAA, Mr. Filler has held positions as a flight test pilot for the Piper Aircraft Corporation, a mechanical and hydraulics test engineer for the Bell Helicopter Company, a dynamics engineer for General Dynamics, and a line pilot for Braniff International airline. He has logged over 12,000 flight hours as a pilot and flight engineer and is both fixed wing and helicopter rated. He is a graduate of Rice University with a Bachelor of Science degree in Mechanical Engineering.

Werner G. Koch has been an Aerospace Mechanical Systems Engineer in the FAA Ft. Worth Airplane Certification Office since 1990. He is currently responsible for reviewing and approving airplane mechanical system design data, test procedures, test reports, and other documents for type design changes and supplemental type certificates. Prior to his employment with the FAA, Mr. Koch worked in the Hydraulic Design Group at Bell Helicopter Textron for 17 years. During this time, he assisted in the design and modification of new/existing helicopter hydraulic systems, prepared hydraulic systems specifications, and supervised the Group during the development and product support activity for the Bell Model 400 helicopter and V-22 tilt-rotor aircraft.

Mr. Koch was also employed as a design, laboratory and flight test engineer of hydraulic systems for LTV and E-Systems from 1961 to 1972. He holds a Bachelor of Science degrees in Mechanical Engineering from the University of Texas, and a Masters of Science Degree in Mechanical Engineering from the University of Southern California.

Danko Kramar has been employed a mechanical systems and equipment engineer at the FAA New York Aircraft Certification Office since 1990. During this time, he has been responsible for the certification and regulatory activities associated with aircraft mechanical systems and equipment, Team member on the (US/Canada, US/Russia and the US/China) bilateral assessment program as a mechanical/hydraulic systems and equipment specialists. He is presently assisting the Wichita Aircraft Certification Office in the certification of the Cessna Citation 10 powered flight controls and hydraulic systems.

Prior to his employment with the FAA, Mr. Kramar was employed by Grumman Aircraft Systems Division in the powered flight controls and hydraulics group. During this time he was responsible for the system concept, analysis, design, and component selection for the power generation (mechanical, hydraulic and pneumatic) and transmission to various subsystems. Mr. Kramar holds a bachelors degree of mechanical engineering from Pratt Institute.

Tom Liepins has been employed as an Airworthiness Inspector for Transport Canada for the last 10 years. He is the Principal Airworthiness Inspector for a major Canadian operator of the B737. He is thoroughly familiar with the requirements for large air carrier maintenance and quality assurance. Mr. Liepins has participated in numerous Transport Canada audits of air carriers and was a Team member in their familiarization and Type Approval of the B747-400. He has also represented Transport Canada at B747-400 Maintenance Review Board meetings. Prior to joining Transport Canada, Mr. Liepins was employed as an aircraft mechanic for an operator of the B737, B747 and DC-10 airplanes, and he completed maintenance type courses on these aircraft.

Mr. Liepins is the holder of a Transport Canada Aircraft Maintenance Engineer's License and has completed additional aircraft maintenance training in the areas of structures, non-destructive inspection, and corrosion prevention. He is a graduate of a two-year Aircraft Maintenance and Avionics program at Southern Alberta Institute of Technology.

Peter McDermott is a full-time technician Chief Master Sergeant in the Colorado Air National Guard. He serves as the Maintenance Superintendent for the 200 Airlift Squadron which operates the T-43, the military version of the Boeing 737. He is responsible for the logistics contract currently held by the Boeing Company, and the maintenance contract for the Air National Guard C-26 (SA-227). He recently completed a re-write of the Air Force maintenance planning document for the T-43. During these activities he represents the Air Force and Air National Guard. He also attends all maintenance and operating conferences which are sponsored by the Boeing Company. Chief Master Sergeant McDermott has a total of 26 years experience in the aircraft maintenance field, the last 12 of which have been associated with the T-43. His experience includes maintaining various aircraft such as the Boeing C-97, DeHavilland C-7, Douglas C-47, Convair T-29/C-131, Cessna 0-2, Voight A-7 and Boeing T-43. He also has over 2,500 hours as a Flight Engineer, accrued in the C-7, C-47 and T-43. His duties have included general aircraft mechanic and Quality Assurance Inspector.

Michael Zielinski is a Project Engineer for the FAA Transport Airplane Directorate. He has held a variety of positions within the FAA since 1983, including aircraft certification in which he developed a number of Advisory Circulars e.g., ETOP, Crew Workload, and Flight Manual standardization. He joined the Flight Standards Service as manager of the Long Beach, Ca. and Seattle, WA. Aircraft Evaluation Groups (AEG), and developed the strategy for the reorganization of the AEG. He also led the development of the FAA and NTSB's Bloodborne Pathogen Training Program for accident investigation personnel. He then returned to the aircraft certification service as project officer involved in the standardization of transport aircraft certification efforts of a number of Aircraft Certification Offices.

From 1965 to 1983, Mr. Zielinski was employed at the Boeing Company. During this time, he participated in the certification of the B737, B747, and B727-200 Advanced airplanes as a flight test Designated Engineering Representative (DER). He was also a noise certification airplane performance lead engineer for then current Boeing models, including the R&D effort in the development of the B727-300. He then joined Boeing Operations Engineering, created an airplane performance/community noise course, taught airplane dispatch course and was the engineering representative for 10 airlines, including both foreign and domestic carriers. He holds a Bachelor of Aeronautical Engineering Degree from the University of Detroit (Detroit - Mercy) and did post graduate work at the University of Washington.

B737 FLIGHT CONTROL SYSTEMS DESCRIPTION

a. General Hydraulic System: The B737 series airplane incorporates three functionally independent hydraulic systems which operate at approximately 3,000 pounds per square-inch (psi) pressure. The systems are designated as system "A," system "B," and the "Standby" system. Each system has its own independent reservoir. The hydraulic fluid used in each system is BMS 3-11. The three reservoirs are pressurized to 45-50 psi by the engine bleed air pneumatic system to assure a positive flow of fluid to the pump suction. In the B737-100/-200 series, the bleed air is supplied by the 13th compressor stage of both engines and is routed to system "A" reservoir. Balance lines then interconnect the three system reservoirs, allowing them all to be pressurized to the 45-50 psi pressure. In the B737-300/-400/-500 series, the pneumatic system distributes air from the right and left pneumatic ducts (allowing hydraulic pump operation with APU power) to both systems "A" and "B" reservoirs. The standby reservoir is then pressurized through the balance line from the "B" reservoir. Although both systems "A" and "B" normally provide hydraulic power for the flight controls, either system alone will power the flight controls. The ailerons and elevators can also be operated manually, without hydraulic power. Powered rudder control can also be obtained from the "standby" hydraulic system. The capacities of the hydraulic pumps in the system are such that the operation of any one of the four "A" or "B" system hydraulic pumps is capable of supplying the flight controls with sufficient pressure and flow to operate them without apparent degradation of authority under normal demands. Available rate and force capability would, however, be limited with respect to fully operable hydraulic systems ("A" and "B").

The "A" hydraulic system is powered by two engine-driven pumps on the B737-100/-200 series aircraft. On the -300\-400\-500 series, the "A" system is powered by the left engine-driven pump and by a three-phase, 115-VAC electric motor-driven pump that is powered by BUS No. 2, which is supplied by the right engine. The engine-driven pumps generate a constant output pressure at a variable flow rate of approximately 25 gpm. The electric motor-driven pumps are, also, constant output pressure units, with a maximum flow rate of 6 gpm. The system is equipped with pressure and return-line filters that are rated at 15 micron absolute. The case drain fluid lines are provided with 25 micron absolute filters. On the B737-100/-200, the "A" system provides power for the inboard brakes, inboard flight spoilers, ground spoilers, ailerons, elevators, rudder, trailing edge flaps, leading edge devices, landing gear, nose wheel steering, and thrust reversers. On the -300/-400/-500 series, system "A" supplies power for the ailerons, rudder, left thrust reverser, elevator, inboard flight spoilers, alternate brakes, ground spoilers, autopilot "A," landing gear, normal nose-wheel steering, and power-transfer unit, in the event of a pressure loss from the system "B" engine-driven pump.

The "B" hydraulic system is powered by two electric motor-driven pumps on the B737-100/-200 series. On the -300/-400/-500 series, the "B" system is supplied by the right engine-driven pump and by a three-phase, 115-VAC electric motor-driven pump powered by BUS NO 1, which is supplied by the left-hand engine. The hydraulic system pump ratings and the fluid filtration are the same as described above for System "A." On the B737-100/-200, the "B" system provides power for the outboard brakes, outboard flight spoilers, ailerons, elevators, rudder, yaw damper, autopilot "B" and the auto brakes. On the ground, "B" system can also be used to pressurize "A" system through the interconnect valve on the B737-100/-200. On the B737-300/-400/-500, the using units are the ailerons, rudder, right thrust reverser, leading edge flaps and slats, auto slats, elevator, outboard flight spoilers, normal brakes, yaw damper, autopilot

"B," trailing edge flaps, and alternate nose wheel steering (if installed). System "B" pressure is available for alternate landing gear extension in the event of a loss of engine No. 1.

The "Standby" hydraulic system (all B737 models) provides an alternate source of hydraulic power to operate the rudder, to extend the leading edge flaps and slats, and to actuate both thrust reversers. It is powered by a three-phase, 115-VAC electric motor-driven pump. The motor is normally supplied by BUS NO. 1, and, alternately, by BUS NO. 2. The pump provides a constant output pressure of 3,000 psi at a maximum flow of 4 gpm. The fluid filtration for the standby system is the same as for the "A" and "B" systems except that no dedicated return filter is provided.

Two flight control hydraulic modules (one each for "A" and "B" hydraulic systems) are installed. Each hydraulic module is a manifold assembly containing a spoiler shutoff valve, flight controls shutoff valve, low pressure warning switch, and compensator cartridge. The compensator cartridge maintains return fluid from the aileron, rudder, and elevator power control units after hydraulic system shutdown. This fluid is used to compensate for volume changes in the hydraulic system, due to temperature changes or fluid loss. Motor operated shutoff valves within the module are commanded to their operating positions by the flight control system switches in the cockpit.

Control and indication of the "A", "B" and "Standby" hydraulic systems necessary for airplane operation are provided in the cockpit. "A" and "B" hydraulic system pressure and reservoir quantity are indicated on gages located on the first officers panel (EIS display on some 737-300, -400, -500 models). The pumps in the "A", "B", and "Standby" hydraulic systems are controlled and indicated by switches and lights located on the forward overhead panel. Each pump in the "A" and "B" system has its own on/off switch and amber low pressure light. Indication of "A" or "B" system electric motor pump overheat is provided by amber overheat lights.

The "Standby" system hydraulic system pump is activated by arming alternate flaps or by selecting either "A" or "B" flight control switch to the Standby rudder (STBY RUD) position. On 737-300,-400, and -500 airplanes, the pump can also be activated by auto-standby circuitry ("A" or "B" flight control pressure low, flaps not up, and airplane in air or wheel speed > 60 kts). Low "Standby" pump pressure and low reservoir quantity are indicated by amber lights.

The master caution system, on the glare shield, provides eye level indication to the pilots that a hydraulic light on the overhead panel has illuminated. Master caution remains illuminated until either the master caution light is depressed or the cause is corrected.

b. Lateral Control System: Lateral control is provided by an aileron and two flight spoilers on each wing. These controls are operated by either control wheel in the cockpit. The pilot's and copilot's control wheels are connected by cables to an aileron control quadrant which operates the aileron power control units (PCUs) through a mechanical linkage. The PCUs move the ailerons directly and also command the spoilers through the spoiler mixer.

(1) The base of the copilot's control column is equipped with a system which allows normal control wheel motion to be transmitted through the left aileron body cables only. If a malfunction occurs that jams the aileron control system, lateral control is accomplished by operating the flight spoilers with the right aileron cables controlled from the copilot's control column. Control wheel movement of more than 12 degrees left or right is required to operate the spoilers through the aileron transfer mechanism.

(2) A spoiler mixer combines lateral input from the aileron system with speed brake lever position to allow the flight spoilers to augment lateral control while simultaneously being used as speed brakes. The spoiler mixer also functions as a ratio changer which varies the output to the spoiler actuators for a given magnitude of input from the aileron system, depending on speed brake lever setting. The output decreases as speed brakes are raised.

(3) An aileron spring cartridge (pogo) provides the mechanical input connection between the aileron power control units and the spoiler input link to the spoiler mixer through the normal control path.

(4) The aileron PCUs are independent units, one connected to system "A" and the other connected to system "B." Either unit is capable of providing full deflection lateral control at reduced rate and limited by 1/2 the force capability in the "blow-down" airspeed regime.

(5) Two flight spoilers on each wing operate in conjunction with the ailerons. The outboard flight spoilers are operated by hydraulic system "B" while the inboard flight spoilers are operated by system "A." All four flight spoilers also may be operated together to serve as aerodynamic speed brakes. Aerodynamic forces limit panel extension within appropriate limits for the airplanes structural design. Two (three on the -300/-400/-500) ground spoilers are also located on each wing to provide aerodynamic drag for ground operation only. The ground spoilers are protected from airborne operation by a ground spoiler by pass valve connected to the right main landing gear. The ground spoilers are powered by hydraulic system "A." Each spoiler has its own hydraulic actuator, and there is no manual reversion backup capability.

(6) If hydraulic power is lost to both "A" and "B" systems, lateral control is provided by manual reversion. In this mode, the pilot's inputs are transmitted mechanically through the PCUs and the aileron control cables to the ailerons. Movement of the ailerons is aided aerodynamically by aileron balance tabs and panels. The spoilers are inactive in this mode because there is no hydraulic power to their actuators.

(7) Aileron trim is provided by a mechanical actuator which repositions the aileron centering mechanism on the B737-100/-200. On the B737-300/-400/-500 this actuator is electrically operated.

c. Longitudinal Control System: The B737's elevators are powered by two independent hydraulic PCUs. One PCU is powered by hydraulic system "A" and the other is powered by hydraulic system "B". Either unit can independently provide full deflection pitch control with reduced rate and force authority. Pilot input to the elevator power control unit is from the control column through a dual cable system and a torque tube that is connected to both elevators. With either hydraulic system off, the elevator control system unlocks an aerodynamic tab for that system on the -100/-200. On the -300/-400/-500 the tab is active all the time. With both hydraulic systems off, the elevator control system automatically reverts to direct manual operation assisted by the elevator tabs and balance panels.

(1) A hydraulic "feel" system provides control column forces proportional to airspeed (differential pressure). The mechanical feel and centering unit receives inputs from the stabilizer position and from a Mach trim actuator to provide center-of-gravity input and speed stability at higher Mach numbers.

(2) Longitudinal trim is provided by a movable horizontal stabilizer, which is operated by a single dual load-path ballscrew. Power for the ballscrew comes from three sources: the main electric trim motor, the autopilot trim motor, and the manual trim system. Manual stabilizer trim control wheels are located in the cockpit and connect through a cable system to the stabilizer.

d. Directional Control System: Directional control of the airplane is provided by rudder pedals through a hydraulically powered single surface rudder without a tab. A rudder PCU is connected directly to the rudder, is powered by hydraulic systems "A" and "B," and operates through a dual load-path linkage. Rudder backup power is provided by a standby actuator, which is powered by the "standby" hydraulic system. Any single hydraulic system power source will provide full deflection rudder control at a reduced rate and limited by 1/2 force capability in the "blow-down" airspeed regime. The rudder is operated only by hydraulic power; there is no manual reversion capability. The feel and centering mechanism provides an artificial feel force gradient at the rudder pedals and holds the rudder at the trimmed position when no force is applied at the pedals. At neutral the rudder breakout force is sixteen pounds and the force increases with pedal deflection to sixty-eight pounds at full rudder pedal travel. Trim commands cause the trim actuator to extend/retract which in turn causes rotation of the feel and centering mechanism. Rotation of the mechanism provides a new zero force rudder pedal position corresponding to the trimmed rudder surface position.

(1) The rudder PCU includes a dual-tandem hydraulic actuator within the unit. Hydraulic system "A" provides power to the forward section through the hydraulic system "A" flight controls module. Hydraulic system "B" provides power to the aft section through the hydraulic system "B" flight controls module.

(2) The standby rudder actuator normally is not powered. When operation is selected by the "A" or "B" flight control switches (either switch positioned to STBY RUD), or automatically upon failure of either "A" or "B" system on the B737-300/-400/-500, the actuator is powered through the standby hydraulic system. At least one side of the main power control unit is not powered when the standby actuator is powered. No more than two hydraulic systems are intended to be used to operate the rudder at any one time.

(3) The rudder is, also, controlled by the yaw damper system. The yaw damper actuator is integrated into the PCU and is powered by the "B" hydraulic system. The damper operates independently of the pilot's control system and does not result in feedback to the rudder pedals. The components of the damper system consist of the yaw damper shutoff valve (engage solenoid), transfer valve, yaw damper actuator (mod piston, yaw damper rate sensor, and associated electronic yaw damper coupler). The yaw damper is limited to a maximum of 3 degrees of rudder deflection in either direction (2 or 4 degrees in some earlier B737 Models). The yaw damper is engaged by activating a solenoid that connects the "B" system hydraulic pressure to the transfer valve. Electric current flow through one of two opposing coil windings within the transfer valve, results in hydraulic fluid flow to position the mod piston, which causes the primary rudder valve to be displaced. This results in PCU output and rudder deflection. The yaw damper authority is mechanically limited inside the PCU by the mod piston stops.

(4) Rudder trim is mechanically controlled. It is operated via cables from a control knob on the aisle stand to a mechanical actuator attached to the feel and centering mechanism at the rudder. On the B737-300/-400/-500 series, the rudder trim actuator at the feel and centering mechanism is electrical, and control is electrical via a switch on the cockpit pedestal. Trim input is obtained by repositioning the feel and centering unit, and thus, offsets the neutral or zero position of the rudder.

B737 CDR TEAM ACTIVITY CALENDAR

The following is an account of the Team's significant activity in support of the Review effort:

DATE	ACTIVITY
Oct. 25 to 28	Team familiarization with design of B737 flight control system.
Oct. 31 to Nov. 4	Team review of certification data of the flight control system.
Nov. 14	Briefing/discussions with FAA Special Certification Review Team (RE: Determination of design or maintenance deficiencies of hydraulic components in flight controls of various Boeing airplanes).
Nov. 15	NTSB briefing on airplane system issues regarding B737 accidents in Colorado Springs and Pittsburgh.
Nov. 15	a. Boeing briefing on B737 accidents. b. Team review of NTSB recommendations regarding B737 flight controls.
Nov. 16	CDR Team Caucus.
Nov. 17	Some Team members participate in "M" Cab simulator exercise of CDR Team developed failure scenarios.
Nov. 17	a. Other Team members participate in review of Component Maintenance/Overhaul Manual procedures for PCU. b. Comparison of "task cards" vs. Boeing MPD requirements for identified Latent and other failures in the flight control system. c. Review of the B737 MRB and subsequent revisions with Seattle AEG.
Nov. 18	a. Team review of TIA and Ironbird tests relevant to the demonstration of failure consequences b. Boeing failure analysis briefing on leading and trailing edge flaps c. Team caucus and review of Nov. 17 activity and results.
Dec. 5 to 6	a. Action to satisfy Team requirements for additional information or design review. b. Team discussions and initiation of CDR report outline
Dec. 7	a. Some members of Team visit TRAMCO for first hand look at B737 in "D" check and PCU component disassembly. b. Other Team members hold discussions with Seattle ACO mechanical systems staff members.
Dec. 12	Discussions with Boeing on outstanding questions.

Dec. 13 to 15	Continuation of Team discussions and review of SB, SL, AD and ASRS reports.
Dec. 16	Some Team members visit Parker and Honeywell.
Dec. 20	Discussions with Fortner on repair of B737 PCU's.
Dec. 21	Meeting with Douglas Aircraft Comp. regarding their philosophy and design of flight control systems.
Jan. 9	Discussions with Boeing regarding the preliminary draft of CDR report
Jan. 10 and 11	Development of presentation of Team results for discussions with management of FAA, NTSB, DOD and Transport Canada.
Jan. 12	Presentation of CDR results to Team management.
Jan. 13	Revise working draft of CDR report as required.
Jan. 18 to 20	Revise working draft of CDR report as required.
Jan. 23	Provide working draft to Boeing for review and comment.
Feb. 7	Review Boeing comments with Team.
Feb. 8 to 10	Revise working draft of CDR report and sort recommendations for distribution to FAA offices for development of action plan.
March 20 to 31	Revised working draft and developed executive summary of report. Began development of report on implementation plan.

BOEING MULTIPURPOSE ENGINEERING SIMULATOR, "M" CAB, EXERCISE

As a result of the identification of a number of potential failures in the B737 flight control system, the CDR Team conducted a series of simulator tests to attempt to evaluate whether these failures could result in the loss of aircraft control. The failures to be evaluated included single, multiple, and latent failures and no attempt was made to determine the probability of any event. The approach taken was that the failure had occurred; now, what is the effect on the flightcrew's ability to control the aircraft?

The simulator used was Boeing's "M" CAB engineering simulator configured as a B737-300. No verification of the simulator's fidelity with respect to the test airplane for the test conditions evaluated was made by the CDR Team. However, several Boeing flight controls, stability and control, and simulator engineers were involved in setting up the test. Their general opinion was that the simulator's fidelity was sufficient for the kind of evaluations being conducted.

The tests were conducted on November 17, 1994. CDR Team pilots were Ron Filler, ASW-150, and Gene Bollin, ACE-160W. CDR Team observers were Tom Donnelly, ASW-190, and Mike Zielinski, ANM-113. The Boeing test director in the simulator was Marty Ingham. Several other Boeing personnel were present to assist with the test.

A basic test plan had been agreed upon and briefed prior to conduct of the test. This test plan is presented herein as Figure 1. A list of data parameters to be recorded was also agreed upon. This list is presented as Figure 2. The test plan lists basic aircraft configuration, weight and c.g., and flight conditions for each test together with a brief test description. All tests were conducted essentially as shown except for test 4, simulated bus bar and cable failures, and test 5, lateral axis auto pilot hardovers without force limiting. These tests could not be accomplished with the simulator as available on November 17. Also, the manual reversion part of test 8 could not be accomplished. Some of these tests may be conducted at a later date.

Two test conditions were added to Test 2; these were rudder hardovers with speed brakes deployed at high altitude, clean configuration, and low altitude, flaps 1, 140 KIAS. One "surprise" rudder hardover was added by the CDR Team observers in the simulator control room. This test turned out to be unrealistic because of the manner in which the rudder malfunction was introduced. All these added tests are discussed together with the tests conducted from the test plan shown in Figure 1 in the Test Results section below.

TEST RESULTS

Familiarization Flights - Prior to conducting the tests outlined in Figure 1 the two FAA pilots flew familiarization flights in the simulator.

Mr. Filler is type rated in the B727 and has flown FAA certification test flights for after market equipment in the B737. He flew a takeoff, traffic pattern circuit, and landing with the left engine failed at V_1. He judged the simulator to be typical of many he has flown but less sensitive in low altitude roll/yaw coupling than one B737 training simulator he has flown. During his flight, the crew and Mr. Ingham attempted to sort out the auto pilot programming, and although its altitude hold function did not work properly, it was judged to be working adequately for its intended use in the rudder trim runaway tests (1.10, 1.20, and 1.30).

Mr. Bollin is type rated in the B747 and has also flown the B737. He intended his familiarization flight to also be a left pattern circuit from takeoff to landing with both engines running. After a normal takeoff a left turn was made to crosswind and, passing through 1400 feet AGL and an airspeed of 225 KIAS in a clean configuration, the CDR Team members in the simulator control room asked the Boeing technician to insert an unannounced "rudder hardover." However, instead of inserting a realistic rudder malfunction, the Boeing software technician inserted an instantaneous aerodynamic equivalent of a 26° right rudder deflection (rudder bias). This rudder bias increased to 34° as sideslip peaked. This resulted in an initial slight roll left and moderate right yaw followed by a violent roll right (66°/sec) and increasing right yaw. Mr. Bollin responded with initial right wheel (1 sec after the event) followed by full left wheel (within 31/2 sec. after the event) and full left pedal (within 31/2 sec. after the event). Left pedal had no effect since the rudder was biased aerodynamically full right with no blow down function or stop to limit its travel. Within 6 seconds after the event the right roll had peaked at 110 degrees, pitch attitude was 33° nose down, altitude was rapidly decreasing, and Mr. Filler remarked "I think we crashed." At this point, Mr. Bollin relaxed recovery controls and the simulator did "crash" 5 seconds later.

This event, unfortunately, was very unrealistic, although the crew surprise factor was realistic. Maximum rudder travel is limited to ± 26° by actuator travel and to approximately 12° by aerodynamic hinge moment (blow down) at 225 KIAS. Also, maximum rudder actuator travel rate is about 63°/sec in terms of rudder deflection with no load. The pilot inputted hardovers flown in the simulator had average rudder deflection rates of approximately 40°/sec. Therefore, the instantaneous rudder was approximately twice the realistic deflection that should have required about 0.3 seconds to reach full travel. Then the model allowed the deflection to increase even further as sideslip increased, resulting in a deflection of about 2 1/2 times what is realistic for this airspeed. No real conclusions can be drawn from this event. As will be noted later, rapid pilot response is crucial to successful recovery from more realistic rudder hardover scenarios.

After resetting the simulator just outside the outer marker, Mr. Bollin completed his familiarization flight with an uneventful approach and landing. His comment was that the simulator felt like a typical simulator and not like an airplane in all respects.

Dutch Roll Characteristics

After the low altitude familiarization flights, the simulator was reset to FL 350, cruise Mach =.74, and both pilots performed rudder doublets to observe the simulator's/airplane's Dutch roll characteristics at high altitude, yaw damper on and off. With yaw damper ON the observed response was very highly damped with one or two small overshoots. With yaw damper OFF, the response was damped; cycles to 1/10 amplitude were approximately 7 giving a damping to critical damping ratio of approximately .05. The characteristics did not change at $M=M_{mo}$ and the simulator was not difficult to fly yaw damper off. Dutch roll frequency was approximately 0.3 cycles/sec.

Rudder and Aileron Trim Runaways (Tests 1.10 thru 1.31)

These tests were devised to investigate whether a rudder or aileron trim runaway that was counteracted by autopilot aileron input could result in a severe upset maneuver following an inadvertent autopilot disconnect or an intentional disconnect by an inattentive pilot.

RESULTS

RUN	CONTROL SURFACE	TEST	ALTITUDE/ VELOCITY (KIAS or M)	MAX. ROLL	MAX. ROLL RATE	MAX. VERT g's	Remarks
6	R	1.10	350/.74	55°	30° / SEC	2.0	HANDS ON RECOVERY
7	R	1.10	350/.74	65°	30°/ SEC	1.9	HANDS OFF RECOVERY; DELAYED RECOG.
8	R	1.20	6/250	45°	15°/ SEC	1.4	HANDS ON RECOVERY
9	R	1.20	6/250	60°	10°/ SEC	1.7	HANDS OFF RECOVERY
10	A	1.21	6/250	75°	28°/ SEC	1.65	NO DELAY
11	A	1.21	6/250	65°	28°/ SEC	1.6	NO DELAY
12	A	1.11	350/.74	100°	44°/ SEC	1.6	RECOVERY AFTER 60° ROLL
13	R	1.30	6/120	35°	13°/ SEC	1.25	3 SEC DELAY, AILERON ONLY RECOVERY
14	A	1.31	6/120	60°	22°/ SEC	1.55	RECOVERY AFTER 45° ROLL; AILERON ONLY
15	A	1.31	6/120	65°	22°/ SEC	-4/ +1.8	HANDS OFF INITIALLY, THEN RUDDER ASSISTED RECOVERY

The autopilot was used for the rudder trim runaways. Full rudder trim always resulted in a heading and roll departure. Delays refer to delayed recognition, not delay after autopilot disconnect. The autopilot was disconnected for recovery, hands on and hands off as noted. This maneuver was more severe at high altitude because of aircraft instability and aileron sensitivity with large sideslip angles under these flight conditions. The lower altitude, lower speed tests were easier to control.

Aileron trim runaways with the autopilot engaged were simulated by the pilot holding the wheel to maintain heading until full trim had been applied. Then the pilot released the wheel to simulate autopilot disconnect and recovered upon recognition with no delay. The high altitude maneuver in this test was easier to control than the rudder trim runaway due to the lack of rudder induced sideslip even though the roll rate and roll excursion were higher. Again, the lower altitude, lower speed test points more easily recovered, even though one of these tests points produced the only significant negative (less than 1) acceleration observed prior to recovery. Use of rudder aided recovery from the aileron runaways by reducing the adverse yaw present with aileron only recoveries.

None of these tests (rudder trim or aileron trim runaways opposed by the autopilot with subsequent disconnect) resulted in loss of control or potential loss of control of the aircraft. They did, however, require prompt recognition and pilot response after autopilot disconnect to prevent excessive (perhaps hazardous) bank angles from developing.

Steady Full Rudder Sideslips and Rudder Hardovers (Tests 2.10 thru 2.41)

These tests were designed to compare roll (aileron/spoiler) and yaw (rudder) control authority in steady heading sideslips and to determine aircraft/pilot response to a sudden full pedal rudder application. The pilot not flying inputted the simulated rudder hardover by putting one pedal to the floor as fast as possible and holding it to the floor. This resulted in rudder deflection rates of approximately 40°/sec as compared to no-load hydraulic system capability of 63°/sec.

No delays other than recognition were applied to pilot response to the sudden rudder inputs because these maneuvers were felt to be so violent that no pilot would delay recovery response by more than recognition time. As can be seen by the roll rates and angles produced, further delay could easily result in roll angles in the inverted flight regime.

All steady heading sideslips resulted in sideslips with full rudder and some aileron left for roll/heading control.

RESULTS

RUN	TEST	ALT./ V	MAX. ROLL	MAX. ROLL(1) RATE	MAX. VERT G'S	MAX. SS(2)	Remarks
16	2.40	6/120	10-12°	50° wheel	____	14°	STEADY HEADING SIDESLIP (SHSS)
17	2.40	6/120	20°	14°/ SEC	-.3 to +1.2	18°	(3) RUDDER HARDOVER (RH); EASY RECOVERY
19	2.41	6/135	10°	50° wheel	____	13°	SHSS
20	2.41	6/135	40°	22°/ SEC	NIL	16°	(3) RH
21	2.31	6/190	10-12°	15° wheel	____	10°	SHSS
22	2.31	6/190	62°	32°/ SEC	+1.6	14°	(4) RH
23	230	6/190	20°	25° wheel	____	12°	SHSS
24	2.30	6/190	65°	34°/ SEC	-.3 to + 2.4	14°	(5) RH
25	2.20	6/250	20°	40° wheel	____	7°	SHSS
26	2.20	6/250	60°	42°/ SEC	1.4	11°	(6)RH
27	2.21	6/250	20°	45° wheel	____	7°	SHSS
28	2.21	6/250	62°	39°/ SEC	1.4	10°	RH-not quite benign
29	2.11	350/ 74	15°	50° wheel	____	6°	SHSS-airplane sensitive
30	2.11	350/ .74	65°	41°/ sec	1.5	10°	(7) RH
31	2.10	350/ .74	15°	40° wheel	____	7°	SHSS
32	210	350/ .74	90°	58°/ sec	-.8/+ 2.2	11°	(8) RH

Notes to SHSS and RH Results Table:

(1) This column is degrees of wheel remaining for SHSS.

(2) This column is steady sideslip for SHSS.

(3) Pilot comments that it "took a minute" to figure out which way to input opposing aileron control due to initial roll rate and lateral acceleration in the opposite direction of the ultimate departure with initial rudder input, before sideslip builds and dihedral effect predominates.

(4) Very slow recovery - full opposite wheel held for 14 seconds before roll returned to zero; commensurate heading change was 80° and yaw rate went from 11°/sec to zero during this time.

(5) At this condition (light/aft, flaps 1, 190 KIAS) recovery from yaw was in doubt; full opposite wheel stabilized the roll angle at 42°; but the yaw rate also stabilized at 5°/sec; airspeed had decreased to 175 KIAS as the pilot recovered to his initial pitch altitude; then the nose was lowered again, airspeed increased to 190 KIAS +; roll angle returned to 15° in the opposite direction and yaw rate reached zero; this sequence of events lasted 35 seconds and 180° of heading change resulted; full opposite wheel was applied for the entire period from 2.5 seconds after the hardover.

(6) Roll recovery easy; yaw oscillation with 4 second period hard to damp out without pilot induced oscillation (PIO).

(7) Airplane is quite unstable in this condition (heavy/fwd, 350/ .74M) with a lot of sideslip; hard to stay out of PIO with ailerons.

(8) Mr. Bollin flew this test; his technique was to take the hardover more "hands off" than Mr. Filler which sometimes resulted in a slightly greater initial excursion; his comment was that the roll was "quick" and "is the yaw damper on?" It was turned on, but we do not know if it is effective with the rudder held to the floor. With roll rates this high, quick pilot response is necessary to prevent going into the inverted flight regime.

Lack of Rudder/Aileron Feel Force (Tests 3.10 thru 3.21)

These tests were designed to determine any hazardous effects of loss of rudder/aileron feel force due to a failure in the feel/centering mechanism. Also, an attempt was made to determine if any of these failures, such as the failure of one of the two redundant feel/centering springs, could be latent.

All the flight conditions shown on the test plan in Figure 1 were flown. Simulator pre-programmed random turbulence, characterized as "heavy" but judged by Mr. Filler to be light, was added for all 1/2 feel force tests.

The two pilots shared the piloting tasks sufficiently during this test series so that each pilot could make a qualitative judgment about all the conditions. The basic aircraft stability and control characteristics influenced the test results as would be expected. Namely, the high altitude tests, where the aircraft is more unstable (sensitive), provided easiest recognition of the malfunction and more control problems in the case of 0 rudder feel. The lower altitude, lower airspeed points were more benign.

In general, the results were as follows:

1. 1/2 aileron feel was pleasantly light and would be hard to recognize as a failure. Thus, potentially, this failure is latent.

2. 1/2 rudder feel was easier to recognize but still might be latent if only observed at low altitude and airspeed. Control with 1/2 feel was not a problem.

3. 0 aileron feel was usually recognizable, although the simulator still had some centering force and a break-out detonate at wheel centered. Control was again not a problem.

4. 0 rudder feel produced a condition similar to a pilot induced rudder hardover, since once displaced there was no return until the pilot recognized the condition and centered the rudder by sensing when his feet were even. As such it was not only recognizable as a failure, but produced a definite control problem, especially at high altitude and airspeed. In the simulator, there was still a recognizable detent at the centered position and, if no rudder input was made, the rudders stayed centered.

Control with Spoilers only after Aileron Jam (tests 6.10 thru 6.13)

This test was intended to investigate the difficulty in aircraft control after aileron or pilot side control jams at 1/2 and full aileron/wheel defection. The simulator force/feel system was set up to duplicate the wheel forces produced by flying the airplane with the co-pilot's wheel through the aileron transfer mechanism. However, in the simulator, both wheels were operative and felt the increased force.

As could have been anticipated per the design force gradient vs. wheel deflection curve, this was a very difficult task. The design force gradient vs. wheel deflection curve is linear over ranges, but discontinuous, and predicts a 200 lbs force requirement from stop to stop.

Current FAR § 25.671 (Amendment 23, 4-8-70) requires that the airplane be capable of continued safe flight and landing after any failure, combination of failures, or jam in the flight control system not shown to be extremely improbable, within the normal flight envelope, without requiring exceptional pilot skill or strength. However, jams are specifically referred to as those occurring in "a control position normally encountered during takeoff climb, cruise, normal turns, descent, and landing." The B737 did not have this version of the rule in its certification basis except for system changes unique to the B737-300, 400, and 500, with respect to the -200. However, Boeing contends that the same philosophy (jams only in normally encountered control positions) was followed for the -100 and -200 in showing compliance with FAR § 25.677(c) that requires trim capability after a failure in the primary flight control system. Since jamming of the primary system will disable the trim system, an equivalent safety finding was made to allow the use of spoiler control through the transfer mechanism to substitute for trim capability. Also, the use of spoilers through the transfer mechanism was used to show compliance with FAR § 25.695(c) which requires that jamming of the power cylinders (power control units) must be considered unless this failure is extremely remote.

Although not tested in this simulator exercise, an aileron jam near neutral or within what Boeing considers a control position "normally encountered" is probably flyable by the copilot through the aileron transfer mechanism. However, jams outside this range where we conducted this test produce control forces almost impossible for the pilot to manage.

Results:

All the test conditions were flown with both 1/2 (actual 10° to 14° of aileron deflection) and full (actual 19° to 20° of aileron deflection) aileron deflection jams. The "1/2" jams resulted in recorded forces oscillating ± 5 to 10 lbs. about 75 lbs., i.e., 70 to 80 or 65 to 85 lbs., as the pilot tried to fly the airplane after recovery from the initial condition where the jam was inserted. The "full" jams resulted in oscillations from 75 to 100 lbs., i.e., 87 ± 12 lbs., for the same conditions. Because the other pilot could help through the other wheel in this simulation (though not in the real airplane case), flight and landings were attempted with both pilots on the wheels. This was marginally successful, and it did not reduce the force on each pilot's wheel for a given deflection, at least according to the data.

The net result of this investigation was that, if the force gradients were realistic as claimed by Boeing to be applicable to the real airplane, flight under these conditions was extremely difficult, tiring, and likely to result in loss of control of the aircraft. The particular flight condition (configuration, speed, altitude) did not seem to make much difference. Again, high altitude flight was most difficult due to reduced stability. Also, the prospect of flying the aircraft to a successful landing from high altitude was in doubt because of the high physical effort required for a relatively long period of time. (See "Recommendations For FAA Action," Section 15. Recommendation -8).

One technique found to be useful and necessary for extended duration flight under these conditions was the use of rudder against the jammed aileron. Differential thrust might have helped but wasn't tried because the pilot was too occupied with both hands on the wheel.

Flight with One or Two Spoiler Panels Up (Tests 7.10 through 7.17)

These tests were planned to investigate the control problems and/or control power lost with one or two spoilers stuck up. The tests were flown as planned (Ref. Fig. 1) except in reverse order (7.17 to 7.10).

Results

The test results were somewhat unexpected, but predictable upon reflection. The asymmetric lift or roll input was easily corrected by opposite wheel input in all cases; although, Mr. Bollin's hands off technique of taking the initial malfunction did result in a 25° roll with the initial spoiler application for the 190 KIAS, flaps 1 case. Steady heading flight required about 55-60° of opposite wheel for 2 spoilers up at 250 KIAS, clean, and no rudder input.

The predictable aerodynamic result, though a surprise for the pilots, was the loss of performance (increased drag, loss of lift) caused by flight in this condition. The failed up spoilers on one side had to be counteracted by both ailerons and raised spoilers on the opposite side. This amounted to flight with speed brakes up plus aileron input. The loss of performance was dramatic in all cases and increased pilot workload considerably. High thrust and higher than normal angle of attack was required to maintain desired flight path. One 45° bank rolling maneuver with a 10° overshoot (to 55° bank) with one spoiler up resulted in autoslat deployment. The landing configuration, two spoilers up, malfunction was flown to a landing and resulted in a hard landing.

The conclusion from these tests was that the malfunctions were easily controllable from a rolling moment consideration, although exactly what had happened might be a little difficult to ascertain without looking out the passenger windows at the wing. Pilot training for this malfunction would be a definite asset in handling it. (See "Recommendations For FAA Action," Section 15. Recommendation -19).

Opposite rudder and differential thrust to alleviate some opposite spoiler deployment would probably be a useful technique, although this was not thoroughly investigated.

Rudder Hardovers with Speed Brakes Deployed (Additional Tests)

Tests 2.10 and 2.11 (Lt/Aft and Hvy/Fwd, 350/.74M) and 2.30 and 2.31 (Lt/Aft and Hvy/Fwd, 190 KIAS, Flaps 1), which were the most critical test cases for rudder hardovers, were repeated with speed brakes deployed prior to the hardover. Steady heading side slips were not flown first because the rudder hardover resulted in a steady heading sideslip after control was regained.

Results:

Run	Test	Alt./V	Max. Roll	Max. Roll Rate	Max. Vert. g's	Max. SS	Remarks
59	2.11	350/.74	60°	50°/sec	-.6/+1.35	8°	(1) RH
61	2.10	350/.74	70°	47°/sec	-.7/+1.9	10°	(1) RH
63	2.30	6/190	55°	30°/sec	-.4/+1.95	14°	(2) RH
64	2.31	6/190	50°	29°/sec	+1.6	13°	(2) RH

(1) These tests were comparable to their speed brake down counterparts but were judged to be slightly more sensitive.

(2) These events were very comparable to their speed brakes down counterparts. Recovery time and heading change for test 2.30 (Lt/Aft) was less than for the speed brakes down test due to pilot technique that never let airspeed get low.

The net result of the speed brakes up rudder hardover tests was that speed brakes didn't make much difference. After the initial recovery, speed brakes were lowered and asymmetric thrust was tried on test 2.30 (run 63) to try to reduce wheel deflection and sideslip. This was partially successful; flight idle thrust on the "dead" engine (dead foot, dead engine) reduced average wheel deflection from 65° to 45° and side slip from 11° to 8°.

190 KIAS, Flaps 1, Rudder Hardover Additional Test

An additional test was added to investigate the result of slowing the aircraft to a flaps 15, airspeed = V_{REF}15 + 5K, preparatory to landing configuration after undergoing a rudder hardover in the configuration/condition of test 2.31.

The result of this test was that the airplane responded with no unusual, or peculiar, characteristics during this reconfiguration and slowing. One observation was that large bank angles (>45°) produced a noticeable over banking tendency. Also, differential thrust to reduce wheel angle and side slip was less effective at flaps 15, V_{REF} 15 + 5K =160 KIAS. Flight idle thrust on the engine opposite the rudder hardover reduced wheel angle from about 45 degrees to 35 degrees and side slip from 11 degrees to 8 degrees.

Flight with Asymmetric Leading & Trailing Edge Devices (Test 8.10 through 8.16)

These tests were planned to investigate the control difficulties resulting from asymmetrical leading edge devices and trailing edge flaps. Three leading edge devices retracted on one side with flaps extended have been successfully flight tested. Tests were planned in this configuration, progressing to a maximum flap asymmetry of 8 degrees as limited by the asymmetry protection, and finally resulting in manual reversion with loss of A & B hydraulic systems. However, the simulator would only allow one leading edge device, the #2 slat, which is supposedly the worst case, to be simulated retracted. Also, manual reversion was not possible with the simulator configured as tested. Therefore, the test was conducted by starting at 210 KIAS and slowing, extending flaps at approximately the normal maneuvering speeds. At the first flap extension, flaps 1, the #2 slat was failed in the retracted position and remained there.

Flaps were extended to 5 degrees, then 15 degrees, and the landing gear was lowered. As flaps were commanded from 15 degrees to 30 degrees, the 8 degree flap asymmetry was inserted and flap extension stopped at approximately 25 degrees. For each configuration, flaps 1, 5, 15, and 25 degrees plus, the aircraft roll asymmetry was investigated as airspeed was reduced and angle of attack was increased to the point of a sharp roll-off which, in the simulator, occurred coincident with or just before stick shaker activation. Very little effect of either the failed slat or the flap asymmetry was noticed prior to initiation of the roll. After the roll-off, a normal stall recovery with more than adequate roll and yaw control was accomplished. This completed tests 8.10, 8.11, and 8.12. As explained above, tests 8.13 and 8.14, loss of hydraulics, could not be accomplished.

The simulator was then reset to a flaps 40, gear down, configuration with the #2 slat retracted and airspeed at 130 KIAS, approximately V_{REF}. Airspeed was then decreased and angle of attack increased until a roll-off in the direction of the failed slat occurred. Stick shaker activation occurred at a wing angle of attack of 17 degrees as roll angle passed through 25 degrees and roll rate peaked at 20 degrees/sec. A normal stall recovery was accomplished. Maximum roll angle reached during recovery was 50 degrees and maximum sideslip angle was 18 degrees. This completed tests 8.15 and 8.16.

The essential results of these tests was that the failure of one leading edge slat to extend upon flap extension, alone, or combined with a flap asymmetry limited to that permitted by the flap asymmetry protection system, had very little effect on aircraft flight characteristics until angles of attack very near the stall were attained.

CONCLUSIONS

(1) Rudder/Aileron Trim Runaways - If the autopilot was disconnected "hands off" after a full displacement trim input, the aircraft rolled rapidly (13 to 22 degrees/sec at lower speeds and 30 to 44 degrees/sec at higher speeds). Prompt pilot reaction was required to prevent excessive (>60°) bank angles from developing.

(2) Lateral versus Directional Control Power Including Rudder "Hardovers" - These tests basically confirmed Boeing's contention that lateral control has more roll authority than does the dihedral effect from full rudder inputs for flight conditions tested. In the flaps 1, 190 KIAS condition lateral control also predominated, but recovery from a rudder "hardover" was slow and required precise

pilot control of resulting pitch/airspeed. Prompt pilot response was required to prevent entering the inverted flight regime at high altitude/speed.

(3) Flight with Zero or One-half Aileron/Rudder Feel Force - Failure of one spring (1/2 feel) in the feel and centering mechanism in either axis was judged to be difficult for a pilot to recognize in flight and potentially latent. Zero feel in the lateral axis was recognizable and control was not a problem. Zero rudder feel was recognizable but produced a control problem due to lack of rudder centering. Pilot inputs resulted in conditions similar to partial or full rudder hardovers.

(4) Control with Spoilers Only After a Simulated Pilot's side Body Cable Jam - With both Ailerons jammed at the displacements tested, 10 to 20 degrees, flight with pilot (copilot) input through the aileron transfer mechanism was extremely difficult, if not impossible, due to the high forces necessary. Control of the aircraft could be regained, but long term flight to a successful landing was questionable due to pilot effort required and fatigue.

(5) Flight with One or Two Spoiler Panels Stuck Up on the Same Side - Roll control in these flight conditions was generally not a problem. The additional pilot workload factor was the loss of performance due to increased drag and loss of lift once the malfunction was countered with opposite wheel. The landing configuration, two spoilers stuck up, malfunction was flown to a landing and resulted in a hard landing.

(6) Flight with the No. 2 Slat Retracted and Flaps Extended, Including Asymmetric Flaps - None of these malfunctions presented a control problem until angle of attack was increased to near stall. Then a sharp roll-off in the direction of the retracted slat occurred almost coincident with stick shaker activation. A normal stall recovery regained aircraft control.

The data resulting from this simulator exercise consists of a video tape of the simulator's computed outside view animation of the aircraft's motions with the cockpit area microphone and speaker on the audio channel plus the digitally recorded data parameters listed in Figure 2. A printout of these parameters versus time was provided to the FAA and that data plus the video/audio tape formed the basis for this report. The data is on file with the Boeing Company and is identified as "FAA Audit Simulator Session, November 17, 1994."

SIMULATOR TEST PLAN - B737 CDR TEAM - November 17, 1994

TEST		TEST			CONDITIONS	COMMENTS
No.	Test Description	WT/CG	M/V	Hp/OAT	Config. -Flap, Gear, Feel Force	Pilot Action
1.10/1.11	Rudder/Aileron Trim Runaway	LT/AFT	CRUISE	350/STD	CLEAN	Disconnect with and
1.20/1.21	Autopilot engaged	LT/AFT	250K	6000/STD	CLEAN	without hands on
1.30/1.31		LT/AFT	V_{REF}	6000/STD	LANDING F30	
2.10	Lateral vs. Directional	LT/AFT	CRUISE	350/STD	CLEAN	Oppose directional
2.11	Control Power; steady	HVY/FWD	"	"	"	hardover with lateral
2.20	sideslip and dynamic transition	LT/AFT	250K	6000/STD	CLEAN	control and vice-versa;
2.21		HVY/FWD	"	"	"	Perform dynamic
2.30		LT/AFT	190K	"	Flaps 1, Gear Up	maneuver and determine
2.31		HVY/FWD	"	"	" "	steady sideslip moment
2.40		LT/AFT	V_{REF}	"	LANDING	
2.41		HVY/FWD		"	"	
3.10	Flight w/o directional	LT/AFT	CRUISE	350	CLEAN/1/2 R feel	Qualitatively
3.11	or lateral feel forces	"	"	"	" /0 R feel	evaluate aircraft
3.12		"	"	"	" /1/2 A feel	controllability with
3.13		"	"	"	" /0 A feel	reduced /0 aileron
3.14		"	250K	6000/STD	" /1/2 R feel	or rudder feel
3.15		"	"	"	" /0 R feel	forces
3.16		"	"	"	" /1/2 A feel	
3.17		"	"	"	" /0 A feel	
3.18		"	V_{REF}	"	Ldg./1/2 R feel	
3.19		"	"	"	" /0 R feel	
3.20		"	"	"	" /1/2 A feel	
3.21		"	"	"	" /0 A feel	

SIMULATOR TEST PLAN - cont'd

TEST		TEST CONDITIONS				COMMENTS
No.	**Test Description**	**WT/CG**	**M/V**	**Hp/OAT**	**Config. Flap, Gear, CG**	**Pilot Action**
4.0	Simulated Rudder Bus					Deferred until
	Bar and Cable Failures					later
5.10	Lateral axis autopilot	High w/delta	M_{mo}	350/STD	CLEAN/AFT CG	Recovery after
5.11	hardovers w/o force	LT/AFT	V_{mo}	Knee/STD	CLEAN	appropriate delay
5.12	limiting	LT/AFT	250K	6000/STD	CLEAN	
5.13		LT/AFT	190K	6000/STD	Flaps 1, Gear Up	
5.14		LT/AFT	V_{REF}	6000/STD	LANDING	
6.10	Control with spoilers	HVY/FWD	CRUISE	350/STD	CLEAN	Determine if
6.11	only with ailerons	"	250K	6000/STD	CLEAN	control is possible
6.12	jammed @ 1/2 and full	"	190K	6000/STD	Flaps 1, Gear Up	
6.13	deflection	"	V_{REF}	6000/STD	LANDING	

SIMULATOR TEST PLAN - cont'd

TEST		TEST CONDITION				
No.	**Test Description**	**WT/CG**	**M/V**	**Hp/OAT**	**Config. Flap,/Slat, Gear**	**Pilot Action**
7.10	Flight with one/two	HVY/FWD	CRUISE	350/STD	CLEAN, 1 S Up	Determine if
7.11	spoiler panels stuck	"	"	"	" , 2 S Up	control is possible
7.12	up on the same side	"	250K	6000/STD	CLEAN, 1 S Up	
7.13		"	"	"	" , 2 S Up	
7.14		"	190K	"	Flaps 1, G R Up, 1S Up	
7.15		"	"	"	" " 2S Up	
7.16		"	V_{REF}	"	Ldg, 1 S Up	
7.17		"	"	"	" , 2 S Up	
8.10	Flight with asymmetric	HVY/FWD	Flaps 1	V_{LE}	Flaps 1, 1 Slat Up	Qualitatively
8.11	LE & TE devices	"	Flaps 5	V_{LE}	Flaps 5, 1 Slat Up	evaluate difficulty
8.12	progressing to manual	"	Flaps 15	V_{LE}	Flaps 15, Gear Dn,	in aircraft control
	reversion - starting				1 Slat Up,* 8% Jackscrew travel Flap asym	
8.13	altitude/OAT is	"	Flaps 25	V_{REF}	same as above,	
	6000/STD for all				"B" Hyd. Sys. /inop.	
8.14	tests	"	"	"	same as above,	
					+"A" Hyd. Sys. /inop.	
8.15		"	Flaps 40	V_{REF}	Flaps 40, Gear Dn.,	
					1 Slat Up	
8.16		"	V_{STALL}		same as above	

Parameters recorded For B737 CDR Team Simulator Test:

1. Roll Attitude, Pitch Attitude, Heading
2. Roll, Pitch, and Yaw Rate
3. Vertical, Lateral, Longitudinal Acceleration
4. IAS, CAS, Hp, Oat
5. Control Wheel Displacement and Force (Pitch and Roll)
6. Rudder Pedal Displacement and Force
7. All Control Surface Positions
8. LE Device and TE Flap Positions
9. All Trim Positions (Actuator or Surface, not Switch)
10. Angle of Attack (Wing or Body with Conversion) and Sideslip Angle
11. A Thrust Parameter for each engine (N_1 or Thrust)
12. Yaw Damper Control Signal or Resultant Rudder Displacement Separated from Total Rudder Position
13. Autopilot pitch and roll engage discretes

SERVICE HISTORY - CONTINUED OPERATIONAL SAFETY REFERENCES

The following tables lists all Airworthiness Directives (ADs), Boeing Service Bulletins (SBs) and Boeing Service Letters (SLs) reviewed by the Team. The initial list was compiled from a series of indexes in which the subject matter may have been relevant to the design review.

Service Letters and Service Bulletins are manufacturer's generated documentation issued for airline customers. Service Letters typically convey general information, i.e., to discuss field problems and highlight information already existing or scheduled to be incorporated in existing documentation; to notify operators of interchangeability or future spare part numbers of equipment which have no effect on aircraft safety, performance, maintainability and reliability; to notify operators of changes in material finishes, protective coatings, etc. Service Bulletins, which are an amendment to the type design, are typically issued to cover modifications to the aircraft, engine, or accessories; substitutions of parts when the parts are not completely interchangeable both functionally and physically; conversions from one engine model to another, etc. Issuance of Service Bulletins may be the result of product improvements, safety issues or customer requests. Incorporation of Service Bulletins are not mandatory unless required by an Airworthiness Directive. (See "Recommendations for FAA Action" Section 15. Recommendation -25, -26).

Service Difficulty Reports are generated from operators who are required, by regulation, to report on certain mechanical discrepancies. In addition to the specific mechanical irregularities specified in the regulations, operators are also directed to report on any other failure, malfunction, or defect in an aircraft that occurs or is detected at any time if, in its opinion, that failure, malfunction, or defect has endangered or may endanger the safe operation of an aircraft used by it. Because opinions of what may constitute endangerment of the safe operation of an aircraft differs from operator to operator, the data base for the SDRs may not fully reveal the extent of particular problems or a lack thereof. In addition, these reports are not verified for accuracy and the actual discrepancy and corrective action may not match the reported discrepancy and corrective action, i.e. a reported rudder hardover may, if fact, have been a yaw damper hardover. Because the accuracy of the data base is not verified, this information was used primarily as indicators of potential problem areas.

The ASRS is a program administered by the National Aeronautics and Space Administration (NASA) and funded by the Federal Aviation Administration (FAA). The ASRS collects, analyzes, and responds to voluntarily submitted aviation safety incident reports in order to lessen the likelihood of aviation accidents. Pilots, mechanics, ground personnel, or others involved in aviation operations submit reports to ASRS when they are involved in, or observe, an incident or situation in which aviation safety was compromised.

AIRWORTHINESS DIRECTIVES

AD #	AD SUBJECT	REF SB/SL	COMMENTS
94-01-07	RUDDER ACTUATOR PISTON	SL 737-SL-27-82B SB 737-27-1185	
93-01-27	FLIGHT CONTROL CABLE GUARDS	SB 737-27-1164	
91-09-17	B737-300 FLAP TRACK BOLTS	SB 737-57-1202 SB 737-57-1212	
91-05-16	MAIN LANDING GEAR ACTUATOR BEAM ARM	SB 737-32-1224	Hitting cables
90-24-04	OUTBOARD FLAP FITTING ATTACHMENT	SB 737-57-1206	
90-17-20	LOSS OF THE OUTBRD FLAP	SB 737-57-1079	-200 Flap track bolts
88-07-04	HYDRAULIC SYS, BRAKES, NOSE WHEEL STEER.	SB 737-32-1202	Installation of MLG brake metering valve tire burst guards.
86-18-04	SELF-LOCKING NUT TORQUE INSPECTION		
80-07-02	FLIGHT CONTROL SYSTEMS		Rudder MPCU servo valve by Fortner

AIRWORTHINESS DIRECTIVES

AD #	AD SUBJECT	REF SB/SL	COMMENTS
90-10-51R0	SEPARATION OF CONTROL WHEEL FROM COLUMN		Inspection
80-26-51	CONTROL SYSTEM JAMMING (ELEVATOR) - BOLTS	SB 737-27A-1109	Pitch Axis.
80-22-12R2	LEADING EDGE DEVICES	SB 737-31-1038R3	
76-11-05R1	CONTROL SYSTEM VIBRATION	SB 737-55A1020R3	Loose elevator tabs
76-01-03	B737-200 FLOOR BEAMS	SB 737-53-1044	
75-24-09	GROUND SPOILERS	SB 737-27-1080	
75-05-01	REPLACEMENT OF ARVAN CABLE PULLEYS	SB 737-27-1073R1	Applied to only a few early models
69-12-06	AILERON TAB MAST FITTING	SB 737-57-1040	

B737 FLIGHT CONTROLS

BOEING SERVICE BULLETINS

BULLETIN #	DATE	SUBJECT	COMMENTS
737-27-1164	09/13/90	ELEVATOR CABLE GUARDS	Prompted by incident - plastic guards melted due to APU bleed air.
737-27-1155	10/26/89	AILERON TRIM/CENTERING MODIFICATION	Degraded aileron feel due to failed spring.
737-27-1154	08/25/88	AILERON AND TRIM PULLEY BRACKET	Only -300 Series
737-27-1145	11/12/87	RUDDER PISTON CAP REPLACEMENT	
737-27-1135	07/10/86	AILERON CABLE IDLER	5 aircraft
737-27-1134	07/11/86	AILERON TRIM/CENTERING MECHANISM	
737-27-1127	10/25/85	RUDDER MPCU COVER PLATE	
737-27-1125	03/08/85	PLASTIC CONTROL CABLE GUARD	
737-27-1091	02/02/70	YAW DAMPER REWORK	
737-27-1081	12/10/76	GROUND SPOILER VALVE CABLES	
737-27-1080	11/21/75	GROUND SPOILER ACTUATOR	Affected -400 series aircraft
737-27-1075	05/30/75	RUDDER PEDAL ADJUSTMENT MOD.	Cable issue

B737 FLIGHT CONTROLS

BOEING SERVICE BULLETINS

BULLETIN #	DATE	SUBJECT	COMMENTS
737-27-1125	03/08/85	CABLE GUARD INSTALLATION	
737-27-1118	06/24/83	AILERON ACTUATOR HYDRAULIC TUBE ASSEMBLY REPLACEMENT	
737-27-1112	02/26/82	FLIGHT SPOILER ACTUATOR MOD.	One spoiler "stuck" up.
737-27A1109	12/11/80	ELEVATOR CU INPUT ROD ASSEMBLY ATTACH BOLT INSPECTION	Alert Bulletin
737-27-1107	05/08/81	RUDDER NOSE FAIRING INSPECTION & MOD.	
737-27-1101	02/01/80	STABILIZER TRIM ACTUATOR TORQUE TEST	AD issued
737-27-1099	10//12/79	STANDBY RUDDER CONTROL MAST FITTINGS WEAR PLATE INSTALLATION	
737-27-1094	12/21/78	FLIGHT CONTROL POSITION SENSOR INSPECTION/REIDENTIFICATION	
737-27-1089	07/07/78	RUDDER ACTUATOR ATTACHMENT FITTING REPLACEMENT	
737-27-1060	08/02/72	RUDDER PRESSURE REDUCER AND RELIEF VALVE INSP/REMOVAL	
737-27-1058	03/10/72	AILERON GEARED TRIM ASSEMBLY COVER REWORK	
737-27-1055	10/25/71	RUDDER RIG PIN HOLE RELOCATION	
737-27-1053	10/28/71	RUDDER TRIM ACTUATOR DRIP SHIELD INSTALLATION	
737-27-1052	08/20/71	BEARING RETENTION SLEEVE REPLACEMENT	

B737 FLIGHT CONTROLS

BOEING SERVICE BULLETINS

BULLETIN #	DATE	SUBJECT	COMMENTS
737-27-1073	02/10/75	ARVAN MANUFACTURED CONTROL SYSTEMS PULLEY INSPECTION AND REPLACEMENT	
737-27-1064	03/29/74	RUDDER PCU INPUT LEVER REVISION	
737-27-1063	09/28/73	RUDDER PCU YAW DAMPER ACTUATOR STROKE REDUCTION	
737-27-1061	03/23/73	AILERON CONTROL WHEEL DRUM SWIVEL JOINT ATTACHMENT NUT INSPECTION/REPLACEMENT	
737-27-1043	06/08/70	RUDDER PEDAL CRANK BOLT REPLACEMENT	
737-27-1033	02/13/70	LATERAL CONTROL SYSTEM TRANSFER MECHANISM MOD.	High forces
737-27-1026	01/15/71	REPLACEMENT OF EXISTING RUDDER FEEL AND CENTERING UNIT ASSEMBLY WITH NEW ALL-MECHANICAL UNIT	
737-27-1025	04/30/69	AILERON TAB ROD REPLACEMENT	
737-27-1018	02/25/69	SPEED BRAKE CABLE PULLEY BRACKET MOD	
737-27-1017	11/22/68	RATIO CHANGER ASSEMBLY CABLE GUARD REPLACEMENT	
737-27-1013	06/24/68	RUDDER AUXILIARY PCU SHEAR PIN REPLACEMENT	
737-27-1004	04/02/68	FORCE TRANSDUCER CONNECTOR MOUNTING BRACKET RELOCATION	
737-27-1001	11/09/67	RUDDER PEDAL ADJUSTMENT MOD.	

B737 FLIGHT CONTROLS

BOEING SERVICE LETTERS

LETTER #	DATE	SUBJECT	COMMENTS
737-SL-27-91	07/12/94	RUDDER PCU ALTERNATE CHECK PROCEDURES	AD
737-SL-27-83	05/06/93	RUDDER PCU DESIGN IMPROVEMENT	AD
737-SL-27-82-B	07/13/93	RUDDER PCU ANOMALIES	AD
737-SL-27-71A	06/19/92	AILERON/ELEVATOR PCU FLOW RESTRICTOR FILTER SCREEN CONTAMINATION	
737-SL-27-57	12/05/89	RUDDER FEEL AND CENTERING UNIT LUBRICATION	
737-SL-27-52-A	05/03/93	AILERON/ELEVATOR POWER CONTROL UNIT INTERCHANGEABILITY	
737-SL-27-50-A	06/22/88	RUDDER PCU AND YAW DAMPER COUPLER INTERCHANGEABILITY	
737-SL-27-48	09/23/87	RUDDER TRIM ACTUATOR DISCREPANT OPERATION	
737-SL-27-46	08/06/87	AILERON FORCE LIMIT MECHANISM IMPROVEMENT	
737-SL-27-40	03/31/86	UNCOMMANDED TRAILING EDGE FLAP MOVEMENT	
737-SL-27-35	08/29/85	UNCOMMANDED LEADING EDGE DEVICE EXTENSION THROUGH STANDBY SYSTEM	
737-SL-27-30	04/01/85	AILERON/ELEVATOR AND RUDDER PCU CYLINDER BORE REWORK	
737-SL-27-24	06/28/83	RUDDER CENTERING UNIT LUBRICATION	
737-SL-27-16	08/25/80	FLIGHT CONTROLS, RUDDER, TRIM CONTROL, ACTUATOR LUBRICATION	
737-SL-27-15	01/10/80	FLIGHT CONTROLS, RUDDER, POWER UNIT, OVERHAUL DISCREPANCY	AD
737-SL-27-13	09/25/79	FLIGHT CONTROLS, RUDDER, JACKSHAFT INST, CONTROL ROD, BENDING	
737-SL-27-07	06/08/77	AIRCRAFT CONTROL CABLE	
737-SL-27-04	03/07/77	AILERON/ELEVATOR PCU AUTOPILOT ENGAGE MECHANISM BINDING	

B737 HYDRAULIC SYSTEM

BOEING SERVICE BULLETINS

BULLETIN #	DATE	SUBJECT
737-29-1069	10/25/85	RUDDER MPCU COVER PLATE
737-29-1064	06/10/93	HYDRAULIC POWER - PTU SYSTEM - REPLACEMENT OF OUTLET PORT CHECK VALVE AND TUBE ASSEMBLY
737-29-1062	02/14/91	HYDRAULIC POWER -PRESSURE FILTER MODIFICATION
737-29-1037	12/07/79	HYDRAULIC RESERVOIR PRESSURIZATION SYSTEM MODIFICATION
737-29-1031	01/16/76	HYDRAULIC SYSTEM HEAT EXCHANGER CLAMP REPLACEMENT
737-29-1030	10/24/75	HYDRAULIC SYSTEM LOW PRESSURE WARNING SWITCH REPLACEMENT

BOEING SERVICE LETTERS

LETTER #	DATE	SUBJECT	COMMENTS
737-SL-29-5	03/03/77	ID OF HYDRAULIC SYSTEM COMPONENTS MOST FREQUENTLY REMOVED FOR INTERNAL LEAKAGE	Rudder MPCU at top of list
737-SL-29-4	02/15/77	BMS 3-11 HYDRAULIC FLUID STATUS	
737-SL-29-3	10/14/76	HYDRAULIC FLUID USAGE	
737-SL-29-2	08/06/76	CONVERSION OF HYDRAULIC FLUID FROM STAUFFER AEROSPACE ER	
737-SL-29-1	04/22/76	RECLAIMED HYDRAULIC FLUID	

B737 HYDRAULIC SYSTEM

BOEING SERVICE LETTERS

LETTER #	DATE	SUBJECT
737-SL-29-50	01/10/91	BMS 3-11 HYDRAULIC FLUID - PURIFY
737-SL-29-46	11/14/89	HYDRAULIC POWER - INTERNAL LEAKAGE CHECK INTERVAL
737-SL-29-37-A	11/18/91	CORROSION PROTECTION FOR HYDRAULIC COMPONENTS
737-SL-29-30	07/25/85	WATER ACCUMULATION IN THE HYDRAULIC RESERVOIR AIR PRESSURIZATION LINE AND FILTER
737-SL-29-18	06/06/79	HYDRAULIC POWER, GENERAL, HYDRAULIC FLUID, EROSION, TEST
737-SL-29-15	09/28/78	HYDRAULIC SYSTEM CONTAMINATION
737-SL-29-08	04/19/77	STANDBY HYDRAULIC SYSTEM INTERNAL LEAKAGE CHECK PROCEDURE
737-SL-29-06	03/07/77	HYDRAULIC SYSTEM "A" FILTER DELTA P INDICATOR BUTTONS

B737 AUTOPILOT

BOEING SERVICE BULLETINS

BULLETIN #	DATE	SUBJECT
737-22-1112	06/18/92	EMI EFFECTS ON YAW DAMPER
737-22-1074	11/27/85	YAW DAMPER DECREASE IN AUTHORITY
737-22-1072	01/17/86	ADDITION OF WIRE IN YAW DAMPER
737-22-1069	08/07/85	YAW DAMPER AUTHORITY INCREASE
737-22-1062	09/16/83	AUTOMATIC FLIGHT CONTROL SYSTEM - AUTOPILOT ACCESSORY UNIT - STABILIZER TRIM FUNCTION MOD.
737-22-1042	07/01/83	AUTOMATIC FLIGHT CONTROL SYSTEM - RUDDER POSITION SENSOR REMOVAL
737-22-1033	03/12/81	SP-177 AUTOPILOT ACTUATOR AUTHORITY REDUCTION
737-22-1025	06/06/80	SP-177 AUTOMATIC FLIGHT CONTROL COMPUTER REPLACEMENT
737-22-1020	05/16/80	YAW DAMPER COUPLER REPLACEMENT

B737 AUTOPILOT

BOEING SERVICE LETTERS

LETTER #	DATE	SUBJECT
737-SL-22-30	12/13/91	AUTOMATIC PILOT - FLIGHT CONTROL COMPUTER P/N 10-62038-4
737-SL-22-20	11/20/87	AUTOPILOT DISENGAGEMENT AS TRAILING EDGE FLAPS TRANSITION TO OR FROM THE UP POSITION
737-SL-22-10	05/16/86	AUTOPILOT STABILIZER TRIM SERVOMOTOR REPLACEMENT
737-SL-22-09	05/05/86	AUTOPILOT DISENGAGEMENT AS TRAILING EDGE FLAPS TRANSITION TO OR FROM THE UP POSITION
737-SL-22-02	08/24/81	AUTOFLIGHT, AUTOPILOT, CTL WHEEL STEER, DETENT FORCES, EXCESSIVE
737-SL-22-01	03/11/76	DELETION OF SYSTEM A YAW DAMPER AND AUTOPILOT

AVIATION SAFETY REPORTING SYSTEM REPORTS

The B737 CDR Team requested all Aviation Safety Reporting System (ASRS) reports addressing B737 (all series) lateral and directional flight control surfaces. The ASRS is a program administered by the National Aeronautics and Space Administration (NASA) and funded by the Federal Aviation Administration (FAA). The ASRS collects, analyzes, and responds to voluntarily submitted aviation safety incident reports in order to lessen the likelihood of aviation accidents. Pilots, mechanics, ground personnel, or others involved in aviation operations submit reports to ASRS when they are involved in, or observe, an incident or situation in which aviation safety was compromised.

The ASRS database is a public repository which serves the FAA's and NASA's needs and those of other organizations world-wide which are engaged in research and the promotion of safe flight. The FAA guarantees not to use ASRS information against reporters in enforcement actions as an incentive to report. ASRS reports identify system deficiencies and issue alerting messages to persons in a position to correct them. ASRS's database includes the narratives submitted by reporters (after they have been sanitized for personal identifying details).

The Team received all reports available since the inception of ASRS on January 1, 1986. According to NASA, the reports received by the Team contained some McDonnell-Douglas MD80 reports due to the limitation of the database to identify B737-specific reports. The Team collectively analyzed each ASRS report and identified/eliminated the MD-80 reports based on information contained in the narratives.

The following analysis was made by the Team:

Directional Axis (Rudder) -

Total Reports Received	25
Non-B737 Reports	-9
Reports Considered	16

Synopsis review and sorting of the reports yielded the following:

# of Events	Reported Issue
11	Rudder trim runaway (two confirmed inadvertent switch activation events)
3	Yaw damper anomalies
2	Rudder pedal adjustment mechanism malfunctions

In all cases, flight was controllable and a safe landing was made. A review of the reports indicated that yaw damper anomalies occur frequently and are a safety concern of flightcrews.

Lateral Axis Including High Lift Devices (Ailerons, Ground and Flight Spoilers, Flaps, Slats) -

Total Reports Received	75
Non-B737 Reports	-22
Reports Considered	53

Synopsis review and sorting of the reports yielded the following:

# of Events	Reported Issue
16	Operational errors (not related to design or hardware)
11	Flap position indicator circuit breaker popped
6	Flaps would not extend on approach
5	Flap/spoiler indicator malfunctions
4	"Split flap" asymmetry malfunctions
2	Flaps would not retract after takeoff
1	Flaps "jammed" at 2 degrees
1	"Vibration" detected during flap extension
1	Ground spoiler motor malfunction
1	Ground spoiler actuator hydraulic line failure
1	Jammed aileron due to frozen water at altitude
1	Aileron cable failure
1	"Abnormal" aileron deflection
1	Aileron trim tab failure/separation
1	Hydraulic system B failure

In all cases, flight was controllable and a safe landing was made. Some of the ASRS reports provided evidence for potential jams in the lateral controls of the B737. One of the jams was reportedly caused by ice formation at altitude after ground operations in the rain. Another was due to an aileron cable breaking.

CDR TEAM TRIP REPORTS -

MANUFACTURER AND REPAIR FACILITY VISIT -

1) TRAMCO. The Team members visited TRAMCO, INC., an overhaul facility located in Everett, Washington. TRAMCO is a FAR Part 145 Repair Station and conducts regularly scheduled heavy maintenance checks on the B737 and other large transport category aircraft. The purpose of the visit was to look at in-service components to observe the condition of the parts and to familiarize the Team members with the actual aircraft hardware. In addition, the Team interviewed TRAMCO employees to get their views on flight control system in-service history and problem areas.

The Team conducted informal inspections of B737 aircraft in various stages of disassembly. Location, orientation and spatial relationships between the various hydraulic, electrical and mechanical components of the flight control systems were reviewed and noted. The function of various flight control system components was observed.

The Team was provided access to the hydraulic component repair facility. In this facility, the Team met with the technicians who did the actual tear down, repair, reassembly and test of the hydraulic components. Specific components that were examined were the B737 aileron and rudder PCUs. These components were examined in detail, including the filters, bypass valves and servo valves. Potential jam areas where moving components had close working clearances or where complex mechanisms were difficult to inspect were identified. The actual physical characteristics (size, surface finish, fit, etc.) of the internal hydraulic components were observed. These examinations resulted in additional questions for Boeing design engineers or hydraulic component manufacturers.

(2) PARKER HANNIFIN. A Team representative visited Parker Hannifin Corporation Control Systems Division in Irvine, California on December 16, 1994 to discuss various aspects of the B737 rudder PCU. Personnel contacted were Bill Simmons, Steve Weik, and Shih-Yung Sheng, all of the Controls Division Engineering Staff. Many items and issues were discussed. The following is a summary of the discussion and findings:

(i) PCU description and function. The internal summing linkage of the unit is of conventional design and arrangement except it is all redundant except the walking beam. However a secondary (or ground) spring provides a redundant linkage pivot to effectively provide redundancy for the beam. No single failure of any linkage element can result in a hazardous condition. The operation of the yaw damper was reviewed with an eye toward determining any possible failure mode that could result in a surface deflection in excess of 3 degrees. The mod piston stroke controls the damper input to the linkage. It bottoms out hard mechanically at the 3 degree input. It appears that only an misassembly could cause an input larger than the 3 degrees. It is believed that misassembly would be detected during the Acceptance Test Procedure (ATP). A copy of the linkage diagram depicting dimensions, displacements, and forces was provided to the CDR Team representative.

The dual concentric servo valve assembly in the B737 rudder PCU was invented circa 1960. It has a primary slide and secondary slide with active strokes of +.045 in. each. The total stroke of both valves with overstroke capability is $\pm$0.110 in. The valving is balanced with 1500 psi. nominal pressure at neutral. The slide friction is 8 oz. maximum for each slide. The secondary slide has centering springs equal to 10-12 # at the slide centerline.

The primary slider is fitted with a bias compression spring that applies a retract preload to the slider. Parker indicates that this was Boeing requirement to load out free play in the linkage and improve the closed loop frequency response.

A brief review of the linkage kinematics and the Boeing Specification for this unit was conducted with Parker Engineering. It appears that the chip shearing force that can be applied to the valve centerline by the pilot can be as low as about 37# based on the requirements of Figure 7 of the Specification Control Drawing, 65-44861.

If this is correct it would be significantly less that Boeing Engineering has previously indicated. In addition it was indicated to the CDR Team representative that Boeing conventionally requires a chip shearing capability of 200# along the valve centerline. Parker is currently designing actuators containing direct drive valves that even have a chip shearing capability of 80#.

The PCU contains three filter elements, two rated at 6 gpm for the systems A and B inlets and one rated at 1 gpm for the yaw damper. Filtration rating for both is 10 micron nominal and 25 micron absolute.

(ii) Recent PCU changes. The rudder PCU design is all on Boeing paper, however, the valve assembly is on Parker paper and is considered to be proprietary to Parker. The production valve assembly P/N is 68010-5003. This is the assembly that can, under adverse tolerance conditions and with a primary slider jam, result in actuator output reversal. The Parker Service Bulletin 68010-27-162 replaces this assembly with the 68010-5005 or -5007 assembly. The -5005 is created by simply replacing the spring guide and other components in the -5003 assembly. The new part then becomes a matched assembly. This could cause a problem downstream during overhaul if conducted by other than knowledgeable Parker staff. The -5007 is a totally redesigned unit with dimensioning and tolerancing differences to ensure that output reversal cannot occur. Parker has incorporated acceptance test procedures to check for possible valve overtravel in both the valve assembly ATP and in the PCU ATP.

(iii) Aileron/Elevator PCU design history. The aileron/elevator PCU with the integrated autopilot function was originally designed and built by National Waterlift. However the current version of the PCU is fabricated by Parker and the separate autopilot unit is built by the Montek Division of E-Systems in Salt Lake City.

(iv) Hydraulic fluid contamination. The Boeing specification requires that the test fluid meet the particulate contamination level of NAS 1638 Class 5. Parker has acceptance standards to control particulate contamination level for all fluids used for testing to the requirements of NAS 1638 Class 5. In addition they also control the fluid properties and chemical contamination levels.

(v) Fabrication and testing of typical valve assemblies. The CDR representative visited the Parker Customer Support Division and met with Wally Walz, the Technical Integrity Manager. Parker says that 75% of the actuators coming in for overhaul have been removed for excessive rod seal leakage (the requirement for in-service components is in the order of 2 drops/25 cycles per seal). Additional causes for removal are "inoperable" and now of course units are removed and sent in to incorporate the replacement or new valve assembly per the Parker Service Bulletin 68010-27-162. All PCUs that come in for repair are subjected to an acceptance test procedure regardless of the customer complaint. Any other malfunctions are evaluated and the customer informed of the problem prior to the repair. If units come in under warranty Parker takes an oil sample. In some cases, if the oil sample contains an excessive amount and size of particles it may nullify the warranty. The filters, inlet and yaw damper, are always removed, cleaned and reinstalled. Other areas of the actuator are only disassembled at customer direction or to correct a malfunction uncovered during test.

The technician conducting the incoming testing stated he had only seen 1 (maybe 2) jammed secondary valves in approximately 1000 units tested, but had not experienced any jammed primary sliders. He stated that he had seen no linkage jams or other anomalies that would have resulted in gross malfunctioning of the unit.

A problem that they occasionally see in the actuator is the lack of not meeting the ATP input force-stroke requirements due to improper spring force, friction, etc. Other problems include excessive neutral or land leakage, excessive phase lag in the damper servo (may require replacement of the damper transfer valve), and elongation of the primary valve drive hole ID due to the valve bias spring preload. The majority of servo valve repairs consist of fabricating new primary sliders due to wear of the metering edges and/or erosion of the orifices in the sleeves.

The sleeve/slider matching operation was observed. Parker match grinds the rudder primary valve to its sleeve to obtain .001-.002 underlap. The secondary slider is matched to its sleeve with .002-.0025 overlap. The aileron/elevator primary valve is machined to a zero lap condition with the secondary matched with .001-.0015 overlap.

The assembly is designed to accommodate a single failure due to a valve jam without a catastrophic or hard over output condition. The degree of control of the surface that the pilot retains after a jam is a function of which valve, primary or secondary, jams and where in its stroke it jams. Inherent in the design philosophy of this configuration is the ability to detect a jam of one of the two concentric valves. However in the B737 rudder PCU implementation, it is questionable whether an initial jam can always be detected or whether some jams may in fact be latent. Consideration could be given to providing the flightcrew with information regarding the characteristics of this valve and suggestions of how the jam free operation of both valves may be ascertained on a pre-flight basis.

(vi) Servo valve fabrication criticality. The valve assembly is a highly complex assembly involving extremely close tolerances, individualized material selection, unique material processes and requiring sophisticated testing equipment and test procedures. The design tolerances must be controlled to provide the necessary surface positionability, keep the internal fluid leakage to an acceptable level and to provide the pilot with the necessary controls fidelity. The complexity of the dual concentric arrangement also requires that its design and its tolerances take into account the installation into the actuator. The design of the valve itself must be such that the resultant installation under adverse tolerances will not bind, jam or malfunction in any way. This was abundantly clear recently when it was discovered that even the OEM apparently overlooked a tolerance stackup resulting in a serious potential malfunction of the rudder PCU. Due to the close tolerances involved in the sleeve and slider mating surfaces extreme care must be applied to the material selection and to the heat treat specifications for the material. The design requires that the metering sleeves for both the primary and secondary be shrunk fit in their respective housings. This process requires accurate component temperature control, special fixtures and experienced operators as well as procedures that are well thought out. After manufacture and assembly, the valve must be subjected to comprehensive testing to ensure that it functions properly. The test procedure and subsequent tests must ensure that the assembly not only meet all its performance parameters but also uncover any manufacturing or assembly anomalies. In addition to the acceptance testing that each manufactured assembly is subjected to, the design must undergo qualification tests to ensure the valve's ability to withstand the operational and environmental stresses that it will see during its life.

Installation of a replacement valve assembly should take into account the above issues as minimum. The granting of a design approval of a replacement dual concentric valve assembly should be granted only after the design and installation has been thoroughly scrutinized; all process specifications verified and approved by Engineering and MIDO; all test procedures, qualification and acceptance, thoroughly reviewed and approved, assembly procedures approved, qualification test witnessed, test report approved, and assembly and acceptance testing witnessed. (See "Recommendations For FAA Action," Section 15. Recommendation -20. -21).

(3) DOUGLAS AIRCRAFT. Several members of the CDR Team visited the Douglas Aircraft Company (DAC) in Long Beach, California, on December 21, 1994. The purpose of the visit was to enhance the Team's knowledge of flight control design philosophies of other aircraft manufacturers in an effort to compare these with the design principles used for the B737.

Team members Mike Zielinski, Ron Filler, and Tom Donnelly were present during the one-day event. The Team was presented with an informative discussion by key DAC engineers and managers regarding the following subject areas: Systems, Aerodynamics, and Avionics as related to the Lateral and Directional Flight Controls on DAC Airplanes; the DAC Failure Modes and Effects Analysis Process; Hydraulic Fluid Contamination and System Maintenance; Flight Control System Maintenance; and a History of DAC Flight Control Anomalies. The discussion below is limited to the lateral/directional axes and does not include the pitch axis.

The basic flight control design for the DC-9/MD-80/MD-90 series airplanes has mechanical cable driven tabs for ailerons, and a hydraulically-powered rudder with manual reversion and "Q-sense" throw limiting. Spoilers are hydraulically-powered; the servo valve for the spoilers is of a dual-spool design; the rudder and yaw damper utilize single-spool servo valves. DAC stated that their hydraulic system designs do not use by-pass valves unless alternate fluid paths are available to prevent hydraulic lock in the event of a by-pass valve failure.

The older DC-8 series airplanes have a similar flight controls design to the DC-9/MD-80/MD-90 series, except that all flight controls are hydraulically actuated (with manual reversion), and the rudder is hinge moment limited.

The DC-10 and MD-11 flight controls are operated solely with hydraulic power and have no manual reversion capability. These airplanes utilize multiple surfaces in all axes. Aerodynamic summing is utilized rather than having multiple actuators on one larger surface. Force override mechanisms are utilized where necessary to allow independent actuation of those surfaces in the same axis necessary to counteract the failure of one hydraulically powered surface, even if the failure is a full deflection hardover.

A dual-concentric servo valve design is utilized to power the spoilers only on most DAC airplane models. The spoilers have no manual reversion capability. A "splitable" tandem valve is used on some applications with two hydraulic sources for one actuator. This valve is a DAC design and has a two spools on one input rod in parallel with break-out springs so that a single spool jam is counteracted by the follow-up through the other spool and hydraulic system. All of the hydraulic valves utilized by DAC have a minimum chip shear capability of 100 pounds.

To design around the potential hazard of an aileron system jam, DAC utilizes a "torque tube and override mechanism" mounted between the pilot and co-pilot control column on the DC-8 and DC-9/MD-80/MD-90 series airplanes. After an initial 60 to 90 pound force is applied to "break-out" the mechanism, the wheel forces return to near normal to control the airplane with the opposite aileron and spoilers. The DC-10/MD-11 airplanes have various spring override devices on each lateral control surface and in each major control mechanism that prevent any single system or surface jam from disabling the rest of the control system.

A discussion on the topic of aerodynamic requirements for rudder design revealed that while DAC did not perform flight testing for rudder hardovers, they have performed "rudder kick" maneuvers to evaluate the relationship between rudder throw and structural strength as a function of dynamic pressure. Besides structural concerns, DAC stated that rudder throw may also be restricted to ensure controllability. The DC-9-30 has an additional mechanical limit since yawing moment characteristics were unacceptable at maximum rudder with certain flap settings. DAC stated that during flight tests, they look for a steady sideslip trim point with sufficient yawing moment margin to handle a crosswind gust.

DAC yaw dampers were then discussed. On the DC-8 and DC-9/MD-80/MD-90 series airplanes, separate series yaw dampers are utilized. On the DC-10/MD-11 yaw damper and autopilot inputs are integrated with the main PCU via electo-hydraulic control valves, mod pistons, and lockout devices, similarly to the B737 rudder and earlier aileron systems.

A system safety engineer from DAC's Safety, Reliability, and Ergonomics group gave a presentation of how DAC conducts a failure modes and effects analysis (FMEA). For its later models, DAC utilizes a comprehensive FMEA review process that allows engineers from various disciplines to provide input and agree on action items. The DAC system safety engineers act as the common thread during this process and provide continuity. DERs authorized to approve FMEAs and system safety analyses are responsible to the safety group.

CDR Team members expressed concern regarding DAC's FMEA process and latent failures. When addressing latent failures, DAC takes credit for the inspection interval of the identified failure, but does not require a specific interval for the inspection except as provided by the MRB process.

A discussion of hydraulic fluid contamination revealed that DAC utilizes a hydraulic fluid specification when procuring the fluid, an in-plant control practice for fluid handling in plant, and recommended in-service practices for airlines to follow. DAC reviewed and synopsized their recommended hydraulic fluid sampling frequencies for our visit. A review of this synopsis revealed that the longest time period between checks was 4,200 flight hours or 18 months. (See Section 13. for hydraulic fluid issues). It should be noted that the MD-80 has no recommended fluid sampling period. DAC stated that they discovered this in the course of their preparation for our visit and will now make a recommendation for the MD-80.

Finally, DAC presented the Team with a summary of reported lateral and directional control anomalies for all of their airplanes. DAC stated that "no accidents have ever been attributed" to the flight control systems of DAC airplanes. DAC excluded "accidents" that did not result in hull loss from this assessment (e.g., the MD-11 flap handle events). Also, the Chicago and Sioux City DC-10 accidents resulted from a loss of control, although both were caused by external events (engine related failures).

To summarize the salient points of the B737 CDR Team's visit to DAC:

- The earlier DAC airplanes employ direct cable-driven surface tabs as the primary control mechanism for many of the flight control systems.

- The airplanes which have a hydraulically powered rudder have built-in hardover protection with the use of split surfaces, or manual reversion via hydraulic power shut-off lever. Earlier airplanes use deflection limit devices with airspeed inputs. Later airplanes use aerodynamic (blowdown) limiting.

- The breakout and resulting prolonged forces required to counter a jam in the lateral control system are significantly lower than those of the B737.

- The DAC minimum chip shearing capability for hydraulic servo valves is significantly higher than that of the B737 rudder PCU servo valve (100# versus 39#).

- DAC has more restrictive contaminated hydraulic fluid inspection requirements than those of the B737.

- DAC performs flight tests of "rudder kicks" to determine structural strength issues; flight tests of rudder hardovers to determine lateral vs. directional authority are not performed.

- DAC employs a Safety, Reliability, and Ergonomics group to perform hazard analysis on newer airplane models.

- DAC's FMEA process is comprehensive and crosses engineering and operational disciplines.

- In the DAC FMEA process for analyzing latent failures, DAC takes credit for the inspection interval of the identified failure, but does not make this inspection a CMR.

(4) FORTNER DISCUSSIONS. On December 20, 1994, several CDR Team members together with Los Angeles ACO and MIDO personnel met with Bob, Bill, and Jim Fortner, principals in Fortner Engineering and Manufacturing, Inc., at the FAA Los Angeles Aircraft Certification Office (LAACO).

The Fortner firm is an authorized Repair Station under FAR Part 145 and repairs and overhauls aircraft hydraulic components of all types for primarily airline and other aircraft operator customers. They repair and/or overhaul power control units (PCUs) on B737s aileron/elevators, and rudder MPCUs and standby PCUs. They have not been involved with rudder MPCUs lately, because AD 94-01-07 specifically requires that the rudder PCU be modified to incorporate a modified servo valve that can only be supplied by the OEM, Parker Hannifin.

Fortner Engineering develops their own FAA-approved data under the provisions of SFAR 36 to produce, repair, or replace parts for the units they overhaul or for use by other overhaul facilities that have sent specific components to them for repair. The most common of these components are what is referred to as "lap assemblies." These are typically servo vales or by-pass valves that have extremely close tolerance mating parts (slides and sleeves) that must be lapped together.

The data developed and approved by Fortner under SFAR 36 may be based on many types of documents including overhaul manuals, primary airframe manufacture drawings (e.g. Boeing or Douglas) and vendor drawings. Many times these documents are supplied to Fortner by their operator (airline) customer. The Los Angeles ACO, MIDO, and FSDO regularly audits Fortner to assure compliance with all pertinent regulations including Part 145, Part 21, SFAR 36, and the airworthiness regulations (Part 25). However, Fortner's overhaul of Boeing hydraulic components is not authorized by, nor coordinated with, Boeing or their OEM vendor, Parker Hannifin. Because of this lack of coordination and in consideration of the criticality of the main rudder PCU, the CDR Team questions the ability of Fortner to continue fabrication of the dual spool servo valve equivalent to that of Parker. (See "Recommendations For FAA Action," Section 15. Recommendation -20, -21, -22).

In fairness, though, it must be said that Fortner Engineering is an established and respected overhaul facility and they have been performing this type of work since the 1950's. They have overhauled over 50,000 lap assemblies and enjoy the confidence of both airframe manufacturers and many airline customers. The CDR Team has found no evidence that Fortner-overhauled components were involved in any of the accidents/incidents that precipitated this review. Specifically, the rudder MPCUs from the 1991 United B737 at Colorado Springs and the 1994 USAir B737 accident at Pittsburgh did not have Fortner-overhauled components. However, a determination that other PCUs on any aircraft did or did not involve Fortner-overhauled components has not been made by the CDR Team. This would be a difficult task, because the "lap assemblies" are widely used by many PCU overhaul facilities and, though Fortner repaired valves are marked and re-serialized where possible, these units are internal to the PCU and the only way of determining they are these is to look at the PCU overhaul/maintenance records, if they are available.

(5) HONEYWELL. A Team representative visited Honeywell/Sperry in Phoenix, Arizona, on December 16, 1994. The purpose of that trip was to review the Honeywell/Sperry Yaw Damper design (Boeing Model No. 10-60447-XX) used on Boeing Models 737-200, -300, -400, and -500 airplanes, and to identify any issues associated with the design that may compromise safety.

(i) Honeywell staff present at that meeting were: Mr. Hal Thomas, Company Designated FAA Engineer; Ms. Pamela Kalish, Quality Assurance Engineer; Mr. Raymond Rummel, Design Engineer; and Mr. Terrance Grimes, Production Engineer. Honeywell was asked for an accounting of the Model 10-60447-XX failures during the preceding 12 months. That accounting revealed an unexpectedly excessive frequency of rate gyro failures. The reason for the excessive frequency of rate gyro failures is a Boeing engine change. The rate gyro is the principal and most significant component in the Yaw Damper design. Of the 200 failures examined, 130 were due to rate gyro failures and all of those were caused by damage to the rotor bearings. Of the remaining 70 failures, 42 were confirmed as "No fault Found" and the remaining 28 failures were considered "typical" (i.e., failed components, cold solder joints etc.). Boeing requested that Honeywell approve the design in a different vibration environment. That new vibration environment was a direct result of the engine change which was the principal difference between the model -200 and the -300 aircraft. Honeywell has an action item to review those failures with Boeing.

(ii) Honeywell was not aware of the Boeing Yaw Damper system failure that can cause the Yaw Damper to command up to 120 seconds of rudder hardover. This failure is caused by an open feedback signal between the Yaw Damper transfer valve position and the actuator integrator. An open or an intermittent at this point can allow the integrator to accumulate via an RC time constant, up to 120 seconds of "On Time" which, when applied to the transfer valve, will command full rudder displacement up to plus or minus three degrees. This malfunction is not considered to be a direct cause of a catastrophic event. Further investigation is being initiated by Honeywell.

NTSB RECOMMENDATIONS ADDRESSING B737 FLIGHT CONTROLS

A request was made by the B737 CDR Team to obtain all National Transportation Safety Board (NTSB) Safety Recommendations, including their associated synopses of responses and current status, related to B737 flight controls. Safety Recommendations are formally issued by the NTSB as a result of accident and incident investigations. They are non-regulatory and are issued to government agencies, airlines, manufacturers, or any other organization which can effect an enhancement in aviation safety. After a Safety Recommendation is issued, the NTSB tracks the responses received by the targeted organization.

A review of NSTB recommendations revealed several that provided further support for the Team's concern for the failures and issues that are identified in this report. (i) Rec. Nos. A-73-073/-074 - CREW TRAINING ON EFFECTS OF SPOILERS. As a result of a B737 accident in Chicago in 1972, the NTSB recommended to the FAA to reassess methods of familiarizing crews with the effects of spoilers and to issue an advisory bulletin warning against the hazards of improper spoiler use.

(ii) Rec. No. A-91-077. - STANDBY RUDDER GALLING. The 1991 investigation of the Colorado Springs B737 accident revealed that the standby rudder was galled due to an improperly designed bearing. While the galling was not cited as a cause or factor in the accident, the NTSB recommended that the FAA issue an AD to check the bearing in all B737s because of the potential hazard of rudder binding. The FAA did not issue an AD, but instead performed testing to prove that the torque tube that connects the standby rudder to the main rudder PCU can has adequate "wind up" to handle a seized bearing, and that the failure would not be latent. The NTSB closed out the recommendation with "acceptable alternative action."

(iii) Rec. Nos. A-92-118/-120/-121 - RUDDER MPCU SERVO VALVE. As a result of a B737 uncommanded rudder reversal incident, the NTSB issued three recommendations to the FAA which resulted in AD 94-01-07. All three recommendations are "closed-acceptable action."

(iv) Rec. Nos. A-93-133/-134/-135 - SPEED BRAKE CABLE ROUTING. As a result of an incident in Charlotte, North Carolina, in which a B737 speedbrake was stuck up, recommendations were made to prevent the misrouting of speed brake cables. One recommendation was for the FAA to issue an AD for a one-time inspection for speed brake cable routing. The FAA did not comply with one recommendation while two others were complied with regarding a revision in the Boeing maintenance manual.

(v) Rec. Nos. A-94-064/-065/-066 - AILERON CABLE WEAR. As a result of a B737 incident in Newark, New Jersey, in which an aileron cable failed and caused an emergency landing back at the departure airport, three recommendations were made to the FAA to issue an AD for the periodic inspection of cable wear (open -unacceptable response as of 9/19/94), require Boeing to examine the consequences of an aileron cable failure, and to conduct a study to determine the frequency of all control cable failures of selected airplanes.

The following Table lists the NTSB recommendations reviewed by the CDR Team:

REC #	SUBJECT	STATUS	COMMENTS
A-73-073	FAA TO REASSESS METHODS TO FAMILIARIZE CREWS FOR EFFECTS OF SPOILERS	CLOSED - ACCEPTABLE ACTION	Accident - 12/8/72 Chicago - Midway
A-73-074	FAA TO ISSUE ADVISORY BULLETIN FOR HAZARDS OF SPOILER IMPROPER USE	CLOSED - ACCEPTABLE ACTION	Accident - 12/8/72 Chicago - Midway
A-82-083	FAA TO ISSUE AD/OPS CHANGE FOR ICING	CLOSED - UNACCEPTABLE ACTION	Accident - 1/13/82 Wash. DC - National
A-89-058	FAA TO DEVELOP INSPECTION PROGRAM FOR FATIGUE CRACKING	OPEN - ACCEPTABLE RESPONSE	Accident - 4/28/88 Maui, Hawaii
A-89-060	FAA TO ISSUE AD TO INSPECT FOR ENGINE CONTROL CABLE CORROSION.	CLOSED - ACCEPTABLE ACTION	Accident - 4/28/88 Maui, Hawaii
A-91-077	FAA TO ISSUE AD TO CHECK BEARING IN STANDBY RUDDER DUE TO GALLING	CLOSED - ACCEPTABLE ALTERNATE ACTION	Accident - 3/3//91 Colorado Springs, CO
A-92-118	FAA TO REQUIRE BOEING DEVELOP TEST FOR MPCU SERVO VALVE OPERATION	CLOSED - ACCEPTABLE ACTION	Rudder reversal incident
A-92-120	FAA TO ISSUE AD FOR DESIGN CHANGES TO RUDDER MPCU TO PREVENT REVERSALS	CLOSED - ACCEPTABLE ACTION	Rudder reversal incident
A-92-121	FAA TO CONDUCT A DESIGN REVIEW OF THE RUDDER MPCU TO PREVENT REVERSE	CLOSED - ACCEPTABLE ACTION	Rudder reversal incident
A-93-133	FAA TO ISSUE AD FOR ONE-TIME INSPECTION OF SPEED BRAKE CABLE ROUTING	CLOSED - UNACCEPTABLE ACTION	Incident - 3/24/93 Charlotte, NC
A-93-134	FAA TO REQUIRE BOEING TO MODIFY MAINT. MANUAL FOR SPEED BRAKE CABLE ROUTE	CLOSED - ACCEPTABLE ACTION	Incident - 3/24/93 Charlotte, NC

REC #	SUBJECT	STATUS	COMMENTS
A-93-135	FAA TO REQUIRE BOEING TO MODIFY MAINT. MANUAL FOR SPEED BRAKE CABLE ROUTE	CLOSED - ACCEPTABLE ACTION	Incident - 3/24/93 Charlotte, NC
A-94-064	FAA TO ISSUE AD FOR PERIODIC INSPECTION OF AILERON CABLE WEAR	OPEN - UNACCEPTABLE RESPONSE (9/19/94)	Incident - 3/15/93 Newark, NJ
A-94-065	FAA TO REQUIRE BOEING EXAMINE AILERON CABLE FAILURE AND PROVIDE OPS	OPEN - ACCEPTABLE RESPONSE (9/19/94)	Incident - 3/15/93 Newark, NJ
A-94-066	FAA TO CONDUCT A STUDY TO DETERMINE FREQUENCY OF ALL B737 FLIGHT CONTROL CABLE FAILURES	OPEN - ACCEPTABLE RESPONSE (9/19/94)	Incident - 3/15/93 Newark, NJ