Submission to the

National Transportation Safety Board

for the

Alaska Airlines Flight 261

Accident Investigation

The Boeing Company

23 August 2002

INTRODUCTION

On 31 January 2000, at approximately 1620 Pacific Standard Time, a McDonnell Douglas MD-83 airplane, N963AS, operating as Alaska Airlines Flight 261 on a flight from Puerto Vallarta, Mexico to Seattle, Washington, with an intermediate stop in San Francisco, California, crashed into the Pacific Ocean just off the coast near Port Hueneme, California. All 83 passengers and 5 crewmembers were fatally injured and the airplane was destroyed. Visual meteorological conditions prevailed at the time of the accident.

Submission Abstract

- The Boeing Company is acting as a technical advisor to the National Transportation Safety Board (NTSB) in this investigation.
- The discussions and conclusions presented in this submission document are based on factual information obtained during the investigation, the use of analytical tools, and Boeing knowledge and expertise.
- The MD-80 series jackscrew assembly is a safely designed system that meets or exceeds all applicable FAA certification requirements.
- Service experience and history, together with a detailed examination of the tooling and procedures used, confirm that the endplay inspection check provides an acceptable means for detecting the need for replacement of a worn jackscrew unit before it reaches a potentially unsafe level of wear. The investigation and analysis conducted by the NTSB show that improvements to this check can be made.
- Based on service experience and extensive testing performed by the NTSB, there is no evidence that the wear rate of the accident airplane's acme nut was adversely affected by the operator's selection of Aeroshell 33, or that any acme nut material was lost due to corrosion or chemical reaction as a result of Aeroshell 33, Mobilgrease 28, or any combination of these two greases.
- Extensive metallurgical studies conducted by the NTSB did not reveal any material or surface condition of either the acme nut or jackscrew from the accident airplane that would have contributed to the accelerated wear rate of the nut threads.
- Based on the factual evidence and the analytical studies conducted for this investigation, Boeing believes that operation of the jackscrew unit on N963AS for an extended period without adequate lubrication resulted in a high wear rate, and, combined with the operator's extended interval for endplay inspection, resulted in the loss of the acme nut threads, leading to loss of control of the airplane.
- Boeing has made several enhancements to the maintenance procedures for both the endplay check and the lubrication task. We are continuing to enhance these maintenance tasks and tools to make them even simpler, easier, and more reliable.

BOEING ASSISTANCE WITH THIS INVESTIGATION

The National Transportation Safety Board (NTSB) led the investigation into this accident. Assisting the NTSB were, in addition to Boeing, the Federal Aviation Administration (FAA), Alaska Airlines (ASA), the Air Line Pilots Association (ALPA), the Aircraft Mechanics Fraternal Association (AMFA), the Association of Flight Attendants (AFA), and other designated parties.

Boeing's specific role in this investigation has been to

- Provide technical information and make company experts on the airplane's design, maintenance, and operation available to assist the NTSB's Performance, Systems, Metallurgical, Operations, Maintenance Records, and Structures groups.
- Assist the NTSB with airplane performance calculations.
- Provide expert-witness testimony at the NTSB Public Hearing in Washington, DC, 12–14 December 2000.
- Provide specific facilities and testing resources for NTSB-sanctioned testing and laboratory examinations of components related to the investigation.
- Conduct specific structural analysis of components related to the investigation.

As a part of the investigation, the NTSB requested that all parties submit proposed findings based on facts and analyses drawn from this investigation. Boeing has responded to the NTSB's request with this document, which

- Provides an assessment of the evidence and other pertinent data.
- Identifies knowledge gained from the investigation and related activities.
- Identifies a conclusion supportive of a finding of probable cause.
- Describes the actions taken by Boeing to further enhance the safety of the in-service fleet.

EVIDENCE ASSESSMENT

The Boeing assessment of the evidence is based on observations and documentation of the recovered airplane wreckage, and the laboratory and computational analyses conducted in the course of this NTSB investigation.

DESCRIPTION OF THE JACKSCREW ASSEMBLY

The MD-83 airplane—a model in the MD-80 series—is a derivative of the DC-9 series designed by the Douglas Aircraft Company (later McDonnell Douglas Corporation) in the 1960s. In this twin-engine, single-aisle jet family[1] (all members of which are referred to hereafter as "Twinjets"), aerodynamic longitudinal trimming is accomplished by varying the angle of attack of the horizontal stabilizer atop the "T" tail. This trimmable stabilizer

1 Models are DC-9, MD-80, MD-90, and 717- series airplanes.

is actuated by a jackscrew mechanism ("jackscrew assembly") that is housed within the jet's vertical stabilizer (fig. 1).

Attached to the top of the vertical stabilizer, the jackscrew assembly (fig. 1) comprises an acme screw about 2 ft long that is mounted in a gimbal-mounted acme nut. When the flight crew adjusts the airplane's pitch trim while hand-flying, or when the autopilot commands a new pitch trim during automated flight, the assembly's electric motors, operating through a gearbox mounted to the front of the horizontal stabilizer, rotate a titanium torque tube that is mounted inside the hardened steel acme screw. In turn, this torque tube rotates the acme screw inside the acme nut, thus raising or lowering the leading edge of the horizontal stabilizer. The resultant vertical positioning establishes the angle of attack of the horizontal stabilizer, and thus the Twinjet's pitch-trim condition.

The Twinjet is capable of safe flight and landing following a jam of the horizontal stabilizer in any position encountered during normal operation. It is not, however, certified for continued safe flight and landing outside of the stabilizer operating travel limits.[2]

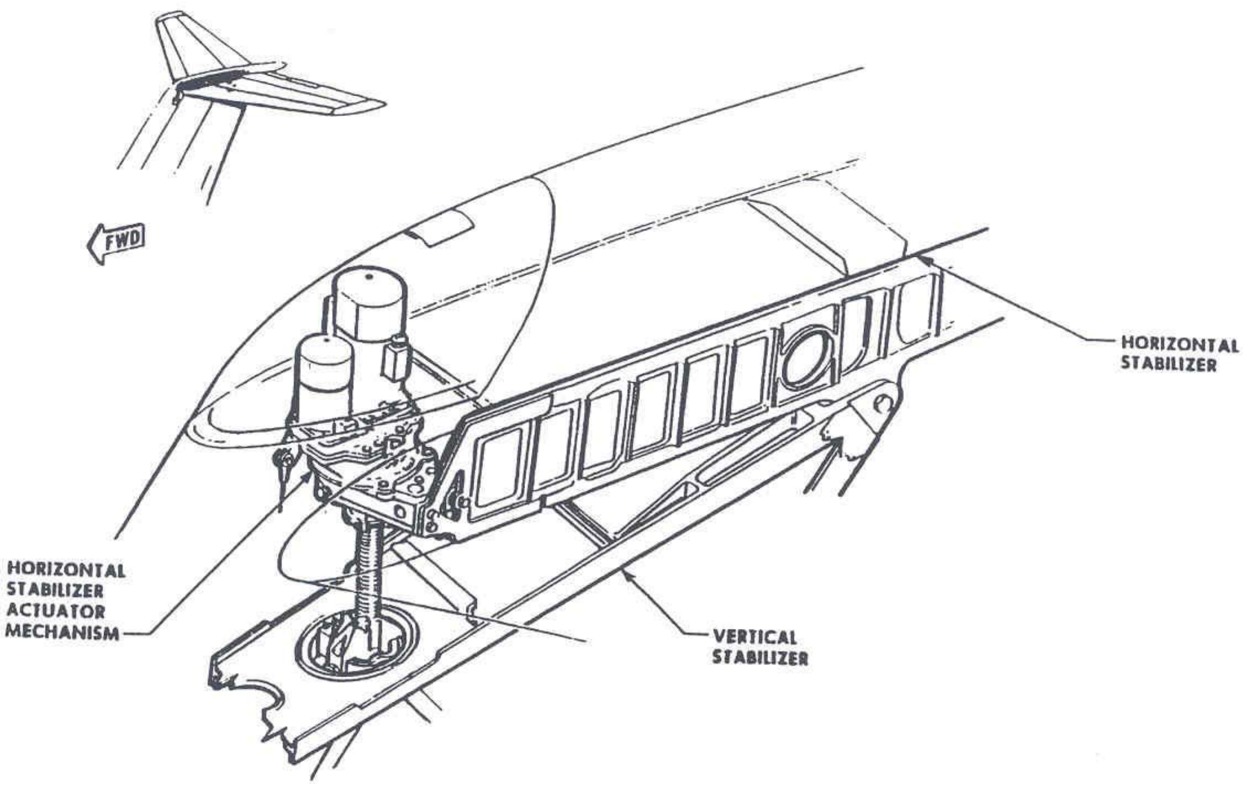

Figure 1. Horizontal Stabilizer Trim System

Design and Certification of the Jackscrew Assembly

The concepts integrated into the design of the Twinjet jackscrew assembly provide for a safe system that met or exceeded all applicable FAA requirements at the time that it was

2 The design limits for travel of the DC-9 / MD-80 horizontal stabilizer are from about 12.2 deg leading edge down (airplane nose up) to approximately 2.1 deg leading edge up (airplane nose down).

certified. In December 2000, the FAA testified that this jackscrew assembly's design would comply with present-day certification requirements as well[3].

The design of the DC-9 horizontal stabilizer jackscrew assembly is derived from successful use of such a system aboard the DC-8 aircraft. The DC-9 design philosophy and criteria created a horizontal stabilizer trim system that met and exceeded the original CAR 4b (amendment level 16) certification requirements. This system can be shown compliant with the more stringent certification requirements in effect today (FAR 25, amendment level 105[4]). Compliance with these structural and flight control design requirements has been verified through testing and analyses, and has been validated by the successful service experience of several generations of the Twinjet series (DC-9, MD-80, MD-90, and 717)[5].

When the jackscrew assembly is actuated, the motors, via the gearbox, drive the torque tube. This in turn drives rotation of the acme screw relative to the fixed acme nut and results in linear (axial) movement of the acme screw that moves the horizontal stabilizer up and down. A spherical bearing at the upper support and the acme nut's gimbal mounting together maintain continuous axial alignment of the screw and nut threads as the stabilizer position changes during trimming. When the acme screw rotates, sliding contact occurs between the threads of the screw and those of the nut. The static weight of the system and the aerodynamic loads of flight are both reacted at this screw-nut thread interface.

With relative motion and a contact load between components, wear is expected at this thread interface and is accounted for in the jackscrew assembly's design. The design approach taken was to have all significant wear occur in the acme nut threads, which—based on the successful service history of the DC-8 system—were intended to wear at a rate of about 0.001 in. per 1,000 flight-hours. At this rate, the jackscrew unit would not need to be replaced during the original service life of the DC-9 airplane (about 30,000 flight-hours). Historical data shows that the average wear rate has been 0.0011 in. per 1,000 flight-hours for the DC-9 and 0.0013 in. per 1,000 flight-hours for the MD-80.[6] Data received during the course of the investigation show that some operators have sustained average wear rates below the 0.001 in. per 1,000 flight-hours.[7]

Because wear occurs almost entirely in the acme nut threads, Douglas designed this nut to be robust (i.e., significantly oversized). When new, the cross-sectional thickness of a single nut thread at the pitch diameter is 0.125 in.[8] (fig. 3). The 32 nut threads that are in contact with the threads of the acme screw define a structural shear area of approximately 20 inches square. This design and the acme nut material properties together provide at least 1.3 million lb. of structural load capability.[9] This robust capability decreases over time as a function of material loss due to the wearing of the nut threads. When the

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3 FAA Testimony, NTSB Public Hearing, Alaska Airlines Flight 261 Accident, 14 Dec. 2000.

4 *Ibid*.

5 All models in the Twinjet (DC-9, MD-80, MD-90, and 717 series) are listed on the same FAA Type Certificate Data Sheet, TCDS A6WE.

6 See All Operators Letter 9-2120A (Docket SA-520, Exhibit 9S).

7 See Systems Group Chairman's Factual Report Addendum (Docket SA-520, Exhibit 9).

8 At its root, the acme nut thread is 0.153 in. thick and at its tip 0.096 in. thick. See figure 3 for these dimensions.

9 Dr. Terry Khaled and Mr. Mike O'Neal testified that this capability exceeds 2 million lb. based on the shear area of the nut thread thickness at the screw major diameter (NTSB Public Hearing, 13–14 Dec. 2000). See Boeing Letter B-H200-17165-ASI dated 12 Feb. 2001 for clarification of these details.

in-service wear removal threshold is reached, the acme nut threads are 0.087 to 0.095 in. thick at the pitch diameter and continue to significantly exceed ultimate load-carrying capability.[10]

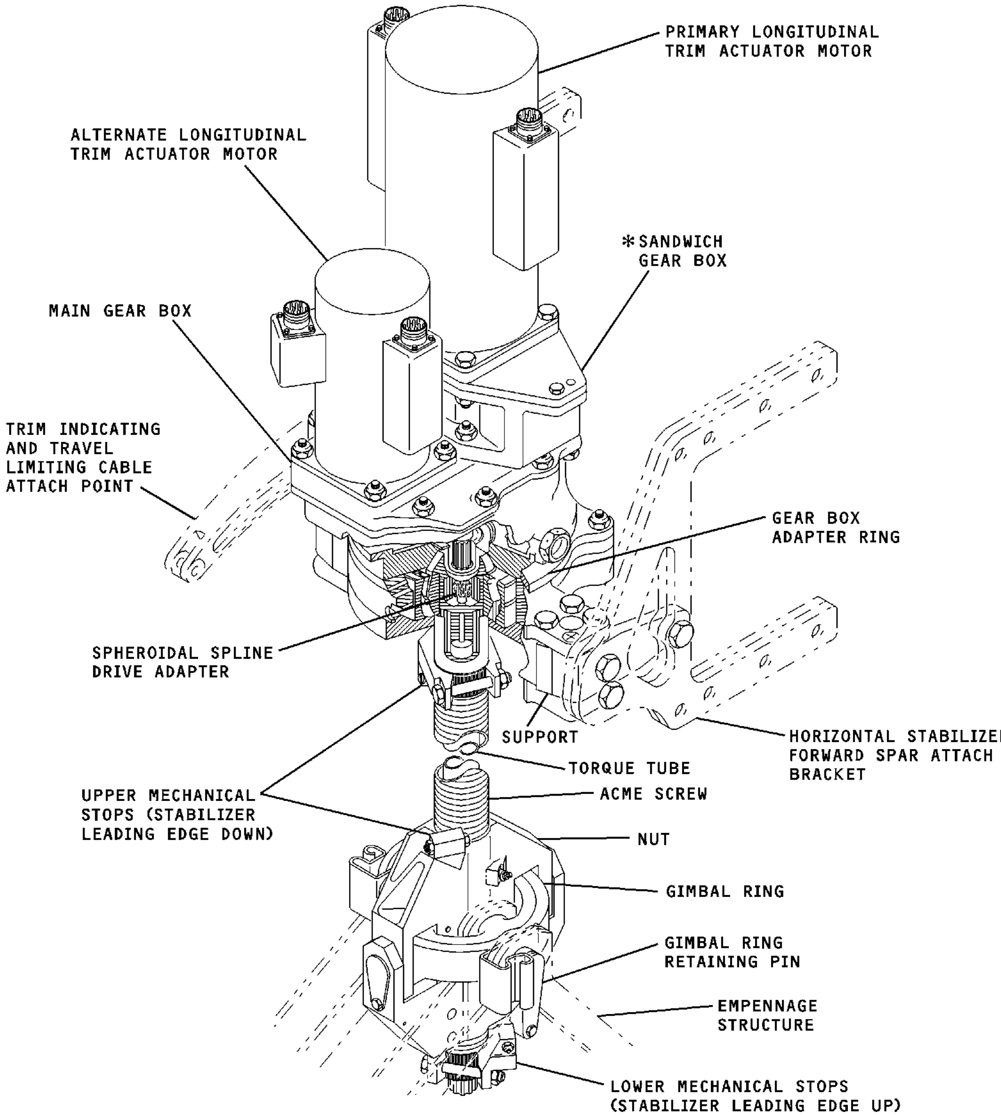

Figure 2. Trim Mechanism Details

In addition to robustness, structural integrity of the horizontal stabilizer trim actuating system is achieved through redundant, fail-safe design that ensures alternate load paths. For example, the torque tube within the acme screw provides dual paths for continued system integrity and controllability in the event of a fracture of either the screw or the torque tube (fig. 2). In the acme nut, this structural redundancy takes the form of dual independent threads that provide protection in the event one thread is mechanically

10 The term "load" refers to the forces placed on the horizontal stabilizer jackscrew assembly. "Limit load" refers to the highest design load expected during the life of the airplane. For the MD-83 horizontal stabilizer jackscrew, this load is approximately 38,000 lb. "Ultimate load" is limit load multiplied by a factor of 1.5 in accordance with FAR 25.303, so the ultimate load for the MD-83 horizontal stabilizer is approximately 57,000 lb.

removed or develops a crack along its root. The multiple support fittings encasing the acme nut provide alternate load-path integrity in the event of an axial, circumferential, or helical crack in the nut. Likewise, dual load paths are provided for the lower gimbal ring mounting as well as the upper support fittings that attach the gearbox to the front of the vertical stabilizer.

For a normal flight, typical operating loads on the jackscrew mechanism measure between 1,600 and 7,500 lb. of tension. Because of its robust design, operating stress levels on the jackscrew assembly's acme nut are extremely low and fatigue cracks will not start or propagate in the nut material.[11]

Complementing these robust strength margins is a recommended maintenance plan that ensures the continuous proper functioning of the system and removal and replacement of the jackscrew assembly at a low (i.e., conservative) level of acme nut thread wear. This maintenance plan manages acme nut wear by specifying recommended intervals for

- Lubrication.
- Inspection.

An inspection process called the *endplay check* (see next section) is used to monitor the amount of nut wear. Performed periodically, this required inspection drives the removal and replacement of worn jackscrew units.

Operators, manufacturers, and government regulatory agencies recognize the importance of reasonable in-service maintenance to preserve the continued integrity and airworthiness of commercial airplanes. Illustrating this point, FAR 25.1309 specifies that the loss of a single element of a system, or the loss of multiple elements not shown to be extremely improbable, cannot cause the loss of the airplane. The Advisory Circular[12] associated with this rule (AC 25.1309-1A) states that, for systems covered by the rule, credit may be taken for the accomplishment of reasonable maintenance tasks as defined for that system. Thus, the pertinent tasks for Twinjet lubrication and endplay check inspection can be presumed to be accomplished properly and when scheduled.

Moreover, it is recognized that because the jackscrew assembly is designed to wear over time, it must be monitored (see next section) to ensure its acme nut is not permitted to wear beyond a structurally safe limit. In short, although the jackscrew assembly is robust and thus intrinsically tolerant of occasional maintenance lapses, wear does occur and the unit must be operated with appropriate and periodic lubrication and inspection.

The concepts and philosophy behind requiring maintenance intervention to maintain type design of an aircraft system or structure, as described above, are not unique to stabilizer trim systems. For example, maintenance of an airplane's primary structure with regard to corrosion and accidental and/or fatigue damage is necessary to ensure continued safety and airworthiness. Without adequate maintenance in these areas, the potential exists for catastrophic or near-catastrophic results. As a result, industrywide inspection programs[13]

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11 NTSB Public Hearing, testimony of Boeing structural engineer Mr. Ken Umeda, 13 Dec. 2000.

12 Advisory Circular (AC) is an FAA document that provides compliance guidance for and an explanation of a given rule.

13 Two examples are the Supplemental Structural Inspection Document (SSID) and the Corrosion Prevention and Control Program (CPCP).

to detect fatigue cracks and/or accidental damage in and corrosion on airframe components are commonplace and are industry-standard practice. Here, as with the Twinjet jackscrew assembly, the requirement for ongoing inspections and maintenance is an integral component of the continued safety and airworthiness of airplanes in service.

At the time of the accident, the intervals recommended for MD-80 series endplay check inspection were denoted by either the MSG-2 or MSG-3 Maintenance Review Board (MRB) documents.[14] These documents specify that endplay measurement is to be accomplished every other "C" check. The MSG-2 MRB document specified an inspection interval of 7,000 flight-hours or 30 months (whichever came first), while the MSG-3 MRB document specified an inspection interval of 7,200 flight-hours or 30 months (whichever came first). Intervals for lubrication are not covered in the MSG-2 MRB document. However, the *On Airplane Maintenance Planning (OAMP)* document[15] corresponding to MSG-2 recommends an interval of 600 to 900 flight-hours. The MSG-3 MRB document (and the MSG-3 OAMP) specifies a lubrication interval of every 3,600 flight-hours.[16]

Alaska Airlines began operating MD-80 airplanes in 1985 using the MRB MSG-2 Report guidelines for establishing an FAA-approved maintenance program. The NTSB investigation notes that Alaska Airlines modified these guidelines. In 1988, the FAA approved this operator's requested change to have its maintenance intervals be based solely on calendar time.[17] As a result of the increased utilization of the operator's fleet of MD-80 airplanes, at the time of the accident the operator's MSG-2 endplay check interval of 30 months equated to approximately 9,550 flight-hours.[18] From 1996 to the time of the accident, the operator specified the lubrication interval as 8 months (coincident with lubrication of the elevator mechanisms). Based on the same utilization of the airplane, this equates to a lubrication maintenance interval of approximately 2,550 flight-hours.[19]

THE LUBRICATION PROCEDURE

As stated, vertical motion of the horizontal stabilizer is achieved through sliding contact between the threads of the screw and those of the acme nut. This sliding contact produces wear that depends primarily on the amount of lubrication present. The steps in the Twinjet maintenance manual outline two avenues that the operator is to use to apply lubricant to the jackscrew assembly, both of which must be used.[20] One is to pump grease through the Zerk fitting located on the forward side of the acme nut. The other is to apply the grease—

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14 MSG stands for Maintenance Steering Group, the responsibilities and history of which are described in the Maintenance Records Group Chairman's Factual Report (Docket SA-520, Exhibit 11A). Airworthiness Directive AD 2000-03-51, released just after the accident, directs that the endplay inspection be accomplished every 2,000 flight-hours and that lubrication inspection be accomplished every 650 flight-hours. The current AD (2000-15-15) supersedes the MRB intervals and is still in effect as of the date of this submission.

15 The *OAMP* is a maintenance planning document prepared by the manufacturer to provide guidance to operators in setting up their maintenance program for that airplane type. Additional details are described in the Maintenance Records Group Chairman's Factual Report (Docket SA-520, Exhibit 11A).

16 The MSG-3 analysis for the MD-80 airplane was completed in 1999. The MD-90 MSG-3 analysis was completed at the time of original certification in 1994. Those operators who have maintained the MSG-3 intervals for either model have not shown a higher rate of jackscrew returns for exceeding the endplay removal threshold.

17 Maintenance Records Group Chairman's Factual Report (Docket SA-520, Exhibit 11A).

18 *Ibid*, p. 21.

19 *Ibid*. Alaska Airlines currently conducts endplay checks every 2,000 flight-hours (or less) and jackscrew lubrication inspection every 650 flight-hours (or less) pursuant to the ADs issued shortly after the accident.

20 Maintenance manual section 12-21-02 covers the lubrication of the jackscrew mechanism.

either by hand or by brush—directly to the threads of the acme screw (i.e., those parts of the screw not covered by the acme nut).

Standard lubrication practice[21] calls for pumping grease into the Zerk fitting until fresh grease extrudes from the top of the acme nut. After grease has been applied directly to the acme screw threads, the jackscrew assembly is operated through its full range of travel to distribute lubricant evenly on the threads.

THE ENDPLAY CHECK INSPECTION

The Twinjet horizontal stabilizer jackscrew *endplay check inspection* is a maintenance task that is performed at regular intervals to ascertain the amount of accrued acme nut wear. The purpose of the endplay check is to identify jackscrew assemblies that have worn beyond the threshold for replacement, as specified in the maintenance manual.

The endplay check measures the air gap present between the thread flanks of the screw and those of the nut in which it is mounted. Because the aluminum-bronze threads of the acme nut have a different coefficient of thermal expansion than the threads of the steel screw, new jackscrew assemblies are manufactured with an air gap of 0.003 to 0.010 in. between the screw and nut threads[22] (fig. 3). This initial gap (which also is the initial endplay value) slowly widens over many thousands of airplane flight-hours as trimming causes wear in the jackscrew assembly.

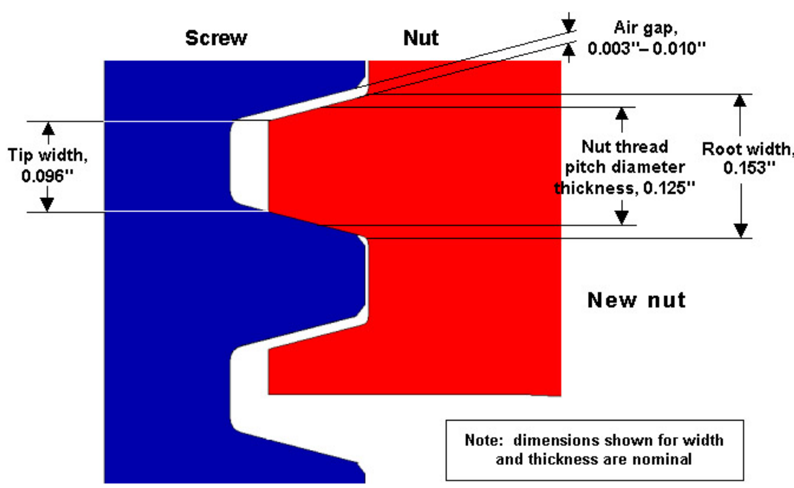

Figure 3. Interface of Screw and Nut Threads, New Jackscrew Assembly

As the airplane sits on the ground, the jackscrew mechanism is in tension because the center of balance of the horizontal stabilizer is located aft of the stabilizer's hinge whereas the jackscrew connects forward of it.[23] The endplay check involves putting the acme screw in compression through a strong nose-down pull on the stabilizer by means of a special tool (i.e., the *restraining fixture)*. This reversal in applied-load direction causes

21 See, for example, the MD-80 Maintenance Manual, section 12-21-00, on Lubrication Service Notes.

22 This air gap on new assemblies constitutes the initial endplay of 0.003 to 0.010 in.

23 This unit is also normally in tension in flight because the center of pressure is aft of the horizontal stabilizer hinge.

the screw to translate vertically downward the distance of the air gap and press its thread lower flanks against the upper side of the acme nut thread flanks. The applied load used in this check, as generated by the restraining fixture, is sufficient to squeeze the lubricant and wear debris out from between the threads for an accurate reading.

The endplay check involves recording the amount of vertical screw movement, or *endplay,* that is detected as displayed on a dial indicator mounted to the jackscrew during the check. Although this check does not directly measure thread thickness, the measured endplay is an indication of the amount of change in thickness of the nut threads because a simple one-to-one ratio exists between acme nut thread wear and the corresponding increase in the air gap between the threads of the acme nut and the jackscrew.

The jackscrew assembly is required to be replaced at an endplay measurement greater than 0.040 in.[24] (the *"removal threshold").* Analysis shows that at this removal threshold value of 0.040 in., the acme nut remains capable of withstanding more than 10 times the force corresponding to the design's ultimate load.[25] At twice the removal threshold, or 0.080 in. of measured endplay, the acme nut retains more than five times the structural strength necessary to withstand the ultimate load.[26]

ENDPLAY ANALYSIS

The NTSB Systems Group conducted a number of on-wing[27] studies to determine the variance in endplay readings based on a number of forced setup errors.[28] The largest variance (attributable to a combination of errors) was determined to be ±0.005 in. Unintended rotation of the screw during the loading sequence in preparation for taking the endplay reading was the largest contributor to this variance. With rotation precluded by restraining the screw during the inspection, the measurement variation was ±0.0015 in.

An erroneous endplay reading also could be produced if the mechanic were to perform the procedure in the wrong direction (i.e., pushing up on the stabilizer rather than pulling down by turning the restraining fixture in the wrong direction).[29] In such a case, an endplay reading of near zero would result. Note that such a reading would be cause for removal of the jackscrew assembly from the airplane if the erroneous reading were not resolved.[30]

It also was determined during the course of the investigation that some operators fabricated their own restraining fixtures, which did not adhere to the manufacturer's drawing

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24 The original value for the removal threshold was 0.0265 in. based on guidance from a military specification. After Twinjet entry into service, this threshold was increased to the present-day 0.040 in. See Systems Group Chairman's Factual Report (Docket SA-520, Exhibit 9A, p. 56).

25 See NTSB Public Hearing Testimony of Mr. Ken Umeda, 13 Dec. 2000.

26 *Ibid*.

27 "On wing" is an industry term that denotes "on the airplane" and is not specifically confined to the wings (e.g., an "on-wing jackscrew assembly" is one that is installed in an airplane's tail section).

28 Addendum to Systems Group Chairman's Factual Report, 28 Feb. 2002 (Docket SA-520, Exhibit 9).

29 An example of this is noted in the Systems Group Chairman's Factual Report (Docket SA-520, Exhibit 9A, p. 48).

30 The maintenance procedure requires jackscrew assembly removal if the endplay measurement is less than 0.003 in. or greater than 0.040 in.

specification. Concern was expressed that such tools could be ineffective in exerting sufficient force to pull the stabilizer down, resulting in a low endplay reading.[31]

Following the accident of Flight 261, the FAA issued ADs that required endplay checks to be conducted for the entire Twinjet fleet within 30 days of release of the AD. Furthermore, operators were required to repeat the endplay check at intervals not exceeding 2,000 flight-hours and to record and submit these measurements to Boeing and the FAA. As of the date of this submission, more than 3,500 individual endplay check measurements have been reported to Boeing. Boeing has provided this data to the NTSB.

The NTSB conducted a statistical study of a portion of this reported endplay data.[32] The study evaluated the endplay check reliability (repeatability) and concluded that endplay check results were not necessarily consistent from check to check when performed on a given airplane. However, the Systems Group activity noted above demonstrates that, when performed properly, the check does yield consistent results. As a result of the Systems Group investigative work, Boeing took steps to enhance the endplay check procedure and is making further enhancements that should reduce check variability (see Boeing Actions at the end of this document).

As stated, the ultimate purpose of the endplay check is to identify jackscrew assemblies that have reached and/or exceeded their replacement threshold thus driving their replacement. In 37 years and more than 100 million flight-hours logged by the DC-9 and its derivatives, including the MD-83, more than 20,000 endplay checks[33] have been performed. During this time, the procedure has accomplished its intended purpose.

THE LAST ENDPLAY CHECK OF N963AS

During a heavy-maintenance check in September 1997, Alaska Airlines personnel performed two sets of endplay check inspections on the accident airplane. After the first check, the result was documented as, “Acme screw and nut has maximum allowable endplay limit (0.040 in.),”[34] and an Alaska Airlines lead mechanic directed removal and replacement of the jackscrew assembly. Three days later, a second set of checks was performed and the results were documented as, “Rechecked acme screw and nut endplay per WC 2462700. Found endplay to be within limits 0.033 … Rechecked five times with same result.”[35] Alaska Airlines returned the airplane to service without replacing the jackscrew assembly. No further endplay checks were performed before the accident.

As noted above, some operators elected to fabricate their own restraining fixtures. Alaska Airlines was one such operator; it manufactured a restraining fixture that did not conform to the Boeing drawing. At the time of the accident, Alaska Airlines reported that there was

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31 The NTSB Systems Group conducted a study of the load output of tools fabricated by Alaska Airlines and by Boeing. See Systems Group Chairman’s Factual Report Addendum (Docket SA-520, Exhibit 9, p. 13).

32 “Jackscrew End Play Study,” NTSB Office of Research and Engineering, 18 Mar. 2002.

33 This estimate is based on a total twinjet fleet of 2,300 airplanes, 100,000,000 flight-hours logged, and an average historical endplay check interval of between 3,000 and 5,000 flight-hours.

34 This notation was made on a nonroutine work card, as indicated in the Maintenance Group Chairman’s Factual Report (Docket SA-520, Exhibit 11M).

35 *Ibid*.

only one such tool in use and that it was the same tool used for the accident airplane's last endplay check in September 1997.

RECOVERED ACME SCREW AND NUT OF N963AS

Following recovery of the accident airplane's acme screw and nut from the ocean floor, examination revealed that the threads were missing from the nut's inner bore (fig. 4). The screw was found with many spirals of thin metal ribbon wrapped around its threads. They were later identified as being of aluminum-bronze nut material and denoted as *thread remnants* (fig. 5). This evidence indicates that the acme nut threads wore down to such an extreme point that the normal operating load deflected them into the screw and they subsequently jammed the mechanism. Further attempts to activate the trim resulted in large rotational forces being applied to the system.[36] Eventually, these large rotational forces led to the acme screw threads shearing the acme nut threads from the interior of the nut element itself, which allowed axial/vertical movement of the acme screw.

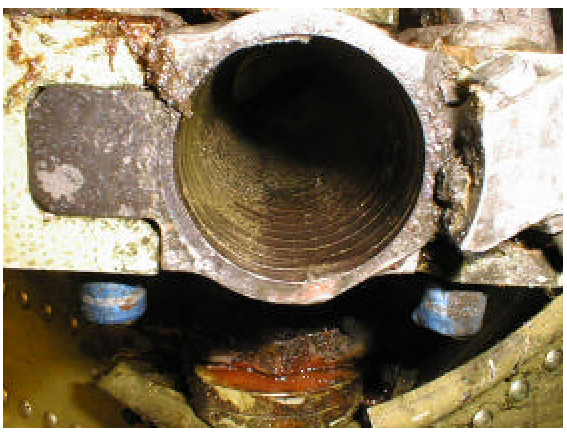

Figure 4. Accident Airplane's Acme Nut Bore

Figure 5. Thread Remnants on Recovered Screw

JACKSCREW ACME NUT WEAR AND WEAR RATE

Based on the metallurgical examination of the recovered thread remnant,[37] and using finite-element modeling techniques, Boeing—with the knowledge of the NTSB—created an analytical model of the development of this thread remnant as a function of material lost over time as the acme nut threads wore down.[38]

36 See Cockpit Voice Recorder Transcript (Docket SA-520, Exhibit 12A, p. 31), discussion pertaining to the crew's note about the ac voltmeter spike upon actuation of the primary trim. This behavior of the meter is consistent with a jammed jackscrew as noted in the Systems Group Chairperson's Factual Report Addendum (Docket SA-520, Exhibit 9).

37 See Materials Laboratory Factual Report 00-145 (Public Docket SA-520, Exhibit 15A).

38 See ASA 261 HS Jackscrew Gimbal Nut Thread Remnant Formation Study, report MDC02K9015, rev. A, July 2002. This was transmitted to the NTSB via Boeing Letter B-H200-17492-ASI dated 22 July 2002.

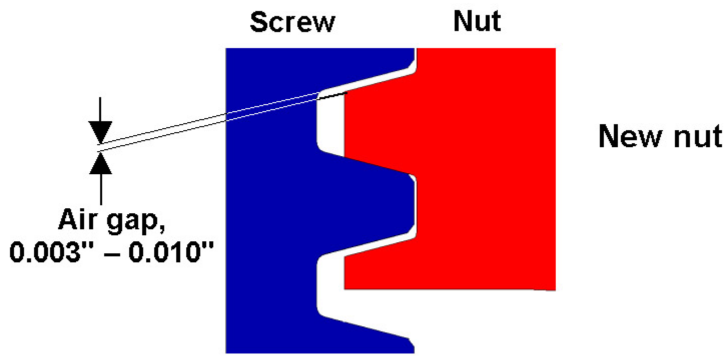

Figure 6

The series of illustrations beginning at right depicts the evolution of this nut thread remnant. Figure 6 shows the cross section of the individual threads of a newly manufactured jackscrew unit. Note that the air gap between the thread flanks of the nut and screw is very small, and that the air gap (and thus the initial endplay measurement) of a new jackscrew unit is 0.003 to 0.010 in.

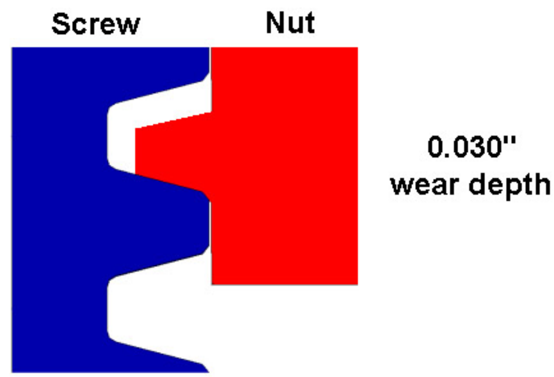

Figure 7

Figure 7 illustrates a nut that has worn to a depth of 0.030 in. At nominal wear rate, this value is consistent with approximately 30,000 flight-hours of in-service use.

The measured endplay value for a jackscrew unit worn to this degree will be between 0.033–0.040 in. (i.e., the initial air gap plus the subsequent wear). Jackscrew assemblies must be replaced at endplay values greater than 0.040 in.

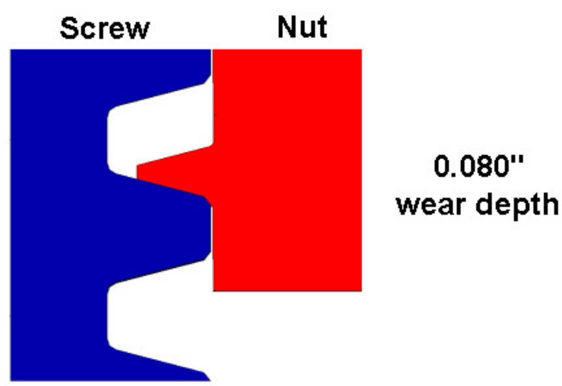

Figure 8

Figure 8 shows the acme nut threads worn to a depth of 0.080 in., which is equivalent to a measured endplay reading of 0.083 to 0.090 in.—more than two times the removal threshold.

Up until this point, the load is distributed relatively uniformly across the flank of the nut thread and the wear rate is predicted to be constant (assuming that the basic environmental conditions are unchanged).[39] Even when worn to this degree, the threads of the acme nut retain more than five times the strength needed to support the ultimate design load.

Beyond a wear depth of 0.080 in., the acme nut threads are predicted to begin yielding and developing a slight permanent deformation. This deformation acts to lift the acme nut thread crest area away from the screw thread flank. As this deformation progresses, it is predicted that the *rate of wear* increases because the contact area pressure will increase toward the root of the nut thread due to the deformation. With the load concentrated more toward the root of the nut thread, this area is subjected to more force per given area and consequently wears down faster. Thus, a formerly constant wear rate has now become an escalating wear rate.

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39 Examples of "unchanged environmental factors" are that the quality of lubrication remains constant, the number of trim cycles remains consistent, the applied loads remain in the normal range, and so on.

Figure 9 represents the acme nut thread worn to a wear depth of 0.130 in.[40] Note that although the acme nut threads are still able to support normal operating loads, the remaining nut thread's shape is now being noticeably deformed. As noted above, this increasing deformation leads to an ever-increasing rate of wear.

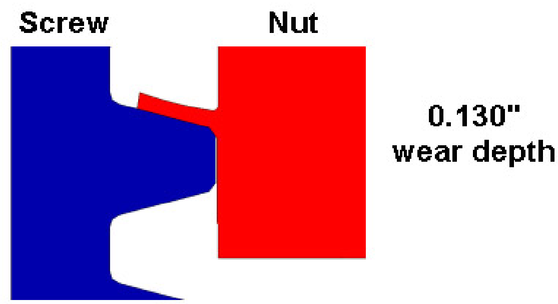

Figure 9

Figure 10 shows an acme nut thread that has now worn to a depth 0.140 in., or more than 4.5 times the amount of wear that is permitted by the replacement threshold of 0.040 in.

The nut threads of the accident airplane appeared very similar to this immediately before they stripped out of the acme nut.[41]

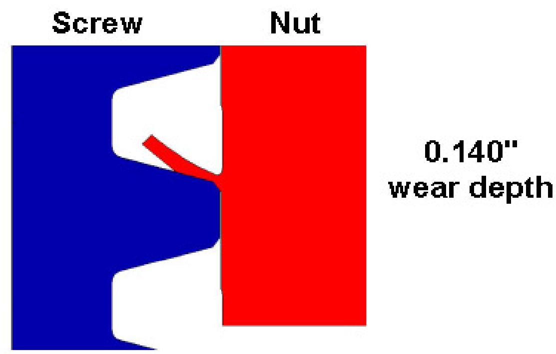

Figure 10

SUMMARY OF WEAR ON N963AS

From the time of its delivery to its last endplay check inspection in September 1997,[42] the accident airplane had accumulated approximately 17,700 flight-hours. As noted previously, the operator reportedly obtained measurements of 0.040 and 0.033 inches in two sets of endplay checks. Approximately 8,900 flight-hours later, the threads of the acme nut sheared at a wear depth of 0.140 in. or greater. Figure 11 summarizes these two points and shows a typical comparative average-wear-rate band (0.001 in. per 1,000 flight-hours), the width of which reflects the initial new-jackscrew-unit endplay measurement range of 0.003 to 0.010 in.

The amount of wear experienced by the accident airplane over its first 17,700 flight-hours of operation was greater than the nominal jackscrew wear behavior. However, subsequent to its last endplay inspection check, a drastic change in the wear behavior of the acme nut occurred. The *average* wear rate from September 1997 to January 2000 was approximately 0.010 in. per 1,000 flight-hours,[43] or ten times the nominal wear rate of 0.001 in. per 1,000 flight-hours.[44]

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40 It is suspected that, because of thread-tip deflection, *measured* endplay would suggest less wear than is actually the case at this point.

41 See NTSB Laboratory Report 00-145 (Docket SA-520, Exhibit 15A), fig. 40 on p. 47 for a picture of the cross section of the thread remnant.

42 See Systems Group Chairman's Factual Report Addendum (Docket SA-520, Exhibit 9, p. 36).

43 See Systems Group Chairman's Factual Report Addendum (Docket SA-520, Exhibit 9, p. 36).

44 See All Operators Letter 9-2120A (Public Docket SA-520, Exhibit 9S).

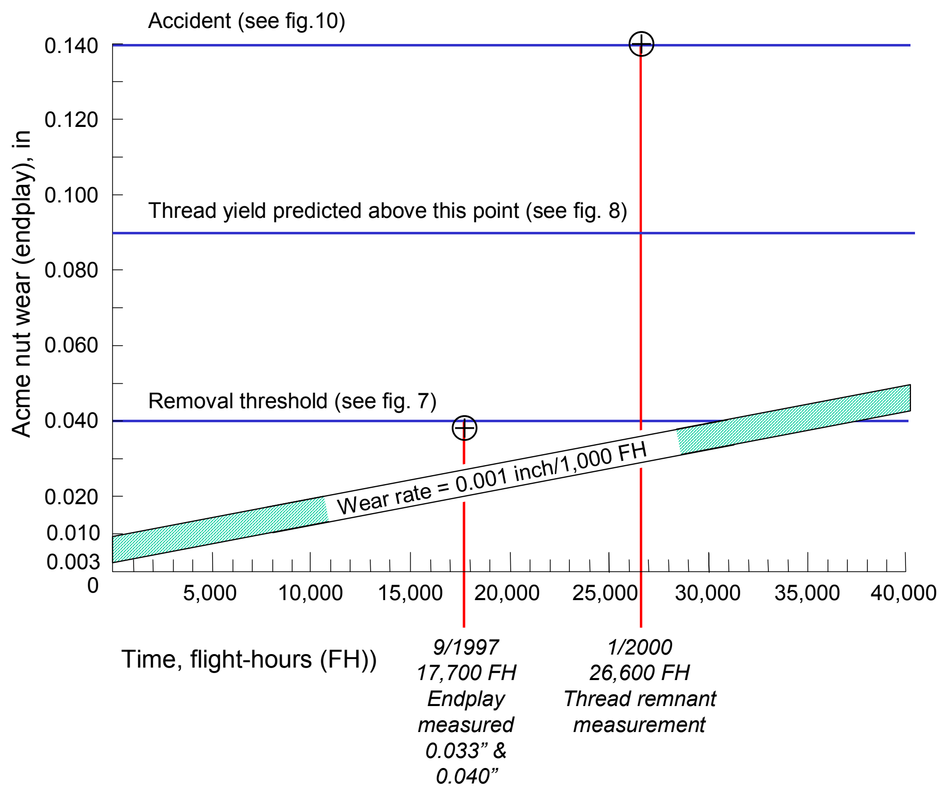

Figure 11. Wear vs. Flight-Hours, Accident Airplane

FACTORS THAT CAN INCREASE THE JACKSCREW WEAR RATE

Following the introduction of the DC-9 airplane, several initial operators reported that the jackscrew assembly acme nut was wearing at nearly 0.004 in. per 1,000 flight-hours, a rate higher than anticipated.[45] At that time, Douglas engineering identified the following factors as possible contributors to this excessive wear rate:

1. Screw and nut materials.
2. Hardening.
3. Screw finish.
4. Screw distortion resulting from torque-tube-nut preload.
5. Pounding from taxiing and flight vibrations (freeplay).
6. Excessive amount of trimming action.
7. Manufacturing quality.
8. Excessive trim loads.
9. Lubrication.

45 See enclosure 5 to Letter B-H200-17495-ASI, 31 July 2002.

During the course of this NTSB investigation, all these potential sources of excessive wear were examined implicitly or explicitly. Based on the evidence, Boeing believes that Factors 1 through 8 did not contribute to this accident. See below in this document (page 16) for more information on these eight issues and two others examined during the investigation.

In contrast, factor 9, Lubrication—or more specifically, the lack of lubrication—should be considered the cause of the observed dramatic increase in the wear rate of the acme nut in the jackscrew mechanism of the accident airplane.

LACK OF LUBRICATION ON JACKSCREW ASSEMBLY OF N963AS

Based on examination of jackscrew assembly components at the recovery site, the NTSB observed that "Visual and tactile inspections of the threaded regions of the acme screw found no evidence of grease or other lubricant in the central 'working' region of the screw threads."[46] Figure 9 shows a portion of this area.

Figure 12. N963AS Jackscrew With Acme-Nut Thread Remnants, Photographed at Recovery Site, 10 February 2000

A footnote in this NTSB factual report states that, "The working region is roughly defined as the threaded screw area that is contacted by the Acme nut during operation between the upper and lower electrical stop limits." [47]

Likewise, the interior of the nut showed no visual indications of grease on the surface where the threads would normally be.[48] Furthermore, the grease passage connecting the acme nut's Zerk grease fitting to the interior of the nut was plugged with hardened-grease residue,[49] indicating an absence of successful grease application via this fitting. Relatively fresh lubricant that had been applied at least four to five months before the accident[50] was found in the Zerk fitting, blocked by the clog. The freshness of this grease and the condition of the clog residue suggest that the clog was present for a prolonged period.

46 "Jackscrew Assembly With Horizontal Stabilizer Structure," NTSB Materials Laboratory Factual Report No. 00-145 (Docket SA-520, Exhibit 15A).

47 *Ibid*.

48 *Ibid*.

49 *Ibid*.

50 See Systems Group Chairman's Factual Report Addendum (Docket SA-520, Exhibit 9).

FINDINGS SUMMARY FOR FACTORS 1 THROUGH 8

Summarized below are pertinent findings related to the other eight factors (items 1–8 on the previous list) that, based on the evidence, can be eliminated as sources of increased nut wear rate in the accident airplane:

1. Screw and nut materials—The basic materials specified for the jackscrew assembly have not changed since the DC-9 was introduced in the 1960s. As this selection of materials has served the fleet well with an excellent service history, the basic materials are not believed to have contributed to the accident.[51]

2. Hardening—While the basic materials specification for the jackscrew assembly has not changed, early in the DC-9 program Douglas specified two significant changes in the treatment of these materials during fabrication. Responding to a higher-than-anticipated wear rate[52], the company performed testing early in 1967 that culminated in an improved heat treatment for the acme screw.[53] This modification resulted as intended in a harder screw surface but subsequent in-service screw returns still showed the wear rate to be above the design target rate of 0.001 in. per 1,000 flight-hours. Therefore, in 1970 Douglas took the further step of specifying screw surface hardening using a commercial process known as *Malcolmizing*.[54] In the decades since, this assembly has demonstrated an in-service wear rate that is very close to the design target of 0.001 in. per 1,000 flight-hours.[55] Metallurgical analysis confirmed that the accident screw met the drawing requirements for surface depth and hardness. Thus, it is deemed that these hardening processes are not contributory to the accident.

3. Screw finish—Based on the evidence and analyses performed in the course of this investigation, metallurgical analysis confirmed that the finish (surface roughness) of the acme screw was in accordance with the drawing specification and did not contribute to excessive wear. Therefore, it is not considered a contributing factor in this accident.[56]

4. Screw distortion resulting from torque-tube-nut preload—The original specification for tightening the nut retaining the torque tube at the base of the jackscrew assembly called for more than 130 ft-lb. of torque to be applied. Following early reports of higher-than-desired acme nut wear rates, excessive nut preload was identified as contributing to this wear by distorting the screw thread lead.[57] Consequently, the preload was reduced to 10 ft-lb., which helped decrease the wear rate but led to reports of loose torque-tube nuts in service. As a result, the retaining nut torquing requirement was subsequently raised to 30 ft-lb., and yet again to its present value of 55 ft-lb.[58] This nut torque has now been

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51 See NTSB Materials Laboratory Factual Report 00-145 (Docket SA-520, Exhibit 15A). The acme screw and nut materials were found to conform to the manufacturer's drawings.

52 See Enclosure 5 to Letter B-H200-17495-ASI, 31 July 2002.

53 DC-9 Service Bulletin 27-84, 19 June 1967.

54 All Operators Letter 9-523, 10 Nov. 1970.

55 Fleet-average wear rates have been determined to be 0.0011 in. for the DC-9 and 0.0013 in. for the MD-80. See All Operator's Letter 9-2121A, 5 Sept. 1991.

56 NTSB Materials Laboratory Factual Report 00-145 (Docket SA-520, Exhibit 15A).

57 Engineering Test Report DAC 33748, *Horizontal Stabilizer Jackscrew and Nut Wear Test*, 18 May 1967.

58 All Operator's Letter 9-613, 30 July 1971. See also Addendum to Systems Group Chairman's Factual Report, 28 Feb. 2002.

standard for almost 30 years and there are no reports that this value has a detrimental effect on acme nut wear rate.

5. Pounding from taxiing and flight vibrations (freeplay)—The original designers of the jackscrew assembly considered the possibility of wear stemming from a possible rapid up-and-down movement of the horizontal stabilizer associated with the gap between the screw and acme nut threads. Throughout the years of service, however, no evidence has been reported that would suggest that such movement occurs or is a contributor to wear rate. Because of the location of the centers of gravity and of pressure, both of which are aft of the horizontal stabilizer hinge point, the loads on the jackscrew unit are almost universally in one direction. From the metallurgical examination of the thread remnants, there was no evidence of impact damage that would have contributed to a high wear rate.[59]

6. Excessive amount of trimming action—The more frequently a jackscrew is operated, the faster the threads of its acme nut wear down. Thus, excessive trimming is a potential source of excessive wear. Examination of the accident airplane's primary and alternate jackscrew motors and their associated trim relays did not reveal severely worn motor brakes, burned or broken relay contacts, or any other abnormal conditions that would be present had excessive trimming been occurring.[60] No maintenance actions relating to brake wear (the major indicator of excessive motor usage) had been taken against either electric motor since the airplane was delivered to Alaska Airlines.[61] Therefore, there is no evidence that excessive trimming action is a source of the accelerated wear experienced in the jackscrew assembly of the accident airplane.

7. Manufacturing quality—As noted above, a metallurgical and visual examination of the accident airplane's screw and nut did not reveal any flaws or conditions from initial manufacture that would have contributed to an abnormally high jackscrew wear rate or the loss of Flight 261.[62]

8. Excessive trim loads—At the time of the accident, Alaska Airlines had a fleet of 34 MD-80 airplanes. During the on-site portion of the investigation, Alaska indicated that all of these airplanes fly the same basic routes (from Alaska to Mexico). None of the evidence documented during the factual portion of this investigation gives any indication that the accident airplane was flown in a manner (e.g., in a unique way or on unique routes) that would lead to higher-than-normal trim loads. Therefore, excessive trim loads can be discounted as a possible source of the excessive jackscrew wear rate experienced by the accident airplane.

Additional Factors Considered During the Investigation

Jackscrew wobbling—"Wobble" refers to the fact that during normal operation, a shallow circumferential wear band can develop along an edge of the upper portion of the torque tube that contacts the jackscrew because of the small differential movement between the tube and the screw. This band can then allow the jackscrew to move slightly off

[59] NTSB Materials Laboratory Factual Report 00-145 (Docket SA-520, Exhibit 15A).
[60] Systems Group Chairman's Factual Report (Docket SA-520, Exhibit 9A).
[61] Maintenance Group Chairman's Factual Report (Docket SA-520, Exhibit 11A).
[62] NTSB Materials Laboratory Factual Report 00-145 (Docket SA-520, Exhibit 15A).

concentricity with the torque tube. The result is that the acme screw orbits or "wobbles" during actuation. It is important to note that the gimbal at the acme nut and the upper mono-ball of the support assembly as designed to maintain continuous axial alignment between the screw and the nut. This wobble has no detrimental effect on this alignment. Indeed, wobble is the response of the gimbal to maintain the required alignment.

The NTSB Structures and Systems groups examined the wobbling jackscrew issue in depth and tasked Boeing to provide an analysis of its possible effects. This analysis demonstrated that the wear band has negligible affect on the structural integrity of the jackscrew system.[63] The Systems Group examined the potential for this wear band to affect the wear rate of an acme nut and found that there is no correlation between wear-band depth and wear rate.[64] Therefore, the contribution of jackscrew wobble to wear rate was negligible.

Grease grit contamination—During the examination of the postaccident AD fleet data, a removed jackscrew assembly was noted to have a very high wear rate. The operator replaced that unit and noted that its replacement unit also sustained a high wear rate.[65] Further examination and investigation into the history of both units revealed the presence of a grit material later identified as having come from an abrasive-cleaning corrosion-removal process previously performed. This material was found in the grease from the first unit removed. An examination of that airplane revealed that the material also was dispersed inside the trim mechanism compartment.

Close examination of the small amount of grease recovered from the bottom of the accident airplane's acme screw did not find foreign material (such as grit) in the sample that would contribute to an increase in the acme nut's thread wear rate. Therefore, there is no evidence that grit contamination was a source of the accelerated wear experienced in the jackscrew assembly of the accident airplane.

LUBRICATION

With the exception of this accident flight, a DC-9 / MD-80 jackscrew assembly has never worn to the point of acme nut thread fracture. As part of the investigation to determine why the acme nut thread fractured in flight, the NTSB conducted extensive studies of the topic of lubrication. Four general categories were studied:

- Lack of lubricant.
- Grease type mixing.
- Contamination of lubricant.
- Corrosion caused by grease type.

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63 See *HS Jackscrew Torque Tube Wear Band Analysis*, Boeing Report MDC01K9053, rev. A, Nov. 2001. This was transmitted to the NTSB via Boeing Letter B-H200-17361-ASI, 20 Dec. 2001.

64 This information was presented in a NTSB progress meeting on 24 & 25 October 2001. See also Systems Group Chairman's Factual Report Addendum (Docket No. SA-520, Exhibit 9).

65 The first unit sustained a calculated acme nut wear rate of 0.013. in per 1,000 flight-hours. The acme screw itself had a measurable wear band as well with a wear rate of 0.002 in. per 1,000 flight-hours. The second unit sustained a calculated wear rate of 0.008 in. per 1,000 flight-hours. See Systems Group Chairman's Factual Report Addendum (Docket SA-520, Exhibit 9, p. 24).

Lack of lubricant—During the lubricant testing conducted as part of the NTSB investigation, the single test condition that resulted in a significant difference in loss of material was when no lubricant was used.[66] This testing showed an order-of-magnitude increase in wear rate for dry test specimens as opposed to those lubricated with either Mobilgrease 28 or Aeroshell 33 aviation grease. This order-of-magnitude effect on wear rate approximates that estimated for the accident airplane's acme nut.[67]

As stated previously, the lubrication maintenance task requires applying grease to the jackscrew assembly in two ways: by way of the Zerk fitting on the acme nut or by hand or brush directly on the exposed acme screw threads and then operating the jackscrew its full range of travel. The NTSB Systems Group conducted a study to assess how effective each of the above methods is in lubricating the jackscrew mechanism.[68] This study used a translucent acme nut threaded onto a screw. After using both methods of application, as required by the lubrication maintenance task, all of the acme screw's threads showed a uniform layer of grease present. Conducted independently, either the Zerk fitting or the hand or brush application procedure also produced a uniform layer of grease on all the working threads (although it should be noted that the direct application by hand/brush provided a more uniform layer of grease). In addition, this test verified that grease extrudes from the top of the acme nut when properly lubed by way of the Zerk fitting.

Grease type mixing—At the time of the accident, Alaska Airlines was in the process of converting from one general-purpose aircraft lubricant (Mobilgrease 28) to another (Aeroshell 33) in its MD-80 fleet. Extensive testing and evaluation of the performance of both lubricants did not reveal a significant difference between them. There also was no evidence of any significant degradation of lubrication efficiency associated with these two lubricants being mixed in any combination of ratios.[69]

Contamination of lubricant—Although no grease was found in the working area of the recovered screw, small amounts of dried lubricant were present at both ends of the screw. The NTSB submitted a sample of this material to the Naval Air Warfare Center, Patuxent River, Maryland, for analysis. The examination found that, aside from wear particles of acme nut material, no foreign matter or debris was found in the grease samples. The only foreign matter found was present on the surface of the sample and was determined to be sand matching that of the ocean bottom from which the jackscrew unit was recovered.[70]

Corrosion caused by grease type—The possibility of accelerated wear resulting from grease-caused corrosion of the acme nut also was studied during this investigation. In particular, several avenues of research were pursued to understand the effects of copper corrosion[71] in association with the use of Aeroshell 33 grease. Areas of discoloration or "staining" at the air-grease interface of acme-nut material samples immersed in A-33

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66 Final Executive Report to the NTSB titled *Investigation of the Wear Rate of Grease-Lubricated C95500 Bronze*, from Rensselaer Polytechnic Institute and Battelle Memorial Institute, 5 Aug. 2002.

67 *Ibid*.

68 For details of this activity, see Systems Group Chairman's Factual Report Addendum (Docket No. SA-520, Exhibit 9).

69 Aerospace Materials Division of the Naval Air Warfare Center in Patuxent River, MD, Report EI-4341-00-005, titled *NTSB Grease Evaluation*.

70 Microstructural Analysis Laboratory Report MA-1044 prepared by the Aerospace Materials Division of the Naval Air Warfare Center in Patuxent River, MD, 4 April 2002.

71 The aluminum-bronze alloy of the acme nut threads consists of approximately 80% copper.

grease were ultimately identified as products of the grease additives and not as corrosion.[72] In addition, the extensive wear testing associated with grease type mixing did not identify any adverse effect of A-33 on wear characteristics.[73]

Alaska Airlines expressed an opinion that Aeroshell 33 grease was responsible for an increase in the replacement rate of 737 nose landing gear steering collars, the bearings of which—like the jackscrew acme nut threads—have a high copper content.[74] However, the NTSB has studied this issue and could not identify any correlation between the type of grease used and the replacement rate of this 737 component.[75]

SUMMARY OF KNOWLEDGE GAINED DURING THE INVESTIGATION

Knowledge Gained About the Specifics of the Accident

The following summarizes knowledge gained in the areas of *design, maintenance,* and *operation* that is pertinent to drawing conclusions regarding the probable cause of this accident:

Design

- A detailed review of the design and philosophy of the Twinjet jackscrew system reconfirmed that the system is safe and appropriately certified.
- There was no evidence of any manufacturing defect that would have contributed to this accident.

Maintenance

Lubrication:

- The operator's lubrication interval for the jackscrew assembly was calendar based only (8 months) and equated to approximately 2,550 flight-hours of operation. This interval fell between the recommended MSG-2 *OAMP* interval of 600 to 900 flight-hours and the MSG-3 recommended interval of 3,600 flight-hours. In-service experience has demonstrated that proper lubrication at a 3,600-flight-hour interval is adequate to keep wear rates low. Therefore, the operator's selected lubrication interval should not have been an adverse factor.
- Alaska Airlines has indicated that both Mobilgrease 28 and Aeroshell 33 greases may have been used to lubricate the jackscrew assembly. Testing verified that both grease types, either alone or in combination (mixed), perform similarly and neither has any adverse effect on the jackscrew assembly wear behavior. The selection of grease type, either Mobilgrease 28 or Aeroshell 33, did not contribute to this accident.

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72 *Surface Chemistry Analysis of Discolorations on Aluminum Bronze Specimens*, by Dr. Thomas Schneider, Final Report, 28 Feb. 2002.

73 *Investigation of the Wear Rate of Grease-Lubricated C95500 Bronze*, Final Executive Report to the NTSB from Rensselaer Polytechnic Institute and Battelle Memorial Institute, 5 Aug. 2002.

74 Addendum II to Systems Group Chairman's Factual Report, *737 NLG Steering Collar Bearing Issue*, 21 Aug. 2002.

75 Ibid.

- The acme nut Zerk fitting was clogged with hardened grease residue. Lubrication of the jackscrew assembly by way of this Zerk fitting was not being accomplished while this clog was present. Relatively fresh lubricant applied at least four to five months before the accident was found in the Zerk fitting, blocked by the clog. The freshness of this grease and the condition of the clog residue suggests that the clog had been present for a prolonged period of time.
- Testing confirmed that direct application of grease to the acme screw alone (by hand/brush; no lube via the Zerk fitting), if done properly, would provide a uniform distribution of grease over the screw and acme nut. The absence of any grease on the working area of the recovered screw and nut indicates that an effective application of grease to the screw was not accomplished.
- The average wear rate of the jackscrew assembly after the September 1997 heavy check was consistent with the expected behavior of an assembly that was not lubricated.

Endplay Check:

- The operator's endplay check interval for the jackscrew assembly was calendar based only (30 months) and equated to approximately 9,550 flight-hours of operation. This interval exceeded both the recommended MSG-2 interval of 7,000 flight-hours and the MSG-3 recommended interval of 7,200 flight-hours.
- The operator conducted the last endplay inspections in September 1997. The accident occurred 31 January 2000. Approximately 8,900 flight-hours had been accumulated since the last endplay check.
- During the last endplay check, the operator initially documented the result as "acme screw and nut has maximum allowable endplay limit (0.040 in.)" and an Alaska Airlines lead mechanic directed removal and replacement of the jackscrew assembly. Three days later, a second set of checks was performed and the results were documented as, "Rechecked acme screw and nut endplay per WC 2462700. Found endplay to be within limits 0.033 … Rechecked five times with same result." Alaska Airlines returned the airplane to service without replacing the jackscrew assembly. No additional endplay checks were performed before the accident.
- The endplay check, when performed properly, yields consistent results.

Operation

- Once the acme nut threads stripped out, continued safe flight was not maintained.

General Knowledge Gained

The following summarizes general knowledge gained or reconfirmed in the areas of *design, maintenance*, and *operation* during the course of this investigation. In conjunction with the knowledge gained about the specifics of the accident (see above), it is pertinent to the follow-on Boeing actions as described at the end of this document.

Design

- The Twinjet series are safe, widely used aircraft with a long history of satisfactory service. The DC-9/MD-80 series, totaling 2,167 airplanes, have accumulated more than 100 million flight-hours over a 37-year period, with no accident involving the horizontal stabilizer's jackscrew assembly except for this accident.
- The concepts and philosophy behind requiring maintenance intervention to maintain type design of an airplane's systems and structure are accepted by the industry and government regulatory agencies as an integral component of the continued safety and airworthiness of airplanes in service.

Maintenance

- The DC-9/MD-80 horizontal stabilizer jackscrew assembly is a wearing airplane component. Wear of the jackscrew assembly's acme nut threads is managed by a combination of robustness of the design with maintenance by the operator through periodic inspection and lubrication.
- On 11 February 2000, the FAA released telegraphic AD 2000-03-51 requiring the visual inspection of all Twinjet jackscrew assemblies for the presence of metal shavings in the vicinity of the jackscrew assembly and acme nut of the horizontal stabilizer as well as inspection of the condition of the jackscrew assembly lubrication and relubrication if the assembly was dry. This AD also required the performance of a test of the horizontal stabilizer shutoff controls. In addition, this AD required that the periodic visual inspection, test of the shutoff controls and lubrication check of the jackscrew assembly not exceed 650 flight-hours, and that periodic inspection of the endplay not exceed 2,000 flight-hours. The motivation for these requirements is discussed in the preamble to the rule. Boeing has taken action to respond to these requirements (see Boeing Actions below).
- On 1 October 2001, the NTSB released to the FAA four safety recommendations associated with the lubrication and inspection of the jackscrew assembly. The motivation for these recommendations is discussed in the recommendation preamble.[76] Boeing has taken action to respond to these recommendations (see Boeing Actions). The recommendations are
  - Require Boeing Commercial Airplanes to revise the lubrication procedure for the horizontal stabilizer trim system of Douglas DC-9, McDonnell Douglas MD-80/90, and Boeing 717 series airplanes to minimize the probability of inadequate lubrication (A-01-41).
  - Require Boeing Commercial Airplanes to revise the endplay check procedure for the horizontal stabilizer trim system of Douglas DC-9, McDonnell Douglas MD-80/90, and Boeing 717 series airplanes to minimize the probability of measurement error and conduct a study to empirically validate the revised procedure against an appropriate physical standard of actual acme screw and acme nut wear. This study should also establish that the procedure produces a measurement that is reliable when conducted on wing (A-01-42).

[76] NTSB Safety Recommendation Letter A-01-41 through -48, 1 Oct. 2001.

- Require maintenance personnel who lubricate the horizontal stabilizer trim system of Douglas DC-9, McDonnell Douglas MD-80/90, and Boeing 717 series airplanes to undergo specialized training for this task (A-01-43).
- Require maintenance personnel who inspect the horizontal stabilizer trim system of Douglas DC-9, McDonnell Douglas MD-80/90, and Boeing 717 series airplanes to undergo specialized training for this task. This training should include familiarization with the selection, inspection, and proper use of the tooling to perform the endplay check (A-01-44).

- On 1 October 2001, the NTSB released to the FAA four safety recommendations associated with the general topics of lubrication practices and grease types used on airplane components. The motivation for these recommendations is discussed in the recommendation preamble.[77] Boeing has taken action to respond to these recommendations (see Boeing Actions below). The recommendations are
    - Before the implementation of any proposed changes in allowable lubrication applications for critical airplane systems, require operators to supply to the FAA technical data (including performance information and test results) demonstrating that the proposed changes will not present any potential hazards and obtain approval of the proposed changes from the principal maintenance inspector and concurrence from the FAA applicable aircraft certification office (A-01-45).
    - Issue guidance to principal maintenance inspectors to notify all operators about the potential hazards of using inappropriate grease types and mixing incompatible grease types (A-01-46).
    - Survey all operators to identify any lubrication practices that deviate from those specified in the manufacturer's airplane maintenance manual, determine whether any of those deviations involve the current use of inappropriate grease types or incompatible grease mixtures on critical airplane systems, and, if so, eliminate the use of any such inappropriate grease types or incompatible mixtures (A-01-47).
    - Within the next 120 days, convene an industry-wide forum to disseminate information about and discuss issues pertaining to the lubrication of airplane components, including the qualification, selection, application methods, performance, inspection, testing, and incompatibility of grease types used on airplane components (A-01-48).
- Examination and investigation into the history of two jackscrew assemblies removed from a single airplane revealed the presence of a grit material that was later identified as having come from an abrasive-cleaning corrosion-removal process previously performed on this airplane. The grit material had contaminated the grease and caused the jackscrew assemblies to wear at a high rate. An examination of that airplane revealed that the material was also dispersed inside the trim mechanism compartment. Boeing has taken action to help operators avoid such exposure in the future (see Boeing Actions below).

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77 *Ibid*.

Operation

- After the stabilizer jammed during climbout from Puerto Vallarta, the airplane flew for more than two hours during which time it was capable of being safely landed (i.e., with the stabilizer jammed). During this period, the flight crew attempted to unjam the stabilizer with the assistance of Alaska Airlines' ground-based SEA Maintenance Control.[78] Boeing has taken action to provide further guidance to operators regarding use of existing check lists for stabilizer trim system malfunctions (see Boeing Actions below).

CONCLUSIONS

Boeing believes that the evidence supports the following conclusion with respect to a finding of probable cause of the Alaska Airlines accident:

> Operation of the jackscrew assembly on N963AS for an extended period without adequate lubrication resulted in a high wear rate and, combined with the operator's extended interval for endplay inspection, resulted in the loss of the acme nut threads, leading to loss of control of the airplane.

BOEING ACTIONS

As a result of this investigation, Boeing

- Released Flight Operations Bulletins DC-9-00-02, MD-80-00-02, MD-90-00-01, and B-717-00-01 on 10 February 2000, which provided instructions for crews that experience a horizontal stabilizer trim system malfunction. The *Flight Crew Operating Manual (FCOM)* checklist is to be completed once. If normal operation of the system is not restored, the crew should consider landing at the nearest suitable airport.
- Released Alert Service Bulletins DC9-27A362, MD90-27A034, and 717-27A0002 on 11 February 2000, which describe procedures for inspecting the general condition of the jackscrew assembly and the area around the jackscrew assembly to detect the presence of metal shavings and flakes. Responsive to AD 2000-03-51.
- Held a Twinjet All Operators Conference on 28 March 2000 to specifically review the horizontal stabilizer system, maintenance procedures, the recently released Alert Service Bulletins, and activities associated with AD 2000-03-51.
- Beginning April 2000, released enhancements to the maintenance manual procedures for lubrication including amplification of standard practices (e.g., observe grease extruding from the top of acme nut during application of lubricant to the Zerk fitting).
- Is currently defining further enhancements for these lubrication procedures. These enhancements will further ensure application of adequate lubrication and will clean the screw of any foreign particles. Responsive to NTSB recommendation A-01-41.

[78] See Summary of tape recording between Alaska Airlines flight 261 and SEA Maintenance Control (Docket SA-520, Exhibit 2-E).

- Beginning in April 2000, released enhancements to the maintenance manual endplay procedures including restraint of jackscrew rotation and care/maintenance of the endplay restraining fixture tool.
- Is currently defining further enhancements for the maintenance manual endplay procedure that will provide improved access, easier tooling installation, a direct measure of the restraining tool force output, and increased readability of the dial indicator. Boeing is presently conducting an in-service evaluation (ISE) of these enhancements as well as conducting a study to empirically validate the revised procedure against an appropriate physical standard of actual acme screw and acme nut wear. Responsive to NTSB recommendation A-01-42.
- Is defining a program of information and training of maintenance personnel of the details pertaining to the enhanced endplay inspection and lubrication practices currently under development. Responsive to NTSB recommendations A-01-43 and A-01-44.
- Is participating in an industry-sponsored forum under the auspices of the Air Transport Association (ATA) that is examining issues of general-purpose lubricant usage. Responsive to NTSB recommendations A-01-45, A-01-46, A-01-47, and A-01-48.
- Released revisions to the Twinjet series *Structural Repair Manuals (SRM)* providing guidance to ensure surrounding areas and components are properly masked and protected from abrasive blast media and that upon completion of abrasive blast operation, all blast media are thoroughly cleaned from the structure and areas adjacent to these components. Similar guidance is being developed for other Boeing models.