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CIVIL AERONAUTICS BOARD

AIRCRAFT ACCIDENT REPORT

ADOPTED: April 24, 1961 **RELEASED:** April 28, 1961

NORTHWEST AIRLINES LOCKHEED ELECTRA, N 121US,
NEAR CANNELTON, INDIANA, MARCH 17, 1960

SYNOPSIS

At 1525 c.s.t., on March 17, 1960, a Lockheed Electra, model L-188C, N 121US, owned and operated by Northwest Airlines, Inc., crashed approximately six miles from Cannelton, Indiana, after failure of the right wing. All 63 persons on board were killed.

Flight 710 departed Chicago, Illinois, at 1438 c.s.t., on an intended nonstop flight to Miami, Florida. The flight was to cruise at 18,000 feet. All reporting points were made on time and the flight was progressing according to plan; no messages were received which indicated that the crew of Flight 710 was experiencing any difficulties.

It is the conclusion of the Board that flutter was induced by oscillations of the outboard nacelles and that this reached a magnitude sufficient to fail the right wing. Reduced stiffness of the structure and the entry of the aircraft into an area of severe clear air turbulence were contributing factors.

Investigation

Northwest Airlines Flight 710 of March 17, 1960, a Lockheed Electra aircraft, N 121US, was scheduled between Minneapolis, Minnesota, and Miami, Florida, with an intermediate stop at Midway Airport, Chicago, Illinois. The crew consisted of Captain Edgar E. LaParle, First Officer Joseph C. Mills, Flight Engineer Arnold W. Kowal, Stewardesses Constance M. Nutter and Barbara A. Schreiber, and Flight Attendant Mitchell D. Foster.

Prior to departure the crew was briefed by the company meteorologist on the present and expected weather conditions along the route. This briefing consisted of a general discussion of the synoptic situation, a review of the en route and terminal forecasts, together with all sequence and pilot reports. The meteorologist said that thunderstorms which were located in Florida were discussed as was the intensity of the jet stream over the southeastern states, the latter because it appeared to be growing in intensity. No mention was made, however, of any clear air turbulence being present along the route.

A flight plan was prepared which indicated a flight in accordance with instrument flight rules (IFR), via Victor Airways 2, 97, and 6, to Midway, a cruising altitude of 15,000 feet, a true airspeed of 340 knots, and an estimated time en route of 53 minutes.

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The flight departed Minneapolis at 1251[1] and arrived at Midway at 1355; the trip to Chicago was routine. It should be noted that some of the passengers said the landing at Chicago was very hard; others said that it was a normal landing in every respect.

During the short time the aircraft was on the ground at Chicago, approximately 30 minutes, it was refueled and prepared for continuation of the flight to Miami. While this was being done Captain LaParle went to the company operations office where he reviewed the latest weather information pertaining to the flight. There is no company meteorologist stationed in Chicago. As a matter of company policy this same weather information was later attached to the flight's clearance papers and given the crew prior to departure. These papers are kept in the cockpit throughout the flight.

The flight plan, prepared by the crew and filed with company operations, indicated a flight from Midway Airport via Victor Airway 53 to Peotone, Illinois, Victor 171 to Scotland, Indiana, Victor 243 to Chattanooga, Tennessee, Victor 51W to Atlanta, Georgia, Victor 97 to Albany, Georgia, Victor 159W to Cross City, Florida, Victor 7 to Fort Myers, Florida, and Victor 35 to Miami, Florida; a cruising altitude of 18,000 feet, a true airspeed of 337 knots, and an estimated time en route of 3 hours and 37 minutes. The clearance given the flight by Air Route Traffic Control (ARTC) was, "NW 710 cleared to the Miami Airport, Peotone, Victor 171 to Scotland, Flight planned route, maintain 18,000."

The flight departed Chicago at 1438 with 57 passengers including one infant. The gross weight of the aircraft at the time of takeoff was 107,661 pounds; this was within the maximum allowable gross takeoff weight limitation of 110,590 pounds, which limitation was imposed in order to comply with the maximum allowable gross landing weight at Miami. According to company records the center of gravity was within prescribed limits.

At 1445, the flight reported to the Indianapolis, Indiana, ARTC Center over Milford, Illinois, at 18,000 feet and estimating Scotland, Indiana, at 1512. At 1513, Flight 710 reported over Scotland maintaining 18,000 feet and estimating Bowling Green, Kentucky, at 1535. At this time the flight was advised by ARTC to contact the Memphis, Tennessee, ARTC Center on 124.6 mcs., at 1530. The 1513 contact was the last known radio communication with the flight.

At approximately 1640, reports were received by Northwest Airlines at Minneapolis that Flight 710 had crashed near Cannelton, Indiana. The time of the crash was established as approximately 1525.

A radar operator at the Indianapolis Air Surveillance Station reported that he monitored the flight by radar to within seven miles of Scotland, Indiana, and that the flight appeared to be normal.

Weather

Surface stations nearest to the route reported a broken to overcast cloud deck from the Chicago area to Terre Haute, Indiana, with an average base altitude

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1/ All times herein are central standard based on the 24-hour clock.

of 1,500 feet above the ground. Above this cloud deck was a second cloud layer which was broken to overcast with its base at approximately 4,000 feet. This upper layer extended from Chicago to the scene of the accident and its tops were reported by pilots as being 7,000 to 7,500 feet near Chicago and becoming 5,000 to 6,000 feet between Evansville, Indiana, and Louisville, Kentucky. Generally clear conditions prevailed above these cloud formations with inflight visibility unrestricted in central United States.

Considering upper wind reports available from ground based observations as well as pilot reports, the following data have been extracted relative to the magnitude of horizontal and vertical shears as well as wind shift across the troughline (along the Illinois-Indiana border).

1800 c.s.t. Data

Horizontal Shear at 16,000 feet = 39 kts./150 N.M.
at 18,000 feet = 52 kts./150 N.M.

Vertical Shear

Nashville, 16,000-18,000 feet = 10 kts./1,000 feet.
Dayton, 16,000-18,000 feet = 2.5 kts./1,000 feet.

Wind shift across trough

At 18,000 feet, 50 degrees between Peoria and Dayton
60 degrees between Peoria and Nashville
At 16,000 feet, 40 degrees between Peoria and Dayton
30 degrees between Peoria and Nashville

0600 c.s.t. Data

Horizontal Shear at 16,000 feet = 48 kts./150 N.M.
at 17,000 feet = 80 kts./150 N.M.

Vertical Shear

Nashville, 16,000-17,000 feet = 26 kts./1,000 feet
Dayton, 16,000-18,000 feet = 0
18,000-20,000 feet = 5.5 kts./1,000 feet

Wind shift across trough

At 18,000 feet, 60 degrees between Peoria and Dayton
At 16,000 feet, 50 degrees between Peoria and Dayton
40 degrees between Peoria and Nashville

Pilot Reports (resume of few of most significant)

1. 1310 c.s.t., 50 miles south Dayton, moderate to severe clear air turbulence 20,000 feet - 500 feet thick - F101.

2. 1400 c.s.t., Cincinnati, moderate to heavy turbulence 20,000 to 25,000 feet, T-33.

3. 1430 c.s.t., New Hope, Kentucky, choppy at 21,000, 10-15 degrees centigrade temperature drop at edge of jet stream. Descended and showed seve: airspeed fluctuation and turbulence - Electra.

4. 1515 c.s.t., Columbus, Ohio, to York, Kentucky, moderate to severe turbulence 11,000 - 17,000 feet - aircraft type unknown.

5. 1500 c.s.t., Louisville to Cincinnati, moderate clear air turbulence 17,000 to 25,500 feet - B-57.

6. 1530 c.s.t., 50 miles north Louisville, decreased speed and descended from between 20,000 and 25,000 to 15,000 feet because of heavy to severe clear air turbulence - B-57.

7. 1640 c.s.t., Louisville to Nabb, Indiana, severe clear air turbulence 19,000 feet - DC-7.

8. 1830 c.s.t., Cincinnati, moderate to severe clear air turbulence 11,000 to 17,000 feet - Constellation.

The synoptic situation as reported on the surface weather chart for the midafternoon of March 17, 1960, was as follows: A low pressure area was centered over the northern portion of the lower peninsula of Michigan. This low pressure area extended to high levels (above 30,000 feet). A marked troughline at all altitudes extended southward from this low along the Illinois-Indiana border. A ridge of high pressure extended from the southern plains northeastward across Arkansas, western Tennessee, central Kentucky, and into southern Ohio.

The written forecasts published by both Northwest Airlines and the United States Weather Bureau and available to the crew of Flight 710 at Minneapolis and Chicago reflected the wind field as shown by the observed data. It is important to note, however, that neither of these sources of weather information mentioned the possibility of clear air turbulence along the route.

Witnesses

Approximately 75 groundwitnesses who were near the accident scene and a number of airmen who were flying in the area at the time were interviewed.

The laywitnesses were located within an area that included the most distant places from which the aircraft could be seen or the aerial explosion heard by a person having normal vision and hearing.

A composite description of what these witnesses saw and heard follows: The time was 1515. The weather was clear except for scattered cumulus clouds with bases at about 4,000 feet; visibility was good. The aircraft was flying in an approximate north to south direction, in level flight, and at a high altitude. Suddenly two puffs of white smoke were seen. Seconds later these were followed by a large cloud of dark smoke. Two loud explosions were then heard and a large object was seen to emerge from the smoke cloud and fall nearly vertically, trailing smoke and flame. Smaller objects were later seen to fall. The fuselage continued in level flight for a few seconds and then fell to the ground describing a large trajectory arc as it did so. It struck the ground with such terrific force that debris was thrown nearly 250 feet into the air.

Six USAF aircraft were on a refueling mission in the area at an altitude of 31,000 to 32,000 feet. Three of these aircraft were KC-135's and three were

B-52's. Airmen manning these aircraft said that they first saw the smoke trail of this accident at 1532. The cloud was the shape of a child's top, dark in color as if produced by burning some product with a petroleum base. The bottom of this smoke disappeared into scattered clouds. A horizontal streamer of dark smoke which began a considerable distance north terminated at the smoke cloud.

The smoke cloud was first sighted when they were 26 nautical miles north-northwest of it. Their bearing of approximately 170 degrees nearly paralleled the course of Flight 710. They passed abeam of the smoke cloud at 1539, at which time they were about 12 nautical miles west of it.

During the seven-minute period, from first sighting the smoke of the abeam check, the smoke cloud and streamer retained its original form with little or no indication of dissipating or breaking up. The USAF airmen estimated the smoke cloud to be at an altitude of 25,000 feet.

Wreckage Distribution

The major portion of the aircraft struck the ground in a nearly vertical attitude in a field where the ground sloped to the south. The soil at the point of impact was soft and contained no rocks. Small trees near the point of impact were not struck by the aircraft. Impact forces formed a crater which measured 30 feet across its top from east to west and 40 feet from north to south; it was 12 feet deep. Most of that portion of the aircraft which struck the ground forming this crater disintegrated and was buried within it. Only a few fragments of wreckage were visible in the bottom of the crater. A shallow depression 2 feet deep and 11 feet wide extended southward from the crater for a distance of 16 feet. Fragments of the left wing were visible in this depression. Portions of the vertical tail were imbedded in the west rim of the crater with the crumpled upper end of the rudder protruding from the ground. Pieces of horizontal tail structure were imbedded in the north rim of the crater. A smoldering fire burned below the surface of the crater bottom for several days until extinguished during excavation. The impact explosion hurled small pieces of wreckage in all directions from the crater, the greatest distance being approximately 1,500 feet to the east and southeast. The heaviest concentration of wreckage scattered by the impact explosion was in the southeast quadrant within a radius of 100 feet from the crater. The southwest quadrant contained a moderate to heavy concentration of pieces, and only a light scattering of pieces was found in the northwest and northeast quadrants. The geographical location of the crater was 37°54"38'N. Lat. and 86°38"W. Long., or approximately six miles due east of Cannelton.

The south end of the crater contained the No. 2 engine and propeller, parts of the left main gear, and wing structure, including flap pieces, aileron, and trim tab sections. The north end of the crater contained the fuselage structure, cockpit control system, electrical panel bits, various system components, nose gear pieces, elevator torque tubes and rudder post, bits of tail structure, servos, etc. Upon removal of the wreckage from the crater it was apparent that the fuselage with its tail, most of the left wing, and the No. 2 powerplant had contacted the ground in an almost vertical nose-down position. All structure removed from the crater was found to be severely fragmented from ground impact.

At the completion of the excavation the main crater measured 53 feet across the top from north to south, excluding the extension into the area where the left wing pieces and No. 2 engine and propeller were removed. The measurement across the top east to west was 44 feet. The excavation of the crater was continued to a depth of 31 feet until there was no further evidence of any structure remaining in either the sidewalls or bottom.

A preliminary survey of the accident area by helicopter disclosed that, in addition to severely fragmented wreckage at the crater, the main portion of the right wing, the outboard powerplants, and many small pieces of wreckage were widely scattered in a general direction north and northeast from the crater.

Approximately 350 soldiers from nearby Fort Knox were used in a ground search of a 21-square mile area. The soldiers covered this area by walking in a line abreast. Investigating personnel followed the line of soldiers, marking, identifying, and plotting the location of each scattered piece of wreckage as it was found.

The parts which separated from the aircraft in flight consisted of the complete right wing with powerplants, the outer end of the left wing and aileron, the No. 1 QEC and nacelle, and the outboard portion of the left elevator.

The right wing was found on a bearing of 10°30"30' at a distance of 11,291 feet from the crater. The Nos. 1 and 4 power sections and their respective propellers with reduction gears were found as four separate pieces all within a radius of less than 2,000 feet of the right wing. Nearly all of the scattered parts of the right and left wings and the outboard nacelles were distributed along a path approximately one mile wide and nearly seven miles long. The magnetic heading of this scatter path was approximately 70 degrees or at nearly right angles to the flightpath, with the heavier of the scattered pieces found at the west end and the least dense at the east end.

The outlying components of the aircraft, the powerplants, and propellers were transported by Army helicopter to an area near the crater. From that location all of the salvaged aircraft structure was transported in CAB sealed vans to the Lockheed Aircraft Corporation at Burbank, California, for further examination. The powerplants were similarly transported to the Allison factory at Indianapolis, Indiana.

Aircraft Structures

Study of the wreckage and wreckage distribution at the scene of the accident disclosed that the outboard powerplants and engine support structures, the complete right wing, and the outer portions of the left wing and aileron separated from the rest of the airplane in flight during such a short time interval that the sequence of these separations was not apparent. In addition, the main wreckage, the outboard engine support structures, the outer end of the left wing, and the portion of the right wing between the fuselage and the inboard nacelles, were so severely disintegrated that detailed study was necessary to identify numerous pieces of wreckage and to determine the nature of the failures.

To facilitate the necessary detailed study of the wreckage, various "reconstructions" of different parts of the structure were made in a restricted area

at the Lockheed factory. Primary interest centered on the outboard engine support structures and on the inboard portion of the right wing. As a result, these portions of the structure were mocked-up in three dimensions. Simpler "reconstructions" were used in connection with the rest of the wing, the horizontal tail, and the vertical tail. Flight control system parts and fuselage wreckage were examined without "reconstruction."

Numerous fractured pieces of wreckage were subjected to metallurgical examinations and analyses in the Lockheed Laboratories. These examinations disclosed no evidence of fatigue cracking, nonconforming material, overtorquing of nuts, or missing attachments. They did yield evidence as to the direction of loads producing failures.

Examination of the fuselage, the vertical tail, the landing gear, and the flight control systems disclosed no indication of malfunction or failure prior to impact with the ground, other than control system failures resulting from the right wing separation in flight.

The only indication of malfunction or failure in the horizontal tail, prior to impact with the ground, was that the portion of the left elevator outboard of the hinge of station 147.8 disintegrated and separated from the airplane. As indicated by the wreckage distribution, this occurred appreciably subsequent to the wing and outboard powerplant separations and very shortly before the main wreckage struck the ground. The separated pieces of elevator skin bore numerous wrinkles and small tears in the wrinkled areas as a result of repeated deformations of high magnitude consistent with both upward and downward twisting and bending of the elevator. This damage is typical of flutter in conventional sheet metal construction.

The left wing "reconstruction" disclosed that from an irregular fracture line, roughly centered at station 482, inboard to the fuselage the left wing structure, aileron, and flap remained attached to the fuselage until it struck the ground. The portions of the left wing and aileron outboard thereof fragmented and separated from the airplane in flight. Study of the fractures in the outer end of the wing box section disclosed that they resulted from excessive fluid pressures pushing the upper and lower covers and the front and rear spars away from the intermediate truss-type ribs. Similarly, outward-acting fluid pressure pushed the solid tip rib at wing station 584 off the ends of the spars. This rib is the outboard bulkhead of the outboard fuel tank, which extends inboard to wing station 221, with no intermediate bulkheads or baffles other than the truss-type ribs at 17 to 18 inch spacings. Failure and separation of the outer end of the left aileron resulted from rearward bending as a consequence of the wing box section disintegrating.

Similar but lesser damage was found at the outer end of the right wing box section. There a large segment of the upper cover was forced upward off the truss-type ribs and separated from the wing in flight. In addition, the solid end rib at station 584 and the outer end of the front spar web were bulged outward and partially separated from each other. The damage to the outer ends of both the right and left wing box sections is consistent only with excessive pressures generated by fuel in the partially filled outboard tanks ramming into the outer end as a result of high rotational accelerations associated with failure of the right wing at the root. Overpressurization of the outboard tanks during refueling would have caused prior distress much farther inboard.

Study of the damage to the right wing between the fuselage and the inboard nacelle disclosed a fracture in the front spar at wing station 78 and one in the rear spar at wing station 101. These were the inboard ends of the spar sections which remained with the separated right wing. The upper and lower wing covers and ribs between the spars in this area were shattered and many pieces fell to the ground separately when the wing separation occurred. The hinged leading edge between the fuselage and the right inboard nacelle also fell to the ground separately in a number of pieces.

This hinged leading edge separated from the wing by the upper skin pulling off the rivet heads in a generally forward direction at the attachment to the terminal extrusion which connects to the upper cap of the front spar. After this failure the leading edge rotated downward to the limit of travel of the piano hinge which attaches to the lower cap of the front spar, and the rear lugs of the piano hinge fractured in bending. The end ribs of this hinged leading edge were damaged by interference with the ends of the adjoining fixed leading edge sections. Some of this damage was normal service wear from interference with the gap seal back-up angles. Superimposed on this were scratches and rib deformations resulting from abnormally large up-and-down movement of the hinged segment relative to the fixed segments and from abnormally large up-and-down spanwise bending deflections.

Prior to separation of the inboard hinged leading edge from the wing, as indicated by an abrupt discontinuity in the direction of the leading edge upper skin pulling off the heads of the rivets in the seam paralleling the upper spar cap, a section of the right wing front spar upper cap flange buckled upward, separating from the vertical leg of the spar cap with outward progression of the crack between stations 78 and 89. At and adjacent to station 78 the upper part of the front spar web buckled and took an "S"-shaped deformation after the above-mentioned flange separation. At station 78 there was also a vertical fracture of the front spar web, which preceded a horizontal fracture extending outboard from station 78. The rear spar failed at station 101 in rearward bending. Tears of the spar cap flanges from the vertical legs of the spar caps progressed outward considerable distances from the spar fractures.

The upper and lower covers of the Electra wing consist of long 7178 and 7075 aluminum alloy extruded planks machined to form spanwise stiffeners integral with the skin. The low energy absorption and yielding of these materials prior to failure results in fractures singularly lacking in indications of the loads producing failure and of failure progression. However, the fact that irregularly saw-toothed diagonal fracture lines in the bottom cover of the right inboard wing extended from the front spar at station 83 to the aft edge of plank 4 at station 155, and from the aft edge of plank 5 at station 155 to the rear spar at station 95, indicates repeated reversals of loading during the breakup. Laboratory examinations of the fractures also disclosed some indications of both tension and compression due to alternate upward and downward loading of the wing, combined with corresponding reversals of shear due to torsion. Slight spanwise bowing of two large separated pieces of the lower cover in this area is consistent with permanent set due to long column buckling at a time when the ribs at stations 83, 101, and 119 were providing little or no lateral restraint.

The fractures of the right wing upper cover between the fuselage and the inboard nacelle had some characteristics of local compression buckling of the upper surface between stations 83 and 101 and some characteristics of the wing

hinging about a chordwise line through the upper surface between stations 83 and 101 after the structural integrity of the front spar and lower surface was destroyed. Directly aft of the front spar, at and adjacent to station 83, the upper cover fractures occurred in conjunction with the spar cap flange separating from the vertical leg and buckling upward.

Reconstruction and study of the right wing ribs at stations 83, 101, 119, 137, 143, and 155 disclosed no uniform pattern of failure in the diagonals, partly due to the lack of sufficient evidence to make a positive determination of the exact manner in which most of the diagonals failed. However, there were a few positive instances of failure consistent with nosedown torsional loading. Several of the rib diagonal failures were quite similar in appearance to corresponding ones found in an American Airlines Electra after the main landing gear wheels struck a snow bank during takeoff. A portion of the lower cap of the rib at station 83, which remained attached to one piece of lower cover by Huck bolts at the plank 1-2 and 3-4 splices, had all rivets sheared in a random pattern at five of the six "H" clips between the above-mentioned points. On this piece of rib cap there were abrasions due to rubbing of separated diagonals against the cap and of one rib tab on the mating "H" clip.

In this area of the wing most attachments of rib caps to diagonals and to the wing cover failed. Both the random pattern of the failures and the abrasions on mating parts are indicative of dynamic conditions with high and changing stresses in the wing covers during and after the rib failures. This random pattern of rib and rib attachment failures in the No. 3 tank area is entirely inconsistent with known failures produced by overpressurization of an Electra fuel tank.

Study of the damage to the left outboard engine support structure and nacelle disclosed that the lower right longeron fitting aft of the firewall failed in a clean tension break. After this the front end of the engine support moved upward and to the left with progression of damage until separation from the airplane occurred. Laboratory examinations of the Lord mounts which support the propeller reduction gear box disclosed evidence of repeated bottoming due to abnormal loading in various directions. Numerous curvilinear scratches, approximately partial ellipses, on the outer surface of the swirl straightener extension and severely scratched areas on the inner surface of the tail pipe bell mouth indicate repeated interference due to large cyclic motions of the engine relative to the wing prior to gross over-all displacement of the engine support structure from its normal position. Initial failure of the right outboard engine support structure consisted of a tension separation of the upper left longeron from the attach fitting at the firewall. The front end of the engine support then moved downward and to the right and rotated with the propeller with progression of damage until separation from the wing occurred. In the process of destruction the right lower longeron tore off the rear attach fitting with repeated interference between the longeron and fitting. The Lord mounts which support the propeller reduction gear box also were damaged due to abnormal loading in various directions.

Numerous fractured fittings and parts of the left and right outboard engine support and nacelle structures were subjected to laboratory examinations. These examinations disclosed no evidence of fatigue cracking, nonconforming material, overtorquing of nuts, or missing attachments. All efforts failed to disclose positive evidence identifying any of the noted damage to the outboard engine support and nacelle structures as having existed prior to the last flight.

All recovered wreckage was examined for evidence of fire having caused the disintegration in flight. Only one probable area of fire prior to the right wing separation was found. This was in the aft part of the right outboard nacelle and the portion of the flap aft thereof and was only of sufficient duration to melt thin aluminum alloy sheet prior to impact with the ground. It produced no weakening of the structure in the areas where the inflight separations of the right wing and outboard engine support structure occurred.

Powerplants

This accident was characterized by separation in the air of portions of Nos. 1 and 4 powerplants as well as the right wing. Major powerplant components were found along the wreckage path in the following order:

1. No. 4 propeller, reduction gear assembly, and torquemeter.
2. No. 1 propeller and major portion of the reduction gear assembly.
3. No. 4 power section.
4. No. 3 powerplant in its entirety with the right wing.
5. No. 1 power section, torquemeter and a portion of the reduction gear assembly.
6. No. 2 powerplant in crater at the fuselage site.

All components lay at the location at which they first contacted the ground except for a minor displacement downslope of the No. 1 power section.

There was no fire damage on any of the powerplants. The blades of all propellers, except those of No. 2, were found in their entirety with or in the immediate vicinity of their respective hubs. The No. 2 propeller, along with the remainder of the powerplant, was dug from the fuselage crater site and only identifiable portions of all blades were recovered.

Powerplant control systems were damaged by separation and impact so that they revealed no reliable information with respect to power configuration at any time prior to impact.

Examination of the engines and propellers for operational failure included:

1. Oil systems for significant contamination.
2. Propeller reduction gear and accessory drive systems for gear and/or bearing failure.
3. Torquemeters for rotational interference.
4. Power section rotors for overtemperature, bearing distress, or rotor failures.
5. Safety couplings for typical operational decoupling markings.
6. Fuel pumps and fuel controls for significant contamination or evidence of malfunction or failure.
7. Propeller pitch-change mechanisms for significant contamination or evidence of malfunction or failure.
8. Propellers and engines for evidence of overspeeds.

This examination was negative with respect to evidence of operational failures. Examination of the Nos. 1 and 4 powerplants showed that the struts remained with the power section of both engines. The torquemeters remained with

the No. 1 engine power section and with the No. 4 propeller reduction gear assembly. Separation of No. 1 engine occurred through the reduction gear case at approximately the main diaphragm split line. Stud failures that occurred at separation were necked down and bent in a pattern showing counterclockwise rotation of the forward part as separation occurred. The separation fractures of Nos. 1 and 4 engines did not show evidence of fatigue or post separation markings which indicated load reversals.

The inner surface of the air inlet housings and compressor cases of Nos. 1 and 4 engines were rubbed by the compressor blades. There were aluminum deposits on the thermocouples and turbine nozzles of the same engines. The high speed pinion of No. 1 engine remained with the torquemeter assembly. Spiral marks were evident on the drive side of the pinion gear teeth. Separation of the rotating parts of No. 4 engine occurred at the forward end of the compressor extension shaft where it engages the torquemeter shaft. Spiral marks were made after disconnect showing the power section end was rotating faster than the torquemeter end. Ends of some of the splines of the extension shaft were upset rearward; also, light axial scrape marks from front to rear showed on some of the extension shaft splines.

Aircraft Systems

Damage to the aircraft was so extensive that no aircraft system, as such, remained intact. Systems components received light to extreme impact damage and in many cases fire damage was evident. The following are the salient facts disclosed by examination of the recovered components.

Many items of the hydraulic system were badly damaged by impact forces and in some cases fire had been present. Damage to valves and pumps precluded operational checks of such units. No operational damage was noted on any units. Hydraulic system items associated with the right main gear remained intact on the gear but were for the most part covered with a moderate coating of smoke deposit. The right fluid heat exchanger was recovered separately with only a small dent in the housing, and undamaged by fire. Both service center packages received moderate impact and fire damage.

Most of the recovered parts of the control surface boosters received severe impact damage. Based on the position of shutoff and bypass valves, the aileron and elevator boosters were in the "ON" position and the rudder was almost completely in the "Manual" position. However, all cables to the controls were broken and the inflight positions of these valves may have been altered at impact.

Loss of electrical or hydraulic power permits the autopilot engaging valve to move to the disengaged position. This was the position of the elevator and rudder valves; however, the solenoid core of the aileron valve was found trapped in the body in the "ON" position, the probable result of impact forces.

The four check valves of each hydraulic manifold were tested. All except three from the aileron manifold passed the test. These three permitted a very slight internal leakage in the closed position and signs of operational distress were noted during their inspection.

The load control units and sensors were considerably damaged. The only operable parts were the pistons that actuate the sensors. The main spool control

valves were distorted but were properly assembled.

One of the two retaining pins of the divider section of the rudder cylinder was missing. There was no indication of flaring on the remaining pin. The hole showed no sign of scoring nor was the barrel damaged in the immediate area of the hole. Nothing was observed during the examination to suggest booster malfunction prior to the accident.

Because of extensive damage examination of the electrical system yielded little information. There was indication of rotation of the No. 2 AC generator at the time of impact and no indication of rotation for those on engines Nos. 1, 3, and 4. Impact marks on the inverter indicate that it was not operating at the time of impact. There was no indication of electrical fire or overload on any of the units or wire bundles.

The radio equipment was completely demolished by impact; there were no indications of electrical overload or burning of any of these units. Examination of the badly damaged components of the various instruments and the autopilot yielded no useful information.

Impact damage prevented testing of fueling valves No. 1, No. 2, and No. 3. Fire damage to seals, switches, etc., prevented the testing of valve No. 4. Disassembly of these valves showed no signs of operational distress or abnormal wear. All four dump valves were in the closed position. The right dump check and swivel valve was relatively undamaged and closed. The left assembly received severe impact damage and was partially open.

The relief valves of the vent valves were bench checked. Although the valves from No. 1 and No. 3 tanks had been burned and were sticking on the first test, all four valves consistently opened at the specified pressure on repeated tests.

Only the right wing fuel shutoff valves were recovered. The No. 3 was approximately 25 percent open and the No. 4 was open. The No. 2 emergency shutoff was not identified among the recovered items. The No. 1 was one-half open, the No. 3 was approximately 5 percent open, and the No. 4 was closed.

All crossfeed valves were accounted for. The No. 1, No. 3, and No. 4 were closed. The No. 2 and the left-to-right wing valves were approximately one-third open.

The engine-driven compressor from the No. 3 engine was intact. It had been damaged by impact but was unburned. The compressor from the No. 2 engine was demolished by impact but was unburned. Examination of oxygen and air-start system items disclosed no significant information.

Inspection of the anti-icing system ducting disclosed no evidence of internal duct fire. The two fire extinguisher containers of the No. 2 nacelle were destroyed by impact. One of the discharge heads was recovered. It had not been fired. Both containers from the No. 3 nacelle were recovered intact and fully charged. One portable CO_2 cylinder, identified as being from the flight station, was damaged by impact. Its handle and discharge horn were missing but it still retained a charge.

Maintenance Records

Review of the maintenance records of N 121US disclosed only one item that appeared of possible significance to the accident investigation. This pertained to a refueling incident in which No. 3 fuel tank developed a leak at a nacelle wing fairing attachment crew location. The leak was attributed by Northwest Airlines personnel to rupture of the tank sealant by an excessively long screw. Although subsequent investigation disclosed that the tank had been overfilled, detailed study of the right wing wreckage, as previously mentioned, disclosed no structural damage or deformations due to over pressurization of the tank. A review of all other Northwest Airlines records pertinent to the airworthiness of this airplane disclosed nothing of significance.

Original Certification of the L-188

To obtain a type certificate for a fixed-wing airplane, which has a weight in excess of 12,500 pounds, compliance must be shown with the provisions of Part 4b of the Civil Air Regulations. As a general rule the provisions of that Part which are in effect on the date of application for a type certificate are the regulations applicable to the type. In the case of the Lockheed Aircraft L-188 application for type certification was made on November 11, 1955, with the result that the applicable airworthiness regulations were contained in Part 4b effective December 31, 1953, and Amendments 4b-1 and 4b-2 of that Part.

In addition to the specific requirements contained in Part 4b, Section 4b.10 of that Part states that an airplane shall be eligible for type certification if it complies with the airworthiness provisions established by the Part or if the Administrator finds that the provisions not complied with are compensated for by other factors which provide an equivalent level of safety. This section also requires the Administrator to make a finding that no feature or characteristic of the airplane would render it unsafe for the transport category.

Since the turbine-powered airplanes, at the time of this application, were still in the design stages, the Civil Air Regulations did not encompass airworthiness requirements specifically applicable to the unique design of these airplanes. Accordingly, the Civil Aeronautics Administration developed a set of special conditions to be applicable to this airplane type. The special conditions were developed through the activities of a Turbine-Powered Transport Evaluation Team composed of employees of the Civil Aeronautics Administration. During the certification process numerous amendments were made to Part 4b of the Civil Air Regulations which included many of the applicable special conditions to the L-188. On July 23, 1957, the Civil Aeronautics Board adopted Special Civil Air Regulation Number SR-422 which became effective on August 27, 1957. This special regulation contained a revised set of performance requirements for turbine-powered airplanes and made applicable the provisions of Part 4b of the Civil Air Regulations effective on the date of application for type certification together with such provisions of all subsequent amendments to Part 4b, in effect prior to August 27, 1957, as the Administrator of Civil Aeronautics finds necessary to insure that the level of safety of such airplanes is equivalent to that generally intended by Part 4b.

In view of Special Civil Air Regulation Number SR-422, the Civil Aeronautics Administration amended the set of special conditions applicable to the Lockheed L-188 to incorporate those provisions of Part 4b in Amendments 4b-3, 4b-4, and

4b-6 which were comparable to those specific special conditions previously established by the Administrator, as well as the performance requirements contained in SR-422. Those special conditions which were not incorporated in the aforementioned amendments were retained.

In order to monitor and approve the type certification of aircraft the Civil Aeronautics Administration established Regional Offices throughout the United States. In the case of the Lockheed L-188, Region IV was responsible for determining that the airplane type complied with the Civil Air Regulations and the applicable special conditions. For many years the Civil Aeronautics Administration has utilized a designee system to assure compliance with the Civil Air Regulations. The establishment of this system was due to the limited number of personnel available in the CAA's field offices. Under this system designated employees of the applicant are delegated to approve certain data, drawings, etc. The approval of the basic data and method of analysis was retained by the Civil Aeronautics Administration, but the actual analysis of the data was approved by the designees and reviewed by the Administrator. The only area of the certification process where designees are used quite sparingly is in the flight test area. In almost all cases the flight tests were conducted by Civil Aeronautics Administration employees.

On August 22, 1958, the Civil Aeronautics Administration issued type certificate No. 4A22 approving the Lockheed L-188A-08, and L-188C type airplanes.

Major Structural Difficulties Encountered after Certification

Subsequent to the delivery of the first few airplanes, Lockheed Aircraft conducted a flight test to determine the characteristics of a mechanical disconnect for the flight control boost system at the design dive speed of 405 knots. This flight test was conducted on October 31, 1959, and consisted of diving the airplane from cruise altitude with various boosters disconnected. On the second dive, with the speed maintained at or slightly below the speed for limit mach number, turbulence was encountered; the speed was dropped off 6 to 8 knots. After passing through the turbulence a fuel leak was observed from under the right wing. Ground inspection disclosed that the main damage was halfway between Nos. 3 and 4 engines. This consisted of some rivets with missing heads from which fuel was leaking; in addition, there was a shallow buckle near the rear beam just inboard of the No. 4 nacelle. The nature of the wing damage and subsequent inflight measurements indicated that the failure was due to high wing torsions.

As a result of this difficulty, the airplanes already delivered were speed restricted until a fix could be designed and installed. The resulting fix consisted of reinforcing the wing between the inboard and outboard nacelles.

During the original certification of the Electra the airplane was equipped with Allison engines and Aeroproducts propellers. Certification included a vibratory stress survey of the propellers. It was determined, based on past experience, that the inboard propellers were the more critical and only the inboard propellers were instrumented. Later a Hamilton Standard propeller was installed on the airplane and a new certification was sought. At this time it was decided to conduct the vibratory stress survey on one outboard and one inboard propeller. As a result of this test it was found that the outboard propellers were more highly stressed than the inboard propellers and that these stresses exceeded acceptable levels. This condition was caused by a higher than anticipated inflow angle due to a

downward torsional bending of the wing with increasing speed. Outboard propeller blade stresses were reduced satisfactorily by reworking the nacelles to provide a 3° uptilt of the propeller plane. Inboard nacelles were similarly modified to reduce cabin noises and vibrations.

Difficulty was encountered on the Electra airplanes with impact stresses during landing which caused cracks in the milled wing skin both outboard and inboard of the inboard nacelles and loosening of the fasteners attaching the upper and lower wing panels to the main landing gear ribs. As a result, Lockheed issued Service Bulletins 306 and 337 which required the installation of a doubler outboard and inboard of each inboard nacelle on the upper wing surface respectively.

In addition, difficulty has resulted from overpressurization of the fuel system. In one case where foreign material was in the fuel manifold system the fuel inlet valve was held in the open position after the tank was filled. Consequently, structural deformation of the wing resulted and an inspection of all fuel manifolds was conducted. Lockheed believes that if the correct procedures are followed during the refueling operation such failures will not occur.

Reevaluation Program

On March 20, 1960, the FAA issued, as a temporary measure, an emergency airworthiness regulation which reduced the Electra V_{no} from 324 knots CAS to 275 knots or 0.55 Mach. Following a meeting on March 22 with representatives of Lockheed, Allison (GMC), Electra operators, NASA, and CAB, the FAA took the following additional action:

1. Because this and a previous Electra accident were believed to have occurred at or near a cruising speed of 275 knots CAS, it was considered necessary to make a further speed reduction to provide an adequate safety margin. Consequently, a second emergency airworthiness regulation was issued on March 25, 1960, limiting V_{no} to 225 knots CAS or 0.55 Mach and establishing a V_{ne} of 245 knots CAS or 0.55 Mach. Also included in this second regulation were requirements calling for immediate propeller feathering if the torquemeter indicator registered zero or full scale; deactivation of the autopilot until appropriate modifications could be designed and installed; adherence to Lockheed prescribed procedures in refueling operations.

2. Under emergency authority specified in Sections 40.21, 41.1, and 42.5 of the Civil Air Regulations, the FAA, in an amendment to the Operations Specifications, ordered a one-time inspection on all Electras within 30 days of the order date, March 25, 1960. The inspection included, in addition to the severe turbulence inspection specified in the Lockheed Structural Repair Manual, an internal examination of the entire wing with emphasis on wing ribs for damaged attachment tabs, buckled rib braces, loose or sheared rivets, and damaged or cracked clips. Additionally, a thorough inspection of the elevators, elevator tabs, and related attachments was also required during the same 30-day period. The amended Operations Specifications further called for daily inspections of powerplant magnetic sump plugs; inspection of fuel tanks involved in a reported tank overpressurization; structural inspections following any reported incidents of flight through severe turbulence, hard landings, or overweight landings.

3. On March 25, 1960, the FAA notified the Chiefs, Flight Standards Divisions that observance and surveillance of L-188 aircraft en route operation

and training was to be increased for a period of 30 days. The telegram specified that inspections should be concentrated in the areas of flight planning, preflight, placard speeds, operating techniques, inadvertent entry into turbulence, abnormal equipment operation, post flight activities, and flight training.

On March 25, 1960, following several meetings in which the Electra problem was discussed, the Administrator requested the Lockheed Aircraft Corporation to conduct an engineering reevaluation of the Electra. The objective of this program was to reveal any design or operational characteristics of the airplane causing structural effects more critical than those provided for and possibly influencing disintegration in flight. Briefly, the program encompassed flight tests, structures investigations, aerodynamics investigations, design studies and special investigations, and tests. Extensive assistance was provided by the NASA, Boeing, Douglas, and other organizations in carrying out this program. A like program, appropriate to the equipment, was also carried out with respect to the engines and propellers.

Included in the flight test program were expanded measurements of wing and nacelle loads and stresses during smooth and abrupt maneuvers, measurement of the dynamic response of the wing and nacelles during gusts, extension of flight flutter response tests, expanded measurements of internal loads and stress distribution in the wing and nacelles, and reanalysis of inflight loads measurements made prior to the accident.

Numerous stiffness and rigidity tests were made on Electra serial No. 1077 for use in flight dynamics analysis. Primary attention was directed to component rigidities from the outboard propeller plane through the engine, nacelle, and wing to the fuselage centerline. The effects of simulated failures at various points in the outboard engine/nacelle installation were measured, but not at any point in the wing structure itself.

In reevaluation of the airplane control system and autopilot characteristics, special attention was directed to the influence of possible malfunctions, failures, and induced effects on the sudden buildup of destructive control forces. The investigation included both analytical methods and the use of an elevator system functional mockup. A rigorous series of tests was conducted on the mockup to induce oscillatory or other performance failures under extreme simulated failures and malfunctions in the system. Nothing was found that might have produced a hazardous situation under the flight conditions of the subject aircraft.

A comprehensive review was made of all strength analysis procedures covering methods of determining internal loads, allowable strengths, and margins of safety. In addition to review of the original analysis, refined procedures were applied to the wing, wing rib, and wing beam analyses. In addition, the effect of damaged ribs on other rib loads and on the rigidity and strength of the wing was computed. Since the QEC structure had previously been static-tested to ultimate strength, attention was focused on changes in the design loads imposed.

Reinvestigation of the structural loads was performed in regard to the following: wing loads in maneuvers, wing loads due to gusts, landing loads, and loads produced by autopilot malfunctions. Loads and stresses determined in the above-mentioned flight tests were used extensively in this program.

Reaudit of the flutter characteristics was divided into two areas of analysis and test. Analytical solutions were obtained by two independent processes of analog and digital. In the latter, 59 degrees of freedom were used. Wind tunnel tests were conducted on three different models. The first consisted of a nacelle-propeller model in the Lockheed 8-by-12-foot tunnel in which stiffness in pitch and yaw was varied over broad ranges. The second was an eighth scale half-span dynamic model of the wing with nacelles and propellers. This was tested in the Lockheed tunnel with varying engine-propeller stiffness and variations in wing fuel quantity. The third, an eighth scale model of the complete airplane, was tested in the NASA 19-foot Langley tunnel. More complete variations of engine-propeller stiffness and damping and wing fuel distributions were covered. In addition, the effects of propeller overspeeding were investigated.

The reevaluation program disclosed two discrepancies in the design of the airplane. One of these was that significant loads imposed on the wing intermediate ribs between the fuselage and outboard nacelles by shell distortion had not been included in the design loads. The other was that the dynamic response of the outboard nacelles in turbulence was different from that used in the original design, with the result that the torsional loading of the wing inboard thereof was increased. In addition, the reevaluation program disclosed that with the stiffness of a powerplant-nacelle installation reduced below normal propeller oscillations could become destructive at the operating speed of N 121US at the time of the accident.

Analysis and Conclusions

A study of the operational aspects of Flight 710 leads to certain definite conclusions. The flight was being conducted in accordance with company procedures, the filed flight plan was being closely followed, and up to the time of breakup all checkpoints had been reported approximately as estimated. In this segment of the investigation nothing was found which would produce a clue as to the cause of the accident.

Examination of all the meteorological and operational evidence at hand reveals that at 18,000 feet in the vicinity of Cannelton, Indiana, the aircraft concerned was operating in an area devoid of clouds with the following significant meteorological characteristics:

(1) just to the east of a marked trough line.
(2) beneath and on the northern edge of a jet stream with high velocity southwest-northeast flow (increasing with height) at all levels from the surface to the jet stream.
(3) marked horizontal and vertical wind shear.
(4) pronounced horizontal thermal gradient and potentially unstable lapse rates.

The above summary is derived from ground-based meteorological observations and a substantial number of pilot weather reports.

The above factors and the magnitude of each clearly indicate that severe clear air turbulence was highly probable at the time and place of the accident.

Pilot weather reports of actual clear air turbulence encounters on that date likewise afford valuable information substantiating the above conclusion.

After observing and forecasting a wind field embodying widely recognized meteorological factors utilized in the forecasting of clear air turbulence, the Board believes that the responsible offices of the U. S. Weather Bureau and Northwest Airlines should have mentioned clear air turbulence in their forecasts.

Three separate and independent studies of the clear air turbulence situation as it relates to this accident have been carried out by agencies other than the CAB (Westher Bureau, New York University, and Meteorology Research, Inc.). The conclusions reached in these studies are in exceptionally good agreement and support the conclusion of the Board's own study as summarized above. It will be recalled that certain pilots flying at 31,000 feet observed a horizontal streamer of smoke extending southward to a smoke cloud with corkscrew-shaped base. Considering the characteristics of clear air turbulence as opposed to convective turbulence, it is not difficult to understand the persistence of a relatively well-defined smoke column.

Trajectory studies of pieces of the aircraft wreckage indicated possible differences in sequence of separation, particularly in regard to light pieces, depending on assumed variables. However, the studies indicated as most probable that the aircraft was in level flight at an altitude of 18,000 feet, and a true course of 170 degrees at an indicated airspeed of approximately 260 knots during the disintegration. This analysis indicates that the first parts to separate were pieces of the right wing upper surface just outboard of the fuselage and that the powerplant and wing disintegrations took place within a period of six to 10 seconds. Disregarding the calculated results involving light pieces and extremely short differences in items of separation, the trajectory analysis indicates also that separations of the left outboard powerplane installation and the left outer wing structure began almost simultaneously with the right wing separation and that separation of the right outboard powerplant installation began shortly afterward.

As previously mentioned, impact and fire damage to components of the various systems of the aircraft precluded functional testing of the majority of such items. However, detailed inspection of all recovered systems components, and functional checks of those items still capable of being tested, failed to disclose any evidence of operational distress or indication of malfunctioning of any component or system. The fuel dump valve and chute positions indicated that fuel dumping was not being attempted and the crossfeed valve positions were consistent with normal tank-to-engine fuel utilization procedures. Examination of the control surface boosters failed to show whether the autopilot was in operation or to indicate conclusively whether the boosters were in the "manual" or "boost" configuration.

Investigation of the powerplants revealed no evidence of malfunction or failure that contributed to the cause of the accident. Of the numerous items studied in detail, no one considered alone provides an answer as to the cause of the accident. However, the powerplants did provide information that can be correlated with other known facts and circumstances of the accident.

Circumstances of the separation within Nos. 1 and 4 engines are of primary significance and there are indications of similarity. The time interval between separations was very short, as evidenced by the locations where they fell and the trajectory studies with No. 1 separating first.

Obviously, abnormal loads were required to bring about these separations since there is a complete lack of evidence of any progressive fatigue failure to the point where separation occurred under normal loadings. Likewise, it is not conceivable that fatigue cracks would start and progress practically simultaneously to failure in two different locations on the two engines. Furthermore, there is no structural failure history of this model engine to suggest such an occurrence.

Aluminum deposits on the thermocouples and turbine inlet guide vanes of Nos. 1 and 4 engines are believed to be significant. Such deposits are expected on turbine engines when the compressor blades contact and machine away aluminum particles while the engine is operating. These deposits on the two outboard engines that separated in the air cannot be accepted as coincidental. It is believed rotational interference which resulted in the aluminum deposits was caused by air inlet and compressor case distortion due to abnormal loads being applied through torquemeter housing and struts of these engines. Furthermore, the abnormal loads followed disruption of the engine supporting structure so that loads normally taken out by the Lord mounts and QEC structure were imposed on the engine structure. It follows that the basic engine structure forward of the compressor must have been intact in order to transmit propeller generated case distorting loads.

A study of the pieces of the No. 1 reduction gear housing did not reveal any evidence of repeated contacts or movements of the parts; however, there were indications of changes in direction and a reversal of the relative motion of adjacent parts, specifically the part which includes the left strut eyebolt base and the adjacent piece which encompasses the left QEC to reduction gear mount pad, identified as pieces one and two, respectively. There are marks that were by the forward side of piece two moving in the outboard direction and scraping against two corners of the castellated eyebolt nut. The location of the marks also indicates that piece two moved a short distance downward and forward. Abrasion marks on the edge of the fracture at the lower rear corner of the left mount pad indicated a slight downward, forward, and twisting of piece two with respect to piece one. These marks probably were made at about the same time that the nut was contacted; subsequently, abrasion marks were made which indicated piece two moved upward and slightly toward the rear. These marks do not substantiate whirl mode; however, they are not inconsistent with what might be expected were whirl mode to be in progress as breakup occurred.

The fractures of the structure of the No. 4 engine did not reveal any markings which showed load reversals as separation occurred. The only indication of load reversals on this engine was at the front end of the compressor shaft extension where separation from the torquemeter occurred. Loadings on both sides of the splines, rearward upset of some of the spline ends, and light longitudinal markings in a rearward direction on some of the splines suggest some movement other than a straight pull away. Gross misalignment as would result from a whirling motion at the propeller, coupled with an r.p.m. differential between the two separating parts, is compatible with the markings.

Examination and study of the aircraft structural wreckage narrowed the failure areas of possible significance to the inboard portion of the right wing, the outboard engine support structures, and the left elevator. This work also eliminated the probability of structural failure due to fatigue cracking, missing parts, nonconforming materials, and overtorquing of nuts.

Although the outer end of the left elevator disintegrated because of flutter, the wreckage distribution proves that this occurred appreciably subsequent to the right wing separation and shortly before the fuselage struck the ground. In addition, the trajectory calculations indicate that at the time of the elevator flutter the airspeed was much in excess of the design dive speed. As a result, the disintegration of the left outboard elevator was a consequence of the wing separation and cannot be considered an indication of unairworthy conditions prior thereto. The only remaining parts of the aircraft which appear to have been involved in the catastrophic disintegration are the wing and engine support structures.

As developed under investigation, a detailed study of the damage to the right wing structure between the fuselage and the inboard nacelle disclosed numerous indications of damage progression during rapid reversals of loading. The separation and upward buckling of the front spar cap flange from the vertical leg between stations 78 and 89 is one example. If this had occurred during a sustained up-gust or positive maneuver, it and the associated disruption of the wing box upper cover could result only in the wing folding upward during separation from the fuselage rather than rearward as it did.

In this same area of the wing the previously discussed damage to the end ribs of the inboard hinged leading edge and the irregularly saw-toothed diagonal fracture lines in the bottom cover are further evidence of reversing loads, both bending and torsion. This type of damage progression appears to be consistent only with catastrophic flutter.

The rib and rib attachment damage found in this same area of the wing could possibly be entirely the result of abnormal reversing stresses associated with the flutter. However, the similarity of some of this damage to that found on other Electras after abnormal ground loading could be indicative of damage prior to the onset of flutter.

The detailed examination of the outboard powerplant support structures disclosed additional evidence of cycling in the form of damage due to repeated bottoming of the front Lord mounts, curved scratches on one of the swirl straighteners, and repeated interference of fractured surfaces. These, particularly the curved scratches on the swirl straightener, are indicative of the propellers having oscillated violently for a short period of time prior to the gross overall displacement which occurred during the disintegration of the powerplant support structure. The energy associated with this violent oscillation obviously caused rapid progression of damage to the powerplant support structure.

Insofar as this accident is concerned, one development of the reevaluation program is most significant. This is that on the Electra the previously mentioned propeller oscillation known as "whirl mode" can under certain conditions cause flutter and structural disintegration.

This is true despite the fact that all of the flutter tests and analyses made by Lockheed during the original certification process and during reevaluation showed the Electra to be flutter-free at and above normal operating speeds, and further disclosed that the wing has a high degree of damping. The latter means that an oscillating motion of the structure will die out rapidly when the exciting force is removed; the damping forces are those which take energy away from the oscillation. A small amount of damping is from internal energy absorption in the structure and in energy absorbers such as engine mounts. The most significant damping, however, is the result of aerodynamic forces acting in opposition, thus absorbing energy from the oscillation. Conversely, if a major change occurs that allows the aerodynamic forces to be additive to the exciting force, the oscillation grows and the result is flutter.

Since the Electra wing is basically flutter resistant, in order to produce flutter there must be an external driving force. The possible force generators are the control surfaces and the propellers. Analyses indicated that the control surfaces would not produce wing oscillations of sufficient amplitude to produce a failure, consequently further analysis was centered around the propeller.

Since the propellers are normally stabilizing, it was necessary to consider abnormal propeller behavior such as overspeeding and wobbling. The studies and tests conducted during the reevaluation program proved that a wobbling outboard propeller caused by a weakened nacelle structure can induce wing oscillations.

Since a propeller has gyroscopic characteristics, it will tend to stay in its plane of rotation until it is displaced by some strong external force such as turbulence, an abrupt maneuver, or power surge. When such a force or moment is applied, the propeller reacts in a direction 90 degrees to the force. For example, if the propeller is displaced upward, the resistance of the structure applies a nosedown pitching moment, causing the propeller disc to swing to the left due to precession. The yaw stiffness resists this motion causing precession downward, resisted by pitching stiffness which produces a precessional swing to the right. This, in turn, is resisted to cause an upward precession to complete the cycle. This effect is termed "whirl mode" and its direction of rotation is counter to that of the propeller.

Normally, whirl mode can operate only within the flexibility limits of the engine mounting structure, and is quickly damped. If, however, the stiffness of the supporting system is reduced through failed or damaged powerplant structure, mounts, or nacelle structure, the damping of whirl mode is reduced to a degree depending on the amount of stiffness reduction.

Powerplant structural weakness or damage does not significantly change the conditions under which whirl mode may be initiated, but in three ways it makes the phenomenon a potential danger:

1. The greater flexibility of a weakened system can allow whirl mode more freedom, hence it can become more violent. In an undamaged system the stiffness increases with increasing deflections, but this is not necessarily true if the structure is damaged.

2. In a weakened installation, the increasing violence of whirl mode can further damage the supporting structure, in turn leading progressively to more violence and even further damage.
3. As the structural system is damaged reducing the spring-constant, the amplitude of whirl mode increases and the frequency decreases from its natural value to lower values which approach the wing fundamental frequencies.

The natural frequency of whirl mode in an undamaged installation is approximately five cycles per second. The wing torsional frequency is about 3.5, and wing bending about two cycles per second, with some slight variation with fuel loading.

As whirl mode progresses in an overly flexible or damaged powerplant installation, its frequency can reduce from five to three cycles per second where it will drive the wing in three cycles per second torsional and bending oscillations. These wing oscillations will reinforce and perpetuate the whirl mode. The three oscillations are then coupled at the same frequency of about three cycles per second, thus becoming a form of induced flutter forced by a powerful harmonic oscillation. This phenomenon can exist, as demonstrated in wind tunnel tests and in analytical methods, at an airspeed far below that at which classical flutter can develop.

The stiffness factor for an undamaged powerplant installation is 15.9×10^6 inch pounds per radian (root-mean-square). The tests indicated that at this stiffness level, whirl mode cannot force wing oscillations at any speed below 120 percent of the design dive speed of the aircraft. If, however, the stiffness is reduced, forced oscillations become more likely depending on amount of stiffness reduction and on equivalent airspeed. More specifically, the data show that if the stiffness is reduced to some value less than 8×10^6 inch pounds per radian, whirl mode could become a driving force on the wing in the cruising speed range. The tests further showed that whirl mode of catastrophic proportions could develop, reduce its frequency, and couple with the wing in a period of from 20 to 40 seconds.

In recapitulation, the reevaluation of the Electra disclosed that the whirl mode can induce flutter in a wing highly resistant to flutter, trajectory studies disclosed that the indicated airspeed of N 121US was approximately 260 knots at the time of disintegration, study of the wreckage of N 121US disclosed that the right wing separation resulted from flutter, the outboard powerplant nacelle disintegrations involved oscillations characteristic of the whirl mode, and analysis of the weather at the time and place of the accident disclosed the existence of clear air turbulence which can excite the whirl mode. It must be concluded, therefore, that the whirl mode provided the driving force essential to destruction of the wing. However, the sequence of events that led to the whirl mode becoming destructive at normal operating speed is not established.

One possibility is that in penetrating the clear air turbulence, no single pulse of which could cause an overload, N 121US may have been subjected to a rapid succession of impulses at the proper frequency to cause dynamic response damaging the engine support structure and enabling the whirl mode to become self-sustaining. However, uniformly timed impulses with sufficient energy at the

necessary frequency are extremely improbable in natural turbulence, which usually has the characteristic of being random both in frequency and in intensity.

A second possibility is that there was sufficient prior damage in one of the outboard nacelles alone to reduce the stiffness to the range where, once excited by turbulence, the whirl mode was self-sustaining and rapidly became divergent. This possibility hinges on extremely severe prior damage, which does not appear likely to have escaped detection during the detailed examination and study of the wreckage.

A third possibility appears to be prior damage to the wing; for example, partially disrupted ribs, as suggested but not proved by the previously mentioned evidence of rubbing between mating parts found on separate pieces of wreckage. With such a condition, penetration of severe clear air turbulence in the area of Cannelton could conceivably result in rapid progression of wing damage. This could also cause change in the already more critical than expected dynamic response sufficient to damage the outboard powerplant support structures, thereby causing the whirl mode to become self-sustaining. Although extensive calculations by the manufacturer tend to discount the possibility of limited prior wing damage having any significant effect in this regard, no dynamic tests have been conducted to support the calculations. Due to the extremely complex interactions under dynamic conditions with damaged rib structure, it is concluded that only such tests of a full-scale structure could either prove or disprove this possibility.

The landing of N 121US at Chicago on the day of the accident may well have caused damage to the wing structure even though some of the passengers considered it a perfectly normal landing. This is due in part to the fact that a person senses only the resultant of the acting forces and that in parts of the cabin of large aircraft very high linear accelerations due to ground loads can be practically canceled by very high angular accelerations. In addition, drag and side impacts on the landing gear sufficient to cause structural damage are smaller than damaging vertical loads with the result that they can occur without alarm. This is borne out by one Electra accident there rearward-acting ground impact loads on the main landing wheels were sufficient to destroy one wing and to collapse the opposite main gear, but the occupants in general had no idea of anything being amiss until the fuselage assumed an extremely abnormal attitude.

In conclusion, the investigation has disclosed that the right wing failed due to flutter involving whirl mode oscillation of the outboard nacelles. Although contributory to the initiation of the flutter, the severe clear air turbulence above appears to have been insufficient to produce the nacelle damage necessary to make the whirl mode self-sustaining. It appears most probable, therefore, that there was unrecognizable prior damage in the wing, or in the wing and outboard nacelles, making the effects of the turbulence more critical than on an undamaged airplane.

Probable Cause

The Board determines that the probable cause of this accident was the separation of the right wing in flight due to flutter induced by oscillations of the outboard nacelles. Contributing factors were a reduced stiffness of the structure and the entry of the aircraft into an area of severe clear air turbulence.

BY THE CIVIL AERONAUTICS BOARD:

/s/ ALAN S. BOYD
Chairman

/s/ ROBERT T. MURPHY
Vice Chairman

/s/ CHAN GURNEY
Member

/s/ G. JOSEPH MINETTI
Member

/s/ WHITNEY GILLILLAND
Member

SUPPLEMENTAL DATA

Investigation and Hearing

The Civil Aeronautics Board was notified of this accident at approximately 1700 c. s. t., March 17, 1960. An investigation was immediately initiated in accordance with the provisions of Title VII of the Federal Aviation Act of 1958. A public hearing was ordered by the Board and held in Evansville, Indiana, on May 10 and 11, 1960, and in Hollywood, California, July 20, 21, and 22, 1960.

The Carrier

Northwest Airlines, Inc., is a Minnesota corporation with its principal office in Minneapolis, Minnesota. The corporation holds a certificate of public convenience and necessity issued by the Civil Aeronautics Board and an air carrier operating certificate issued by the Federal Aviation Agency. These certificates authorize the carrier to engage in air transportation of persons, cargo, and mail within the United States, including the route involved.

Flight Personnel

Captain Edgar E. LaParle, age 57, was employed by the company March 15, 1937. He was promoted to captain June 4, 1940. He held a valid FAA airline transport pilot certificate with ratings: AMEL, C-46, B-377, DC-3, DC-4, DC-6, M-202, and L-188 aircraft. He had a total of 27,523 flying hours, of which 254 were in L-188 aircraft. His last FAA first-class medical examination was taken December 7, 1959; no limitations or defects were noted. His last check flight in L-188 equipment was December 16, 1959.

First Officer Joseph C. Mills, age 27, was employed by the company on August 7, 1957. He held a valid FAA commercial pilot certificate with ratings: AS & MEL, B-25, instrument. He had a total of 2,974 flying hours, of which 200 were in L-188 aircraft. His last instrument check was December 6, 1959. His last FAA first-class medical examination was taken July 14, 1959; no limitations were noted.

Flight Engineer Arnold W. Kowal, age 40, was employed by the company March 19, 1942. He held a valid FAA flight engineer certificate and was qualified in L-188, B-377, DC-6, and DC-7 aircraft. He had a total of 5,230 flying hours, of which 63:36 were in L-188 aircraft. His last second-class FAA medical examination was taken January 18, 1960.

Stewardesses Constance M. Nutter and Barbara A. Schreiber and Flight Attendant Mitchell D. Foster were properly qualified.

The Aircraft

N 121US, a Lockheed Electra, model 188C, was manufactured July 20, 1959. The aircraft had a total flying time since manufacture of 1,786 hours. The last major inspection was accomplished on March 9, 1960, 74 hours prior to the accident. It was equipped with four Allison 501-D 13 engines and Aero Products propellers, model A 644 FN-606.