NASA TECHNICAL NOTE

NASA TN D-7775

NASA TN D-7775

LIGHTNING DAMAGE TO A GENERAL AVIATION AIRCRAFT - DESCRIPTION AND ANALYSIS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1974

1. Report No. NASA TN D-7775	2. Government Accession No.
3. Recipient's Catalog No.	
4. Title and Subtitle LIGHTNING DAMAGE TO A GENERAL AVIATION AIRCRAFT - DESCRIPTION AND ANALYSIS	5. Report Date SEPTEMBER 1974
	6. Performing Organization Code
7. Author(s) Paul T. Hacker	8. Performing Organization Report No. E-7967
9. Performing Organization Name and Address Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135	10. Work Unit No. 501-38
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546	13. Type of Report and Period Covered Technical Note
	14. Sponsoring Agency Code
15. Supplementary Notes	

16. Abstract

The damage sustained by a Beechcraft King Air Model B90 aircraft by a single lightning discharge is presented and analyzed. The incident occurred during landing approach at Jackson, Michigan, on Feb. 19, 1971. In addition to the usual melted-metal damage at the lightning attachment points, there was severe implosion-type damage over a large area on the lower right side of the aircraft and impact- and crushing-type damage on the upper and lower surfaces on the left wingtip near the trailing edge. Analyses indicate that the implosion-type damage was probably caused by lightning-generated shock waves, that the impact- and crushing-type damage was caused by magnetic forces, and that the lightning discharge was a multiple strike with at least 11 strokes separated in time by about 4.5 milliseconds. The evidence indicates that the lightning discharge was rather different from the average in character and severity.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aircraft hazards; Operational hazards; Weather; Lightning; Thunderstorms	Unclassified - unlimited; Category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	53	$3.75

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

A Beechcraft King Air Model B90 aircraft was struck by lightning at an altitude of 2743 meters (9000 ft) during landing at the Jackson, Michigan, airport on February 19, 1971. Witnesses on the ground and in the aircraft reported that there was only one lightning discharge at the time of the incident and that it was between ground and cloud. No other thunderstorms were reported in the area within 2 hours prior to or following the incident.

The damage sustained by the aircraft was widespread, rather severe, and unusual in several respects. The lightning attachment points on the aircraft were (1) the outboard trailing edge of the left wingtip, (2) the right engine propeller tip, (3) the ventral fin on the aft end of the fuselage, and (4) the navigation light on the top of the vertical stabilizer. In addition to the usual melted metal and cracked nonmetallic materials at the attachment points, there was (1) severe implosion-type damage to the aircraft skin on the lower right wing from the fuselage to a short distance outboard of the engine nacelle, including the nacelle and both sections of flaps; (2) impact- and crushing-type damage over an area of about 900 square centimeters (1 sq ft) on the top and bottom surfaces of the left wingtip at the lightning attachment point; (3) pitting by electrical arcing of all support and control rod bearings on both sections of flaps on the left side of the aircraft; and (4) interruption of electrical power due to tripping of the circuit breaker on the generator on the right engine.

Photographs showing the damage in detail are presented. Analyses are made that show (1) that the implosion-type damage was probably due to shock waves generated by the high-current portions of the lightning discharge, (2) that the impact-type damage was probably due to magnetic forces created by the lightning currents flowing along different paths in the aircraft structure, and (3) that the lightning discharge was a multiple-stroke type with at least 11 high-current strokes (spikes) with an average time between strokes of about 4.5 milliseconds.

INTRODUCTION

A Beechcraft King Air Model B90 aircraft owned by Marathon Oil Company was dispatched on a routine passenger mission on Friday, February 19, 1971, from Findlay, Ohio, to Robinson, Illinois, to Jackson, Michigan, and back to Findlay, Ohio. The aircraft departed Robinson for Jackson at 1600 e.s.t. on an instrument flight plan. The aircraft was cleared to 3962 meters (13 000 ft) enroute, and in the vicinity of Jackson (Reynolds Field) was cleared to descend from 3962 meters to 2134 meters (7000 ft). While descending through 2743 meters (9000 ft) with flaps extended and at a speed of 82 m/sec (160 knots), the aircraft experienced a lightning strike.

The pilot witnessed a large flash and a ball of fire in the lower right side of the cockpit. An inspection of the instruments and working systems indicated that they were all normal except that the electrical generator on the right engine was off line. Following reset of the circuit breaker, the generator worked normally and the crew continued on a normal descent and landing. After landing, the flaps were retracted. Landing time was 1713 e.s.t.

After landing at Jackson, the crew inspected the aircraft under limited lighting conditions. The following observations were made: the upper cowl on the right nacelle had become unlocked and was held by safety fasteners, a hole about 1.25 centimeters (1/2 in.) in diameter had been burned in the lower aft corner of the ventral fin, and a lightning discharge area approximately 10 centimeters (4 in.) in length had been burned on the trailing edge of the left wingtip. No other damage was observed, so the aircraft was ferried to home base. The aircraft and its systems operated normally on this leg of the flight; however, during landing, the flaps failed to extend, but a safe landing was accomplished. (Extended flaps are not required for takeoff.)

Inspection of the aircraft in the light of the hangar revealed that it had apparently suffered from an external explosion on the lower right side, from the fuselage to slightly outboard of the right nacelle. Panels were caved in, rivets were missing, paint was discolored, the inboard flap was bowed backwards, and the outboard flap showed three damage wrinkles.

The unusual characteristics and extensiveness of the damage prompted M. Murphy, the Chief Pilot for the Marathon Oil company to contact NASA Headquarter's Safety Office, whom he knew to be interested in lightning damage to aircraft. They, in turn, requested that the Aerospace Safety Research and Data Institute, NASA Lewis Research Center, Cleveland, Ohio, inspect the damaged aircraft and document the incident. This report describes the damage and attempts to analyze both the damage and the lightning strike that caused the damage.

The Marathon Oil Company, Findlay, Ohio, and M. Murphy, their Chief Pilot, are to be commended for notifying NASA of the incident, making the airplane available for photographs and inspection, and providing information on the flight and the aircraft. Without this excellent cooperation, this report could not have been written and valuable information would have been lost.

OBSERVATIONS AND COMMENTS OF WITNESSES

The pilot, J. R. Day, and the copilot, J. W. Maxie, reported after the incident that radar indicated no thunderstorm cells, that no heavy turbulence was encountered, and that only the one lightning flash was seen. The air traffic controller on duty, T. Stevens, stated that the aircraft was on approach to Reynolds Field, Jackson, Michigan, from the northeast and was preparing to land on runway 23, which is 1615 meters (5300 ft) long. He then observed one large, very bright, ground-to-air lightning flash and notified the pilot of this observation. The pilot responded that he thought they were hit by it. The controller believes that the thunderclap lasted for more than 30 seconds and that it was one continuous roll. The off-duty controller, R. Grove, who lives 3.2 kilometers (2 miles) east of Reynolds Field was at home at the time of the incident. The long, rolling clap of thunder shook his house, jarring some plaques on the wall.

These observations indicate that the lightning discharge or at least the resulting thunder was probably more severe than the average lightning discharge.

METEOROLOGICAL CONDITIONS

The weather reports for Jackson, Michigan, for February 19, 1971, near the time of the incident are as follows:

Time, e.s.t.	Cloud height		Cloud coverage	Visibility		Conditions	Temperature		Dewpoint		Wind direction		Wind speed		Barometric pressure		Remarks
	m	ft		m	miles		°C	°F	°C	°F	rad	deg	m/sec	knots	kN/m^2	in. Hg	
[a]1659	152 305	500 1000	Broken Overcast	1609	1	Light rain and fog	5.6	42	208	37	2.62	150	7.7	15	100.7	29.74	--------------------
[b]1710	152	500	Overcast	1207	3/4	Thunderstorm, moderate rain showers, and fog	---	--	---	--	2.62	150	7.2	14	-----	-----	Thunderstorm overhead started at 1710 e.s.t.
[b]1728	152	500	Overcast	1207	3/4	Light rain showers and fog	---	--	---	--	2.01	115	7.2	14	100.7	29.74	Thunderstorm ended at 1725 e.s.t.
[a]1754	183 305	600 1000	Broken Overcast	2414	$1\frac{1}{2}$	Light rain and fog	7.2	45	4.4	40	2.62	150	7.2	15	100.6	29.72	--------------------

[a]Regular report.
[b]Special report.

The low cloud ceiling, fog, and rain persisted throughout the entire day. Only one thunderstorm was observed at Jackson, Michigan, from 1500 e.s.t. to 2000 e.s.t. Sunset on February 19, 1971, at Jackson, Michigan, was 1815 e.s.t. The weather across the southern portion of lower Michigan was very similar to that in Jackson around the time of the incident. The synoptic weather situation at 2000 e.s.t. (about 3 hr after the incident) showed a region of low barometric pressure in central Illinois. A cold front extended southwestward from the low, and a warm front extended eastward from the low across Indiana. The direction of travel of the low was north-northeast toward Lake Michigan.

DESCRIPTION OF AIRCRAFT

The aircraft involved in the lightning strike is shown in figure 1. According to reference 1, the King Air is a pressurized 6- to 10-seat business aircraft powered by two Pratt & Whitney PT6A-20 turboprop engines with the following characteristics:

Wing span, m (ft)	15.32 (50.25)
Overall length, m (ft)	10.82 (35.5)
Height over tail, m (ft)	4.47 (14.66)
Empty weight equipped, kg (lbm)	2578 (5685)
Maximum takeoff weight, kg (lbm)	4377 (9650)
Maximum cruising speed at 4875 m (16 000 ft), km/hr (mph)	407 (253)
Stalling speed with wheels and flaps down, km/hr (mph)	137 (85)

The wings are cantilevered, two-spar, aluminum alloy structures. The fuselage is an aluminum alloy semimonocoque structure. The standard avionics comprise FAA Category II complete all-weather navigation and communication systems and weather radar.

DESCRIPTION OF DAMAGE AND HAZARDOUS EFFECTS

The damage and hazardous effects produced by the lightning discharge were rather severe and widespread and resulted from the various phenomena associated with a lightning discharge. There was melting of metals and cracking of nonmetals at lightning stroke attachment points on the aircraft. Metal skins were distorted due to the "magnetic pinch effect" as the lightning current flowed through them. Metal skins were also distorted by the overpressure in shock waves generated by the lightning discharge. Interior movable mating surfaces were pitted by electrical arcing as the lighting current flowed through the structure. The circuit breaker in the electrical generator system was tripped by transient voltages induced in the electrical system. The damage and hazardous effects are described in detail in the following sections.

Lightning Attachment Points

Lightning is a flow of current between two regions of electrical charge of opposite sign. These charged regions may be in the atmosphere or in the atmosphere and the ground. When lightning strikes an aircraft, the aircraft becomes a part of the electrical path. So there are at least two attachment points, an entrance and an exit. Both entrance and exit points may shift positions, however, during a discharge due to motion of the aircraft with respect to the relatively stationary lightning path. Thus, several attachment points are created.

Left wingtip. - One attachment point of the lightning strike was at the trailing edge of the left wingtip. The damage at this point is shown in figure 2. Besides the metal being melted (figs. 2(b) and (g)), which is typical lightning discharge damage, the trailing edge has been pushed forward (fig. 2(b)). This forward motion of the trailing edge created two pronounced ridges in both the upper and lower surfaces of the wing which were approximately parallel to the trailing edge. The rearmost ridge coincided with a normal bend line in the wing and was so sharp that the metal was torn (figs. 2(b) and (g)). Forward of the ridges, both surfaces of the wing skin were pushed inward. This crumpling damage is probably due to electromotive forces created by the interaction of magnetic fields generated by the lightning electrical currents flowing in the upper and lower surfaces of the wing. This phenomenon is commonly called the "magnetic pinch effect." An analysis and an estimation of the magnetic forces involved in the magnetic pinch effect are presented in a later section.

Propeller. - One blade of the right propeller was another lightning attachment point. Damage to the aluminum propeller was minor, as can be seen in figure 3. The amount of damage is typical for lightning strikes to propellers. The massiveness of the propeller provided a good heat sink and thus not much melting of material occurred.

Ventral fin. - Another area of lightning attachment was the bottom edge of the ventral fin. These damage points are shown in figure 4. The lightning attachment on the fin is typical of what is generally referred to as a "swept stroke." The stroke first attached itself at a forward position on the fin. Then, because of the motion of the aircraft relative to the nearly stationary lightning discharge path, the attachment point moved rearward along the fin, creating damage that ranged from small pitmarks to relatively large holes.

Vertical stabilizer. - Another possible lightning attachment point was the navigation light on the top of the vertical stabilizer. There was no evidence of burning or melting, but the plastic mounting for the light was cracked, as can be seen in figure 5.

Implosion-Type Damage

An extensive area on the right bottom side of the aircraft suffered damage that appeared to be caused by an external explosion. The damaged area included the fuselage near the wing root, the wing from the fuselage to just outboard of the engine, both sides and the bottom of the aft end of the engine nacelle, and both sections of the wing flap. The inward buckling of skin was sufficient in some sections to pull the skin over the rivet heads.

The damage to the inboard section of the wing, the inboard side of the engine nacelle, and the fuselage is shown in figures 6 to 13.

Figure 6 is a general view of the damage to the lower surface of wing and the inboard side of the engine nacelle. The major damage on the wing occurred to two skin panels: the hatch cover for the battery compartment and a wing root fairing. Closeup views of the implosion-type damage to these panels are shown in figures 7 and 8. The inward force on the fairing panel was sufficient to pull the skin over the rivet heads. The fairing panel had no internal stiffeners, but the hatch cover had a stiffener as is evidenced by the rows of weld spots visible in figure 7. All the damaged skin panels were aluminum alloy. Typical thicknesses of damaged skin panels are given in table I. In addition to the implosion-type damage, the paint in an area containing a part of the hatch cover, the wing root fairing, and a section of the fuselage was discolored as though it had been exposed to high temperature. This area of discoloration is shown in figures 8 and 9. Most of the discoloration was slight, except on the fuselage, where it was moderate. The longitudinal black streak on the bottom of fuselage (fig. 9) is not paint discoloration but exhaust deposits from the cabin heater.

A drain fitting for a cabin coffee bar was located in the area of moderate paint discoloration. The mounting holes for this fitting are shown in figures 8 and 9. The fitting is shown in figure 10. The fitting flange was mounted on the internal surface of the skin with five rivets. The fitting was found inside the fuselage skin and completely separated from it.

Damage to the lower inboard side of the right engine nacelle is shown in figures 11 to 13. The damaged area was below the wing chord line and extended from about 35 centimeters (13.8 in.) in front of the wing leading edge to the aft end of the nacelle (fig. 12). The severity of the damage increased markedly in the aft direction. The forward panels showed some wrinkling and sharp creases at an internal structural member. The aft skin panels were severely buckled. The landing gear doors showed no evidence of damage. However, the bottom of the nacelle aft of the landing gear doors was damaged, as is shown in figure 13.

The damage to the outboard bottom side of the right engine nacelle is shown in figures 14 and 15. The area of damage is almost identical to that on the inboard side of the nacelle. The magnitude of the damage also increased in the aft direction but overall was not as severe as that on the inboard side. Damage to the lower wing surface on the outboard side of the engine was minor, as shown in figure 14. Figure 15 presents another view (see fig. 13) of the damage to the aft bottom of the nacelle.

Each wing of the aircraft is fitted with about 3.6 meters (11.8 ft) of wing flap which is divided into two sections of about 1.8 meters (5.9 ft) each. The inboard section extends from the fuselage to just beyond the engine nacelle. The flaps are made of aluminum alloy and have an airfoil shape, with the lower surface nearly straight in both the chordwise and spanwise directions. The flaps were extended and lowered at the time of the lightning strike, and both sections on the right side of the aircraft sustained severe damage, as shown in figures 16 to 22.

As might be expected from the damage shown in previous photographs of the wing and nacelle, the inboard flap received the greatest damage. In general, the inboard flap was bowed upward, as can easily be seen in figures 16 and 17. The centerline of the bow appears to be oriented in approximately the chordwise direction and located about 13 centimeters (5.1 in.) from the inboard side of the engine nacelle fairing that is attached to the flap (figs. 16 and 18). In addition to the bowing, both upper and lower surfaces sustained extensive damage in the form of buckling and dents. The severest buckling occurred at the leading edge of the flap near the centerline of the bow. Both the lower surface (point A, fig. 18) and the upper surface (point A, fig. 19) were sharply creased inward. The creasing was sufficient to tear the metal on the leading edge. A depression in the metal at the inboard end of the inboard flap at the leading edge (point B, fig. 18) was sufficient to create a sharp crease in the metal on the leading edge. There was a similar depression in the lower-surface leading edge of the inboard flap at the outboard end (point C, fig. 20). The trailing edge of the inboard flap near the midsection was sharply bent downward, as can be seen in figures 16 and 17. The skins of the flaps, especially on the upper surface at the aft end of the flap attachment fittings, were distorted (figs. 19 and 21). The metal on each side of the engine nacelle fairing adjacent to the lower flap surface was dented inward (figs. 16 and 20).

Damage to the outboard flap was minor compared with that to the inboard flap. There was no evidence of general bowing or widespread buckling. The lower surface near the leading edge was dented inward in three areas. These are shown at points D, E, and F in figure 22. Point D is also shown in figure 20. There was also some distortion of the upper surface flap skin at the aft end of the flap attachment fitting on the inboard side (fig. 21).

Other Damage and Hazardous Effects

The lightning strike produced the following additional damage and hazardous effects:

Electrical system. - The circuit breaker on the electrical generator on the right engine tripped during the strike. Power was restored by resetting the circuit breaker. Inspection of the generator system showed no evidence of physical damage.

Engine cover latches. - The engine cover latches on the right engine were found unlatched but secured by safety latches after landing following the lightning strike.

Flap bearings. - Each section of the flaps is mounted to the wing by two slotted tracks (fig. 19) attached to the wing in which four bearings (two bearings per slot) attached to the flap can roll when the flap is moved. Each section of flap is moved by a control rod which is connected through a ball bearing at the pivot point to a fixture on the flap (fig. 19). All eight bearings on the two left flaps showed pitting due to electrical arcing on the outside surface of the outer bearing race. This is the surface that contacted the slot surface in the track. The severest pitting occurred to the pair of bearings at the outboard end of the outboard flap, which was closest to the lightning attachment point on the left wingtip. The degree of pitting decreased in an inboard direction until it was just barely detectable on the inboard pair of bearings. Damage to the outer surface of the outboard pair is shown in figure 23. Although the mounting bearings were not disassembled, it was obvious by turning the inner race with respect to the outer race that the rolling elements and their mating surfaces were also damaged. This difficult turning was especially marked for the outboard pair of bearings. Both control rod bearings were also damaged. The side faces, the mounting bolts, and the bolt holes showed melted areas. The bearing for the outboard flap is shown in figure 24. Damage to the rolling elements and mating surfaces was also indicated by difficulty in turning the bearing.

DISCUSSION AND ANALYSIS OF LIGHTNING STRIKE AND RESULTANT DAMAGE

Implosion-Type Damage

The implosion-type damage to the lower right wing surface, engine nacelle, and flaps (figs. 6 to 22) probably resulted from overpressures in the shock wave generated by the lightning discharge. Lightning releases a large amount of energy (of the order of 10^5 J/m of discharge path) at a very high rate (1 to 10 μsec) into a relatively small volume of air. The air in the channel is heated to extremely high temperatures (of the order of 20 000 to 30 000 K), which creates a very high pressure in the channel. As the gases in the heated channel expand, a shock wave is generated which moves radially outward from the center of the discharge channel. As the shock wave moves outward, the overpressure immediately behind the shock front decreases and the shock wave eventually degenerates into the sound wave of thunder. Analytically predicted values of shock wave overpressures as a function of distance as given in reference 2 for typical lightning discharges are shown in figure 25 as curves A and B. The calculations for the two curves are based upon different assumptions, as indicated in the figure and give widely different results at large distances. Curve B at distances of about 5 meters (16.4 ft) gives overpressures equivalent to 0.454 kilogram (1 lbm) of TNT, curve C (ref. 3). When a traveling shock wave is intercepted by a solid surface, the load imposed on the surface is greater than that due to the overpressure in the incident shock wave itself. The kinetic energy of motion of the incident shock wave is transformed into a pressure rise, which increases the overpressure in the reflected shock wave. For shock waves traveling in a direction normal to a surface that does not absorb any energy from the wave, the ratio of the overpressures, reflected to incident, varies from 2 for very low overpressures in the incident shock wave to many times for incident shock waves with large overpressures. When the direction of travel of the shock wave is not normal to the surface, the imposed load is less.

The predicted overpressures given in figure 25 would be sufficient to have caused the observed damage if the lightning discharge path was close enough. Therefore, it may be of interest to theorize on the probable lightning discharge path and lightning characteristics.

Lightning Discharge Path and Characteristics

An indication of the probable lightning discharge path with respect to the airplane and some of the characteristics of the discharge may be obtained from the observed damage and lightning attachment points. First, however, some general characteristics of lightning should be reviewed. The lightning phenomenon is well described in references 2 and 4. Lightning discharges generally consist of a series of high-current, short-duration strokes (spikes) separated by relatively low-level, long-duration continuing currents. The duration of the high-amperage current is of the order of microseconds, while the duration of the continuing currents is of the order of milliseconds. Shock waves are created by the high-current strokes. The melting of metal at the attachment points is caused primarily by the continuing currents.

As pointed out earlier, two lightning attachment points on the aircraft were the trailing edge of the left wingtip and a tip of the propeller on the right engine. If it is assumed that these points were the initial attachment points, a probable discharge path was from a charged region in a cloud above and ahead of the aircraft to the left wingtip, through the aircraft to the right propeller tip, and then to the ground to the rear of the aircraft. If the propeller tip at the time of initial attachment was near or below the plane of the wing, then the ground portion of the discharge would be under the wing and relatively close to the wing surface. Inasmuch as there was implosion-type damage on the lower wing surface and the nacelle surfaces on both sides of the nacelle, (figs. 6

to 22), there must have been at least two high-current strokes, one on each side of the nacelle. Since the propeller rotates in a counterclockwise direction (viewed from in front of aircraft), the first stroke had to occur when the effected propeller tip was on the outboard side of the nacelle.

Damage sustained outboard of the nacelle was substantially less than that on the inboard side. This could be due to either or both of two factors: the lightning was farther away from the aircraft surfaces, or the current level in the first stroke was less than in the second stroke. The probable reason is the distance since in the usual lightning discharge the first stroke is generally the largest (ref. 2). As the effected propeller tip moved from outboard of the nacelle to inboard, several factors would tend to cause the lightning discharge path to move toward the lower surface of the aircraft. Such a discharge path would result, for example, if the aircraft was moving toward the lightning. The air containing the ionized discharge path would also move toward the lower wing surface because of the upward flow of air as it approached the wing leading edge and also because of the contraction of the propeller slipstream downstream of the propeller. The paint discoloration and severe implosion-type damage at the wing root and the adjacent fuselage (figs. 8 to 10) indicate that the discharge path for a stroke was very near the aircraft surface. A stroke occurring when the effected propeller tip was near the plane of the lower wing surface on the inboard side with the lightning discharge path almost horizontal is consistent with the lightning attachment point moving from the propeller tip to the ventral fin (fig. 4).

Some damage sustained on the lower right surfaces of the aircraft cannot be easily associated with the shock waves created by only two strokes. These damages are the localized indentations sustained by the lower surfaces of the wing flaps near their leading edges as indicated in figures 18 to 20 and 22. The locations of these indentations on the flaps with respect to the wing, nacelle, and propeller tip circle are shown in figure 26. The most severe damage was at point A. The damage at points B, C, and D is moderate. Damage at point E was slight and at point F very light. It is proposed that these localized indentations were caused by five different strokes while the lightning was attached to the propeller tip. They resulted from the orientation of the stroke with respect to the aircraft, the cylindrical nature of the lightning-generated shock wave, and the wing-flap geometry. At the time of the lightning strike, the flaps were extended and lowered, creating a corner along the junction of the flap leading edge and the wing. The localized indentations were all in the flap and located along this corner line.

In order to explain the occurrence of these localized indentations, we assumed that the portion of the lightning discharge path from the propeller tip to the ground was oriented in a general longitudinal or chordwise direction under the wing, as illustrated in figure 27(a). There is a high probability that the lightning discharge path was parallel neither to the underneath surfaces of the flap or wing, except maybe at a point on the forward portion of the wing where the surface is highly curved, nor to the wing-flap corner line. Also shown in figure 27 are positions of the cylindrical shock wave at arbitrary points in time as it moved radially away from the lightning discharge path, intercepted the wing and flap surfaces, and was reflected. As was mentioned previously, the greatest load imposed on a surface by a shock wave with a given overpressure occurs when the direction of travel of the shock wave is normal to the surface. That is, the maximum imposed load occurs at points on the surface where the direction of travel of the shock wave is mutually perpendicular to the lightning discharge path and the surface. The lightning discharge path and the wing-flap corner line can be considered as two nonparallel lines. There is, therefore, only one line between them that is mutually perpendicular to both. This is represented in figure 27 by line O-P. In the spanwise direction along the wing-flap corner line from point O (fig. 27(b)), the imposed load on the surface decreases not only because the direction of travel of the shock wave is not normal to the surface but also because the surface is further away from the lightning discharge path and thus subjected to a lower overpressure (fig. 25). In the chordwise direction, the imposed load for points near point O may be less than the load imposed at point O because of the nonnormal direction of travel of the shock wave. At greater distances from point O the imposed load may become greater as the distance between lightning discharge path and the wing and flap surfaces becomes less. This distribution of the imposed load in the chordwise direction is in agreement with the damage sustained, especially on the lower inboard sections of the wing and the flap. On the wing the damage was greater on the forward portion than on the aft portion (figs. 6 to 12). The flap was also damaged near the trailing edge (fig. 17). The preceding argument can be extended to show that localized damage can also occur at a corner point formed by three intersecting surfaces.

It may appear odd that all the localized indentations occurred in the flap and not in the wing material, but there is a possible explanation. The wing skin near the corner line is reinforced by doubling the material, whereas the flap is single thickness. The flap skin thickness is also only 0.56 millimeter (0.022 in.), which is thinner than for representative wing skin panels for which measurements are available (table I).

The preceding discussion indicates that localized damage can occur along the wing-flap corner line. Based upon the location of the damaged areas and a reasonable assumption of the orientation of the lightning discharge path with respect to the aircraft, the possible location of the propeller tip to which the lightning was attached when the high-amperage strokes occurred can be determined. From these locations and the known propeller rotational speed, the time interval between strokes can be estimated. Consider first point A (fig. 26), which sustained the greatest damage, and assume the lightning discharge path from the propeller tip was oriented in a chordwise direction. A line normal to the wing-flap corner line at point A (line A-A' in fig. 26) and the lightning discharge path which it intersects defines a plane which intersects the propeller circle at point 4. Point 4 is a possible position of the effected propeller tip at the time of the stroke that caused the damage at point A.

Next consider points C, D_1, and D_2 (fig. 26) on the outboard side of the nacelle. The overall damage here was not as great as it was at point A. There appear to be three distinct damage points, but it can be argued that all three were the result of a single stroke. The wing-flap corner line for the outboard flap is swept forward with respect to the inboard wing-flap corner line. Thus, the wing and the two flaps create a corner where they meet. Based on the argument presented previously, this geometry could lead to four distinct localized damage areas. One on each of the three corner lines (those formed by the junctions of the wing and the outboard flap, the wing and the inboard flap, and the inboard and outboard flaps), and the corner formed by these three surfaces. The damage at point D_2 is, therefore, explainable. The damage on the inboard wing-flap corner line could be that shown at point C. It could be, however, that the damage that could occur on the inboard wing-flap corner line did not occur because of the shielding effect of the nacelle. If this is true, points C and D could be associated with the damage that might normally occur in the corner. Points C and D are very near the corner but are on different flaps. The ends of each flap contain end plates which stiffen the flaps near the corner so that the resulting damage occurred in the weaker material on either side of the corner. There was no localized damage area along the inboard-outboard flap corner line. There would be no damage along this corner line, if the corner line and the lightning discharge path were in the same plane. If they were not in the same plane, there may have been no visible localized damage because the point of maximum imposed load was either foreward or aft of the flap. Now if it is assumed that the lightning discharge path was oriented under the wing in an almost chordwise direction and almost in the same plane as the inboard-outboard flap corner line, another position of the effected propeller tip when a stroke occurred, point 3, can be established.

The angle subtended by points 3 and 4 on the propeller tip circle is 0.87 radian (49°). At the nominal propeller rotational speed of 1800 rpm (ref. 1), the time between strokes 3 and 4 is about 4.5 milliseconds. This time interval is much less than the most frequently observed interval of about 40 milliseconds and only slightly larger than the minimum time of 3 milliseconds for multiple-stroke discharges that do not have continuing currents between each stroke (ref. 2).

It is frequently observed in multiple-stroke lightning discharges that the time interval between successive strokes is fairly constant throughout the discharge (ref. 4). The time interval or distance between points 3 and 4 on the propeller tip circle can then be used to locate the position of the effected tip for the three other strokes which are assumed to have occurred. The other positions are shown as points 1, 2, and 5 in figure 26. Points 2 and 5 are very close to the localized-damage points E and B, respectively. This leaves point 1 to be associated with the damage at point F. Since the propeller rotates in a counterclockwise direction, the successive strokes in the discharge go from point 1 to point 5. After point 5, the lightning discharge path would be interrupted by the wing, and the attachment point for this portion of the discharge path would have to change.

The lightning attachment point did move to the lower edge of the ventral fin and became what is generally referred to as a swept stroke, as shown in figure 4. The swept stroke left a series of damaged areas that ranged from scorched paint with small pits in the metal to large holes through the sheet metal. The positions of the damaged areas along the ventral fin are shown in figure 28. The relative magnitude of the damage at each position is qualitatively indicated by the length of the line marking the position. Altogether there were 12 damaged areas, with six of these more pronounced than the others. The spacing of these pronounced damaged areas along the fin was fairly uniform, 35.6 to 43.2 centimeters (14 to 17 in.), except the one at the aft end which was 20.3 centimeters (8.0 in.) from the preceding area. The average spacing, not including the 20.3 centimeters (8.0 in.), was 39.7 centimeters (15.6 in.). At the time of the lightning strike, the aircraft speed was 82.3 m/sec (160 knots). The time required for the aircraft to move 39.7 centimeters (15.6 in.) was 4.8 milliseconds. This is very close to the 4.5 milliseconds calculated earlier for the time between the high-amperage strokes of the discharge. This suggests that the change in attachment point for a swept stroke is triggered by the high-amperage strokes. After attachment, the continuing current flow caused the melting-type damage. The amount of current flow required to melt aircraft structural materials is discussed in reference 5. Meanwhile, because of the motion of the aircraft, the lightning discharge path near the aircraft was stretched and bent with respect to the original path which was relatively fixed in space. When the next stroke occurred, the large magnetic field created around the path ruptured the discharge path at the bend, causing a new attachment at a point on the aircraft near the original discharge path. The minor damage occurring between the major damage positions (fig. 28) could have been caused either by momentary contact between the discharge path and the structure as the attachment point was carried forward with the aircraft or by momentary contact as the attachment point changed position.

The last attachment point for the ground portion of the lightning strike was probably the aft end of the ventral fin. How long it remained attached here cannot be estimated but was probably fairly long since the damage here was the greatest. During most of the time interval between the attachment of the ground portion of the lightning discharge to the propeller tip until it moved to the aft end of the ventral fin, the cloud portion of the discharge was probably attached to the left wingtip. Near the end of the discharge, the cloud-portion attachment point moved to the plastic light housing on the tip of the vertical stabilizer. The probable lightning path with respect to the aircraft as a function of time is shown in figure 29.

Based upon the foregoing analysis, the number of strokes in the discharge was at least 11 and the total duration was greater than 42 milliseconds. Statistics on lightning discharges presented in reference 2 give (1) the average number of strokes per discharge as about four, with 11 strokes per discharge occurring in only about 5 percent of discharges; and (2) the average total duration of discharges with 11 strokes as about 350 milliseconds. According to these statistics, this lightning discharge was far from average.

Damage due to Magnetically Induced Forces

The crumpling-type damage sustained at the lightning attachment point on the trailing edge of the left wingtip (fig. 2) appears to have been caused by an impact on the trailing edge since the trailing edge has been pushed downward and forward. The approximate geometry of a chordwise cross section of the wingtip trailing edge before and after the lightning strike is shown in figure 30. In the analysis that follows, it will be shown that the damage probably resulted from magnetically induced forces created by the lightning current as it flowed through the aircraft wing skin.

It is well known that a current-carrying conductor is surrounded by a magnetic field. If the magnetic field for one conductor encompasses a second current-carrying conductor, the magnetic field of the first conductor produces a force on the second conductor and the magnetic field of the second conductor produces a force on the first conductor. For the simple case of two parallel current-carrying conductors, the forces are such as to create an attraction of the conductors when the currents are in the same direction and a repulsion when they are in opposite directions. In the case of a single current-carrying conductor which is not straight, the magnetic field generated in one section can produce a force on another section of the conductor. For the general case, the force on conductor 2 by a current in conductor 1 is given by the vector differential equation (ref. 6)

$$d\vec{F}_2 = i_2 \, d\vec{l}_2 \times \mu\vec{H}_1 \tag{1}$$

where

$\vec{F}_2$ force on conductor 2

i_2 current in conductor 2

$d\vec{l}_2$ element of length along conductor 2 in direction of current flow

μ permeability of media surrounding conductors

$\vec{H}_1$ magnetic intensity of field at conductor 2 due to current flow in conductor 1

The magnetic field intensity $\vec{H}_1$ is given by the vector differential equation (ref. 6)

$$d\vec{H}_1 = i_1 \frac{d\vec{s}_1 \times \vec{r}}{r^3} \tag{2}$$

where

i_1 current in conductor 1

$d\vec{s}_1$ element of length along conductor 1 in direction of current flow

$\vec{r}$ vector distance from a point on conductor 1 to a point on conductor 2

r magnitude of $\vec{r}$

(The units for the parameters of eqs. (1) and (2) depend upon the system of units used.)

In order to illustrate the direction and order of magnitude of the magnetic forces on the wingtip surfaces, equations (1) and (2) were applied to a system of conductors whose geometry represents the wingtip trailing-edge chordwise cross section shown in figure 30. In addition, the lightning discharge path was included as part of the circuit. The lightning path was assumed to be in the plane of the wing cross section and attached to the trailing edge (point A, fig. 30) at an angle of 0.7854 radian (45°) with respect to the trailing-edge section. The lightning current I was assumed to flow into the wing at a point A (fig. 30) and to divide equally at point O into the conductor segments OBE and OCD, representing the upper and lower surfaces of the wing. Equation (2) can be integrated to give the magnetic field intensity H produced by the current flow in one segment of the circuit at various points along other segments of the circuit. The resulting equation is

$$H_1 = \frac{bI_1}{l \sin\beta}\left[\frac{S_2 - l\cos\beta}{\sqrt{l^2 - (2l\cos\beta)S_2 + S_2^2}} - \frac{S_1 - l\cos\beta}{\sqrt{l^2 - (2l\cos\beta)S_1 + S_1^2}}\right] \tag{3}$$

where

I_1 current in conductor 1, A

b conversion factor to convert amperes to abamperes, $b = 0.1$

β angle between conductor 1, the field-producing conductor, and conductor 2, along which the field is to be calculated

S_1, S_2 distances from vertex of angle β to end points of conductor 1, such as points C and D, respectively, in fig. 30, cm

l distance along conductor 2 measured from vertex of angle β, cm

H_1 magnetic field intensity at conductor 2 due to current in conductor 1, Oe

The current I used in equation (3) is either equal to the lightning current I or to one-half the lightning current, depending upon the segment of the conductor system involved.

The total magnetic field intensity along one segment of the conductor system is the vector sum of the contributions from all the other segments. Since all segments of the conductor system are in one plane, the magnetic field along these segments is perpendicular to the plane. The magnetic field intensity per ampere of lightning current for each segment of the conductor system is presented in table II for various positions along the conductor.

By using the magnetic field intensities in table II and the integrated form of equation (1), the forces per unit length of conductor per ampere squared of lightning current were calculated. These forces are also presented in table II in newtons per meter per ampere squared. Current squared appears because force is directly proportional to the product of magnetic field strength H and current I and because the field strength is also directly proportional to the current.

As has been pointed out, for the assumed conductor system configuration, the magnetic field is perpendicular to the direction of current flow and the plane of the conductor system. The vector equation (1) requires the force vector to be perpendicular to both the direction of the current and the magnetic field. Thus, the forces on the various segments of the conductor system are in the plane of the conductor system.

The calculated forces presented in table II are shown plotted on a schematic representation of the wing trailing-edge chordwise cross section in figure 31, in order to show the relation between the forces on the various segments and to compare the forces with the damage sustained (fig. 30). The directions of the calculated forces correlate very well with the damage. The forces on the trailing-edge segment (A-O) are downward, which agrees with the final configuration in the damaged area. The forces on A-O, especially near A, are mainly due to the lightning, which was assumed for the calculation to come from above and behind the trailing edge. If it had been selected as coming from above and forward, the downward forces on the upper surfaces and especially on the trailing edge would have been greater. If the lightning had come from below, the trailing edge would have been forced upward. The calculated forces on segments O-B and O-C near point O are such as to force the two segments together, which actually occurred. At points B and C, the calculated forces are such as to cause the points to move away from the interior and also to cause separation of segments O-B and O-C from segments B-E and C-D, respectively. Points B and C were actually pushed outward, and the metal was torn at point B. The calculated forces on most of the upper surface (segment B-E) and lower surface (segment C-D) are such as to cause the surfaces to move inwardly toward each other, which was the actual case.

The forces presented in table II and figure 31 are the calculated forces per ampere squared for a 1-meter-long conductor. (The maximum current measured in a stroke portion of a lightning discharge was slightly greater than 200 kA, with 2 percent of all strokes greater than 100 kA (ref. 2).) For the trailing-edge segment (A-O), whose length is 1.25 centimeters (0.48 in.), the average force over its length would be about 10^{-5} N/(A^2)(m). Thus, the average force for a 100-kiloampere stroke on segment A-O would be 1250 newtons (281 lbf). On the upper and lower surfaces, B-E and C-D, respectively, at about 2-centimeter (0.79-in.) position the force would be about 0.5×10^{-5} N/(A^2)(m), which gives for a 100-kiloampere stroke a force of 500 N/cm (286 lbf/in.).

The foregoing calculated forces are based on the assumption that all the lightning current flows in a line circuit defined by a chordwise section of the wing trailing edge. In the case of a stroke to the aircraft wingtip, the lightning current flowing in the upper and lower wing skins will spread out as it flows away from the attachment point. This diffusion of the current decreases the intensity of the magnetic field and thus the forces. The actual current diffusion pattern in the wing skin is not known and if it were known, it might be difficult to calculate the magnetic field and the forces. An estimate of the forces on the upper and lower wing surfaces can be made, however, if it is assumed that the current flow paths on the two surfaces, or conductors, are parallel ribbons of infinite length, as shown in figure 32(a). If it is further assumed that the current distribution across the width is uniform, the x- and y-components of the magnetic field intensity, H_x and H_y, respectively, produced by one of the conductors derived from a vector potential equation given in reference 7 are given by

$$H_x = \frac{I}{8\pi a}\left(2 \tan^{-1} \frac{a + x}{y} + 2 \tan^{-1} \frac{a - x}{y}\right) \tag{4}$$

and

$$H_y = \frac{I}{8\pi a}\left\{\log\left[(a + x)^2 + y^2\right] - \log\left[(a - x)^2 + y^2\right]\right\} \tag{5}$$

where

I total current in conductor

a half-width of conductor (fig. 32(a))

y distance between conductors 1 and 2, m x distance from centerline of conductor 2, meter

For

a 2 cm (0.79 in.)

I 1 A

y 1 cm (0.39 in.)

The x- and y-components of the magnetic field intensity on conductor 2 due to current flow in conductor 1 are presented in figure 32(b). The x- and y-components of the force per meter per ampere squared along conductor 2 due to the magnetic field of conductor 1 are presented in figure 32(c). The forces were derived from the magnetic field intensities of figure 32(b) by

$$F_2 = \mu_0 H_1 I_2 \tag{6}$$

where the permeability μ_0 has a value of 1.257×10^{-6} N/A^2. Since the force on a conductor is perpendicular to both the direction of the magnetic field and the direction of the current flow, the x-component of the magnetic field produces a force in the negative y-direction. Inasmuch as the currents in both conductors were chosen as equal and flowing in the same direction, the forces on conductor 1 are equal, but opposite in direction, to those given in figure 32(b). That is, the conductors will move toward each other. The forces per meter of the conductors for other than unit current are obtained by multiplying the forces given in figure 32(c) by the product of the two individual currents. For example, the average y-component of force from figure 32(c) is about -8.6 N/(A^2)(m). If it is assumed that the current in each conductor is 50 kiloamperes (equivalent to a 100-kA lightning stroke that is divided equally between the conductors), the force on conductor 2 in the negative y-direction is

$$8.6\times10^{-6} \times 25\times10^{8} = 215\times10^{2} \text{ N/m}$$

or 215 N/cm (123 lbf/in.). The corresponding force per unit length calculated previously for the line circuit for the same total current was 500 N/cm. Thus, spreading the current from a line circuit to 4-centimeter (1.58-in.) wide conductors reduces the forces on the conductors by 57 percent, but the forces are still high. The forces per unit length of the ribbon conductors can be converted to pressure or force per unit area, since the ribbons have width. The pressure on the 4-centimeter (1.58-in.) ribbon is 5375×10^2 N/m^2 (78 psi). This is extremely high pressure when compared to the design wing loading for the King Air airplane, which is given in reference 1 as about 1.7×10^3 N/m^2 (0.25 psi). Thus, it appears that the magnetic force generated by lightning currents flowing in the aircraft wingtip was sufficient to cause the damage sustained.

Flap Bearing Pitting

The pitting of the left wing-flap bearings (figs. 23 and 24) by electrical arcing is typical of damage that can occur on mating surfaces which are not adequately electrically bonded. Bonding in this case is difficult because the flaps have to be free to move with respect to the wing. The bonding provided on the aircraft consisted of flexible cables, one for each of the four flap support and attachment points (two per flap). These cables were about 0.5 centimeter (3/16 in.) in diameter and 25 centimeters (10 in.) long and were connected to the main wing structure near the flap support structure and to the sheet metal structure to which the flap bearings were attached, as shown in figures 33 and 20. The flap actuators (fig. 19) also provided, through the bearing surfaces, a connection between the flaps and the main wing structure.

Arcing at mating surfaces is easy to understand when the direct lightning-current flow path is through the mating surfaces. In this case, the lightning did not attach itself to the flap. The primary lightning path was through the main section of the left wing. The complex geometry of the wing structure, the flap structure, and the associated attachments presents a very complex electrical circuit. A simplified representation of this electrical circuit is presented in figure 34. Because of the transient nature of lightning, especially the high rate of change of current in the high-current portion of the discharge, the metallic structure presents an impedance to the current flow. This impedance is primarily composed of resistance and inductance. The bearing mating surface in the flap support structures and flap actuator acts like a capacitor because of the presence of oil or oxide films. The effective resistance of the structural member of the circuit is much greater than the direct-current resistance because of the "skin effect" produced by the rapidly changing current. When the lightning current begins to flow through the wing structure, the primary lightning flow path, the impedance of the wing structure establishes a voltage drop between points A and B. This voltage drop can be fairly large, even though the impedance is small, because the lightning current is very large. As the voltage drop develops between points A and B, current begins to flow between the wing and the flap through the various attachments. Most of the current flow between the wing and the flap is through the bonding cables since the capacitance of the capacitor formed by the bearing mating surfaces is small. The current flow through the bonding cables because of impedance creates a voltage difference between the wing and the flap. Although the bonding cables are rather short and fairly large in diameter, their impedance to the high-frequency lightning current can be sufficient to create a large voltage difference between the wing and the flap. If this voltage difference exceeds the breakdown potential of the dielectric material (oil or oxide) of the capacitors formed by the bearing surfaces, electrical arcing will begin. With the onset of arcing, the current flow through the bearings will increase sharply and probably exceed the current flow through the bonding cables since the bearing support structure is more massive (larger cross-sectional area) than the bonding cable. Once arcing is started it will continue until the voltage difference between the wing and the flap reaches a critical minimum value, which may be considerably less than the voltage necessary to start the arcing. Thus, arcing across inadequately bonded mating surfaces which is initiated by the short-duration, high-current portion of the lightning discharge may continue throughout the continuing-current (long duration, relatively low current) portion of the lightning discharge. Most of the arcing damage is caused by the continuing current.

Although bonding cables were provided around each of the flap bearing assemblies, they were obviously inadequate for the lightning strike encountered. Electrical arc pitting damage of mating surfaces on movable components may not immediately create a serious problem but with time may lead to a serious problem unless the damage is detected and repaired. Detection of arcing on internal or hidden components such as these bearings may be a time-consuming task. Arcing inside integral fuel tanks is a hazard to be avoided. Thus, not only is good electrical bonding required in the design and fabrication of an aircraft, but periodic inspection and maintenance of bonds should also be made.

Loss of Electrical Power

Tripping of circuit breakers in aircraft electrical generator circuits by lightning is not an uncommon occurrence. In an airlines lightning reporting project (ref. 8), tripping of the alternating-current generator circuit breaker was reported for 2 of 46 incidents. Tripping of circuit breakers can result from either direct passage of the lightning current into a circuit (direct strike to a conductor) or by voltages induced in circuits by the lightning current flowing in the aircraft structure. The mechanism by which lightning trips a circuit breaker is not fully understood. Circuit breakers usually have a built-in time lag to prevent actuation by transients, and lightning is a rather short transient phenomenon. Tripping by direct strikes to conductors is more easily comprehended than tripping by induced effects since the currents and voltages in the lightning are orders of magnitude greater than those induced indirectly. Measurements and discussions on induced voltages and currents in aircraft electrical systems can be found in references 9 to 11. The magnitude of induced voltages and currents depends upon many factors: the electrical characteristics of the lightning strike itself, the length and location of the lightning path through the aircraft, the length and location of the electrical circuit with respect to the lightning path, and the physical and electrical characteristics of the circuit. In simulated lightning tests (ref. 9), induced open-circuit voltages of 96 volts and short-circuit currents of 23 amperes have been measured.

Since inspection of the King Air aircraft did not reveal any direct strike to any electrical circuit, the tripping of the circuit breaker was probably due to induced voltages. The most likely circuit in which voltages were induced is the circuit for the navigation light on the left wingtip. This circuit extends the full length of the wing and nearly parallels the lightning flow path when the lightning was attached to the trailing edge of the left wingtip and to the propeller on the right engine. Another possible circuit is the navigation light on the top of the vertical stabilizer since the lightning also struck the mounting for the light.

Damage to Navigation Light Mounting

The crack in the plastic mounting for the navigation light on the top of the vertical stabilizer (fig. 5) is typical of damage produced when lightning strikes an electrical insulating or dielectric material. When the lightning attaches to the exterior of the plastic housing, the insulating plastic is in the current path and an electric field is generated across the material. When the electric field exceeds the dielectric strength or breakdown potential of the dielectric material, the material is punctured or cracked. The dielectric strength of most insulating materials ranges from 10^3 to 10^7 volts per centimeter. Potential gradients of this order of magnitude are easily obtained when the dielectric material is a part of a lightning discharge path. Dielectric material can be protected by use of electrical conductive paints or metallic strips bonded on the exterior surfaces and connected electrically to the metal aircraft.

CONCLUDING REMARKS

The aircraft in this incident suffered most of the hazards associated with lightning except the ignition of fuel and a direct strike to the electrical system. The photographic documentation and analysis presented may serve to inform designers and operators of aircraft of the many types of lightning hazards and their magnitudes. Operators and maintenance personnel should also be aware of the possibility that some lightning damage, such as the pitted flap bearing that occurred in this incident, may not be immediately obvious.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 22, 1974,
501-38.

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TABLE I. - TYPICAL SKIN THICKNESSES

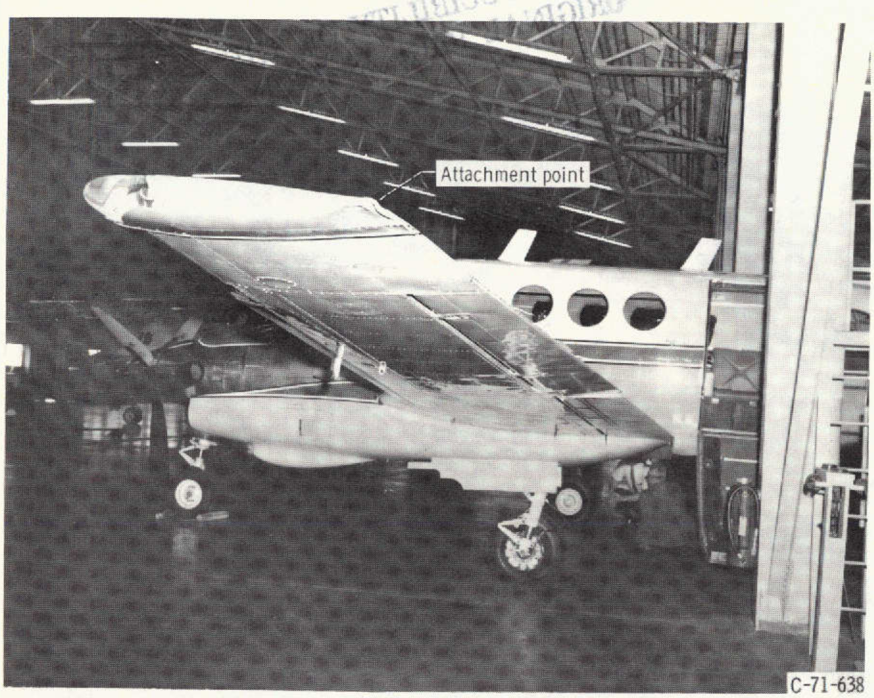
Component	Thickness, mm	Thickness, in.	Figure	Panel number
Upper wingtip	0.71	0.028	2(b)	1
Lower wingtip	.80	.031	2(c), (d)	2
Wing-to-fuselage fairing	.64	.025	2	3
Panel around battery hatch	.94	.037	8	4, 5
Skin on aft end of nacelle	.64	.025	15	6
Wingtip fairing	.97	.038	2(g)	---
Wing flap	.56	.022	------	---

TABLE II. - MAGNETIC FIELD INTENSITIES AND FORCES ON SEGMENTS OF CONDUCTOR SYSTEM REPRESENTING CHORDWISE CROSS SECTION OF WINGTIP TRAILING EDGE (FIG. 30)

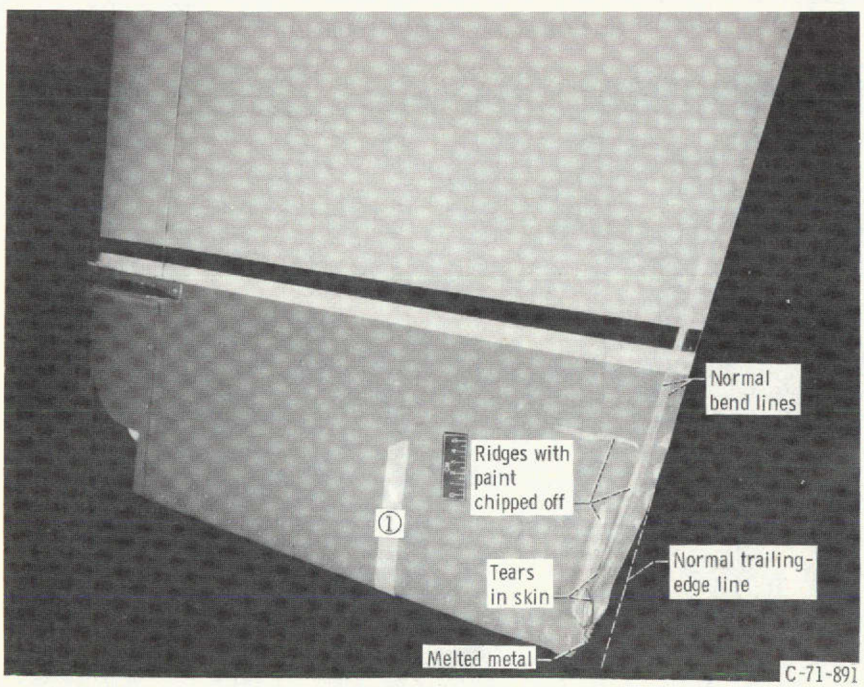
Location,[a] d, cm	Field, H/I, (A/m)/A[b]	Force, $F/I^2 l$, $N/(A^2)(m)$	Location,[c] d, cm	Field, H/I, (A/m)/A[b]	Force, $F/I^2 l$, $N/(A^2)(m)$	Location,[c] d, cm	Field, H/I, (A/m)/A[b]	Force, $F/I^2 l$, $N/(A^2)(m)$	Location,[d] d, cm	Field, H/I, (A/m)/A[b]	Force, $F/I^2 l$, $N/(A^2)(m)$	Location,[e] d, cm	Field, H/I, (A/m)/A[b]	Force, $F/I^2 l$, $N/(A^2)(m)$
Part A (segment A-O)			Part B (segment O-B)			Part C (segment O-C)			Part D (segment C-D)			Part E (segment B-E)		
0	$+\infty$	$+\infty$	0	$+\infty$	$+\infty$	0	$-\infty$	$-\infty$	0	$+\infty$	$+\infty$	0	$-\infty$	$-\infty$
.01	254.72	320.00×10^{-6}	.02	448.01	281.42×10^{-6}	.02	-504.93	-317.16×10^{-6}	.10	1.42	0.89×10^{-6}	.10	3.18	2.00×10^{-6}
.03	135.32	170.00	.04	238.80	150.00	.04	-218.90	-137.50	.20	-.96	-.60	.20	7.08	4.45
.05	66.06	82.99	.06	175.12	110.00	.06	-157.61	-99.00	.40	-5.49	-3.45	.40	9.15	5.75
.10	20.70	26.00	.08	127.36	80.00	.08	-118.49	-74.43	.60	-7.08	-4.45	.60	10.03	6.30
.20	11.94	15.00	.10	93.90	58.98	.10	-93.13	-58.50	.80	-7.76	-4.88	.80	10.20	6.41
.30	9.63	12.10	.20	45.77	28.75	.15	-57.31	-36.00	1.00	-7.83	-4.92	1.00	10.13	6.36
.40	8.04	10.10	.30	33.03	20.75	.20	-41.39	-26.00	2.00	-7.58	-4.76	2.00	8.96	5.63
.50	6.79	8.53	.40	25.07	15.75	.25	-33.43	-21.00	4.00	-6.81	-4.28	4.00	7.72	4.85
.60	5.81	7.30	.50	20.44	12.84	.30	-27.06	-17.00	6.00	-6.11	-3.84	6.00	6.80	4.27
.70	4.86	6.10	.60	16.72	10.50	.35	-22.29	-14.00	8.00	-5.53	-3.48	8.00	6.08	3.82
.80	4.38	5.50	.70	14.01	8.80	.40	-19.90	-12.50	10.00	-5.05	-3.17	10.00	5.51	3.46
.90	3.82	4.80	.80	10.98	6.90	.45	-14.33	-9.00	12.00	-4.64	-2.92	12.00	5.03	3.16
1.00	3.73	4.69	.90	4.66	2.92	.50	-10.35	-6.50	14.00	-4.30	-2.70	14.00	4.63	2.91
1.10	3.58	4.50	.92	0	0	.55	-3.98	-2.50	16.00	-4.07	-2.56	16.00	4.30	2.76
1.20	3.47	4.37	.94	-6.29	-.39	.60	+13.53	+8.50	18.00	-3.72	-2.34	18.00	4.00	2.52
1.25	3.38	4.24	.96	-15.92	-10.00	.62	+35.80	+22.99	20.00	-3.57	-2.25	20.00	3.75	2.36
			.98	-35.49	-22.29	.64	$+\infty$	$+\infty$	22.00	-3.30	-2.07	22.00	3.53	2.22
			1.00	$-\infty$	$-\infty$				24.00	-3.10	-1.95	24.00	3.33	2.09

[a]Distance from point A.
[b]Oersteds (cgs electromagnetic system) = 79.6 A/m (SI system).
[c]Distance from point O.
[d]Distance from point C.
[e]Distance from point B.

Figure 1. - Beechcraft King Air Model B90 aircraft.

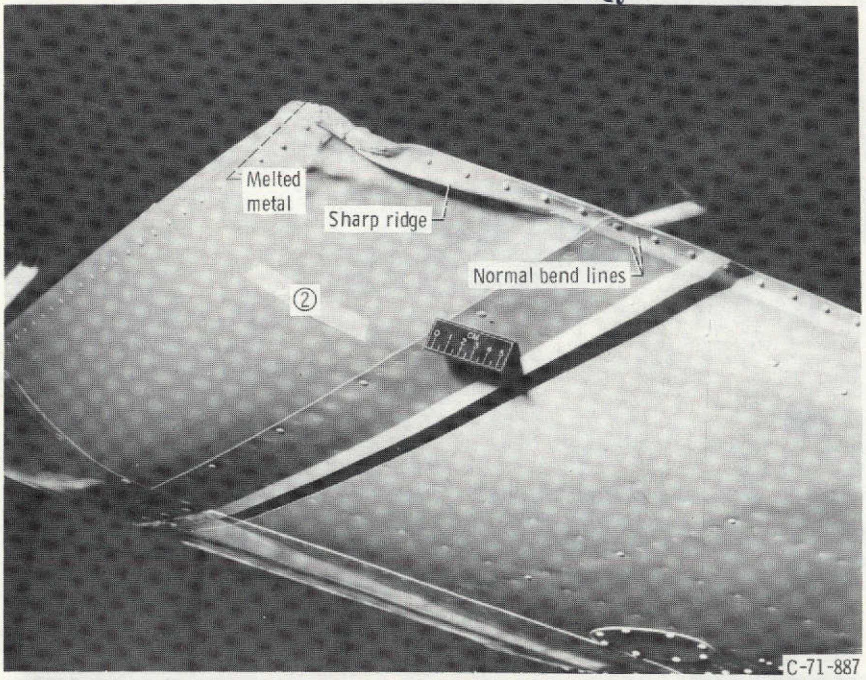


(a) General view.

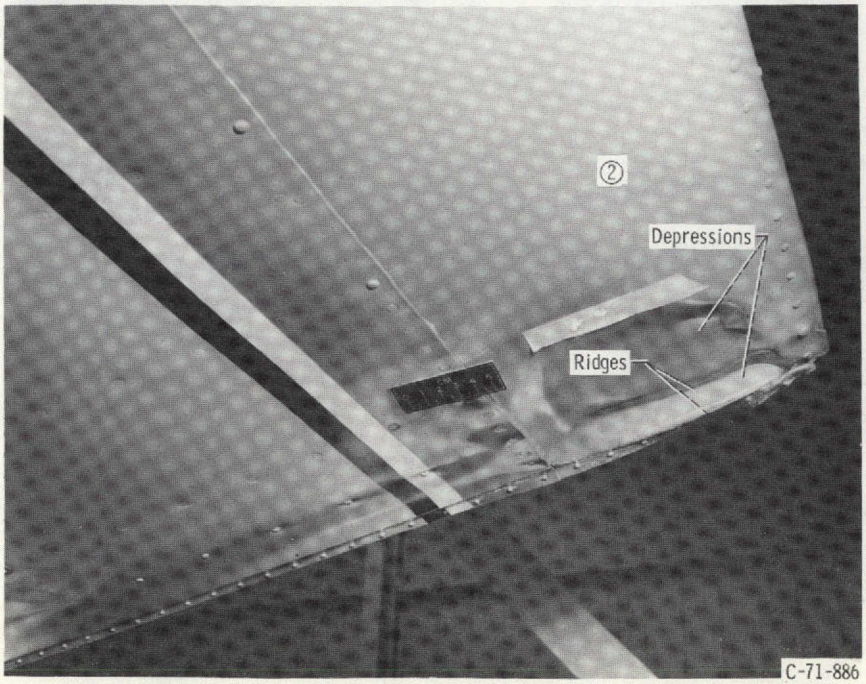


(b) Top surface of wingtip.

Figure 2. - Damage at lightning attachment point on trailing edge of left wingtip.

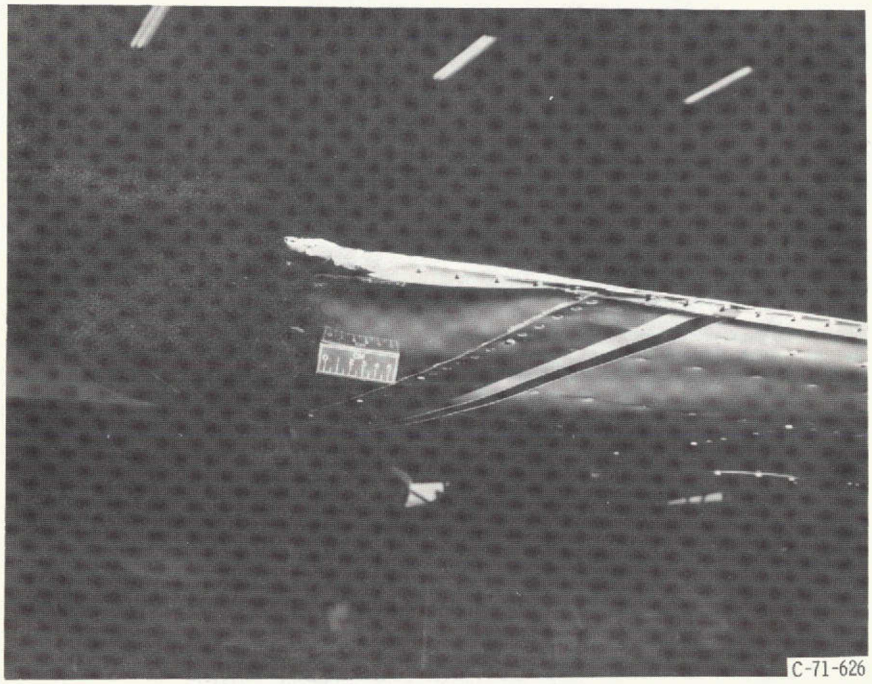


(c) Lower surface of wingtip looking forward.

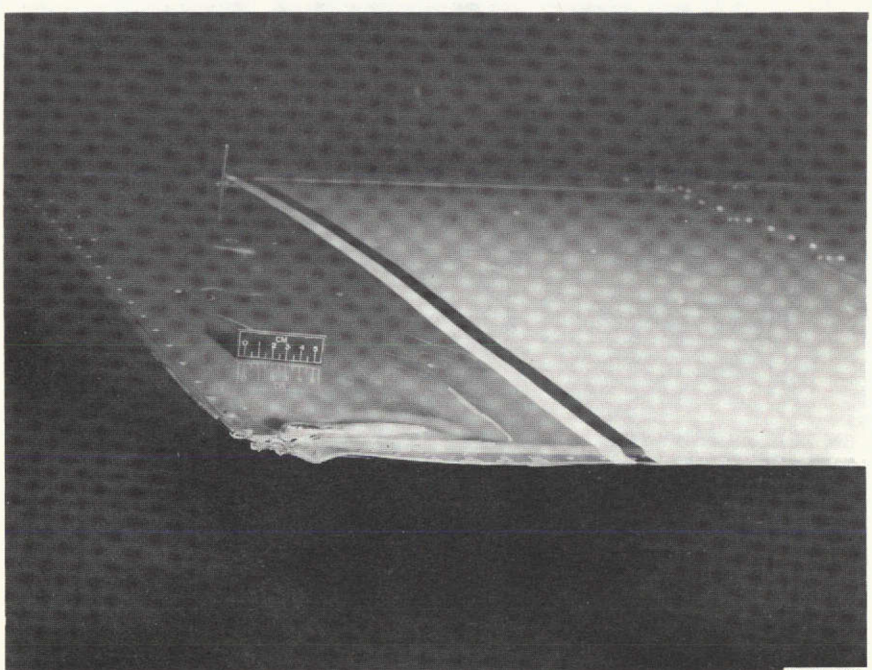


(d) Lower surface of wingtip looking aft.

Figure 2. - Continued.

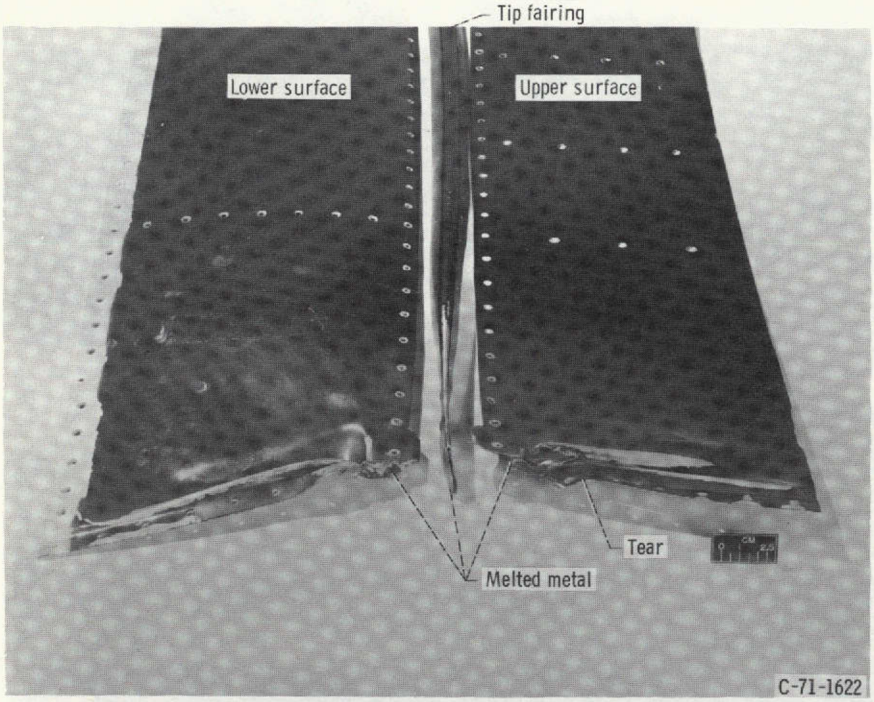

C-71-626

(e) Trailing edge from below.

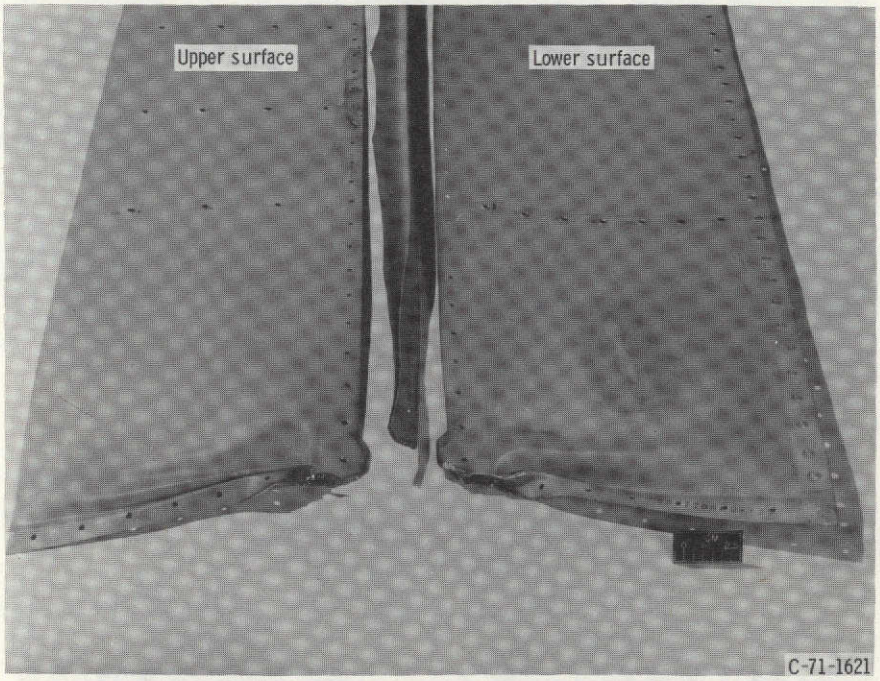

C-71-625

(f) Trailing edge from above.

Figure 2. - Continued.



(g) Wingtip disassembled - view of outside surfaces.



(h) Wingtip disassembled - view of inside surfaces.

Figure 2. - Concluded.

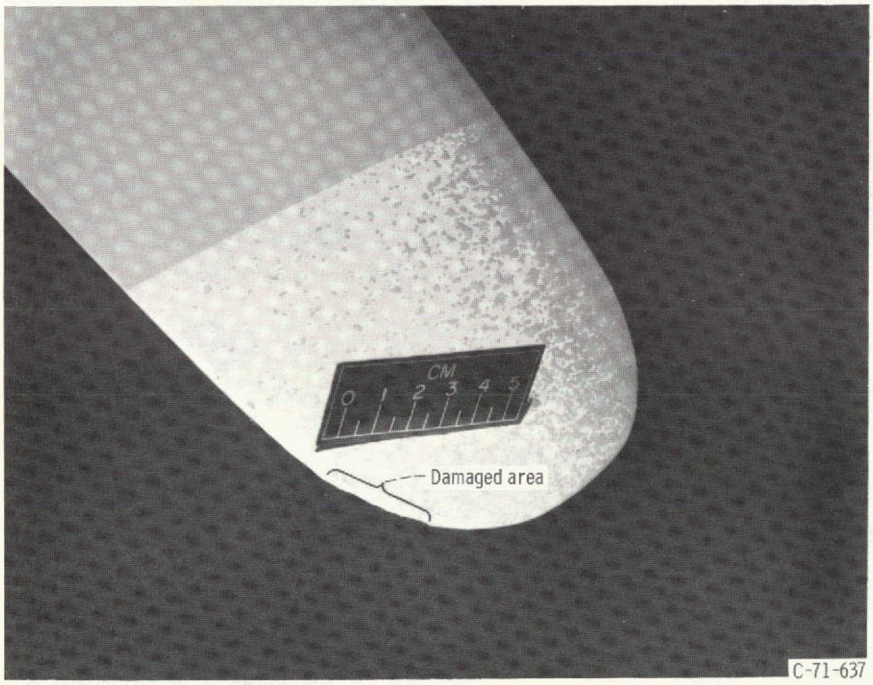
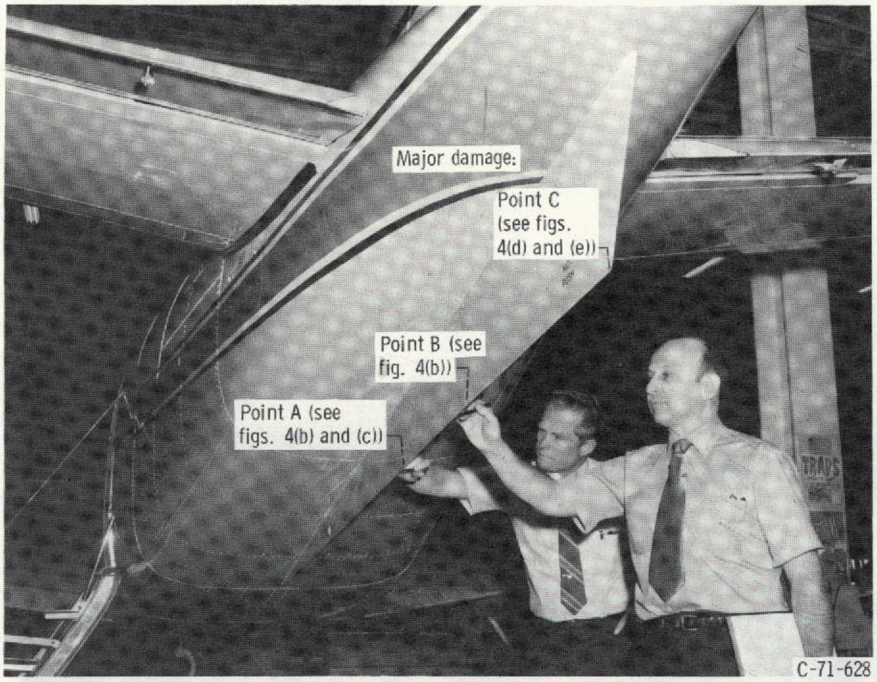
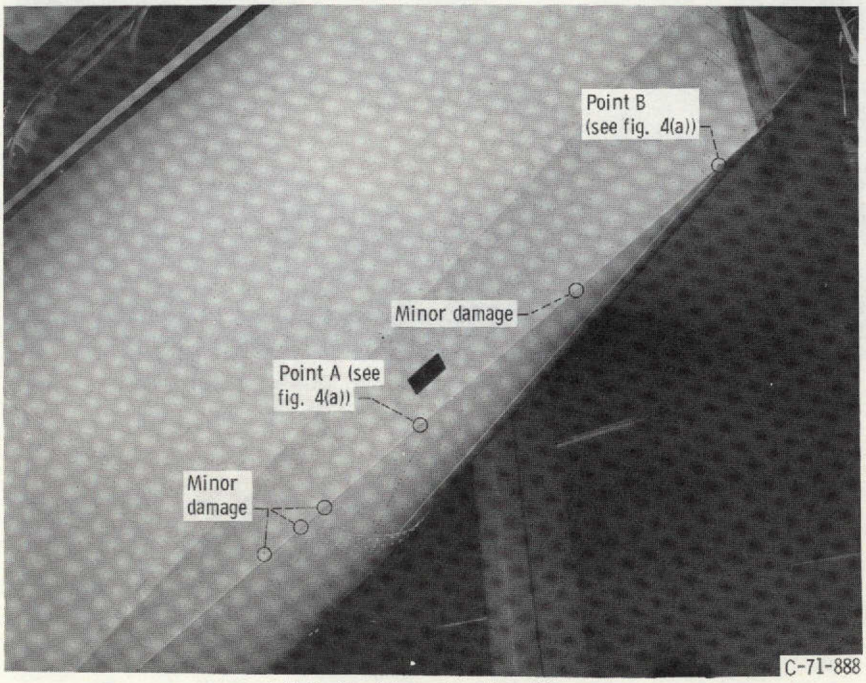


Figure 3. - Tip of blade on right propeller, showing lightning erosion damage.

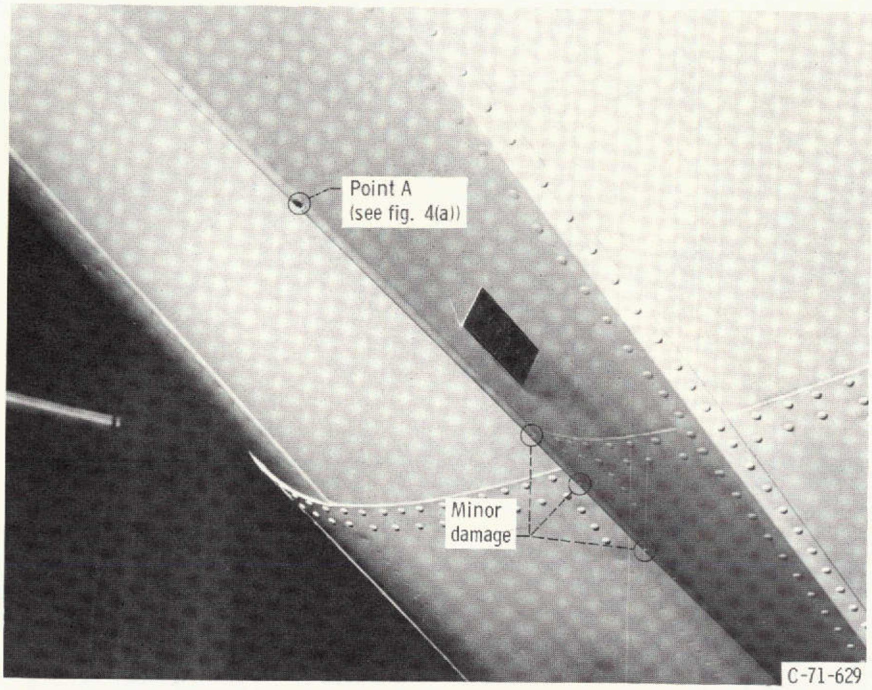


(a) General view indicating location of major damage.

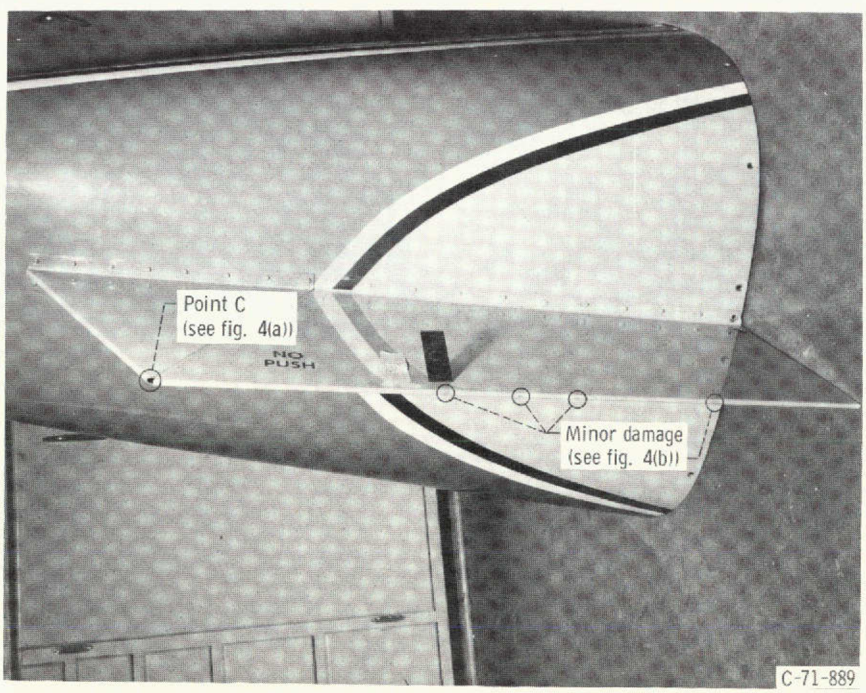


(b) Left side of forward section of fin.

Figure 4. - Lightning attachment points on ventral fin.

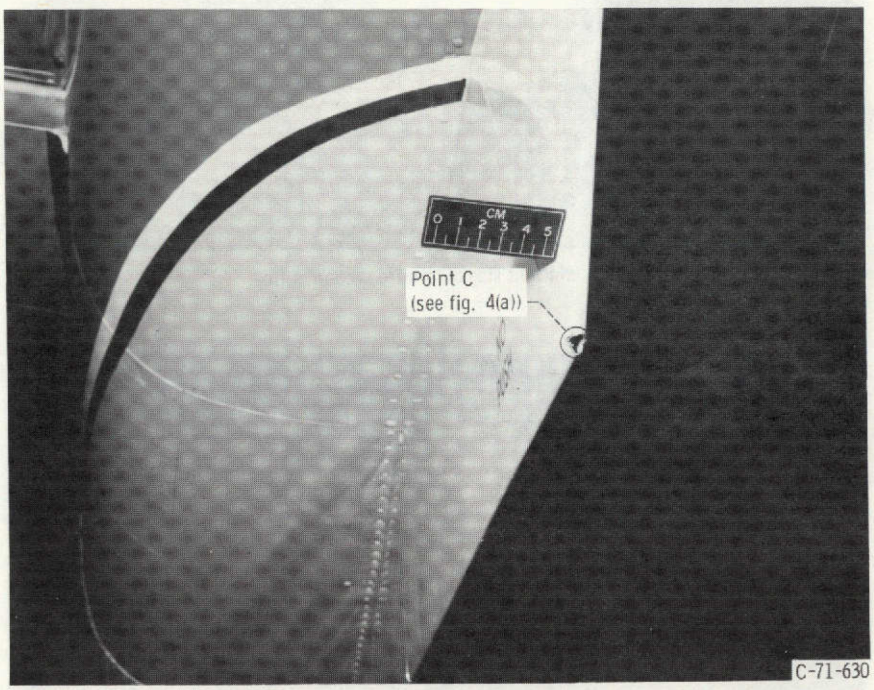


(c) Right side of forward section of fin.

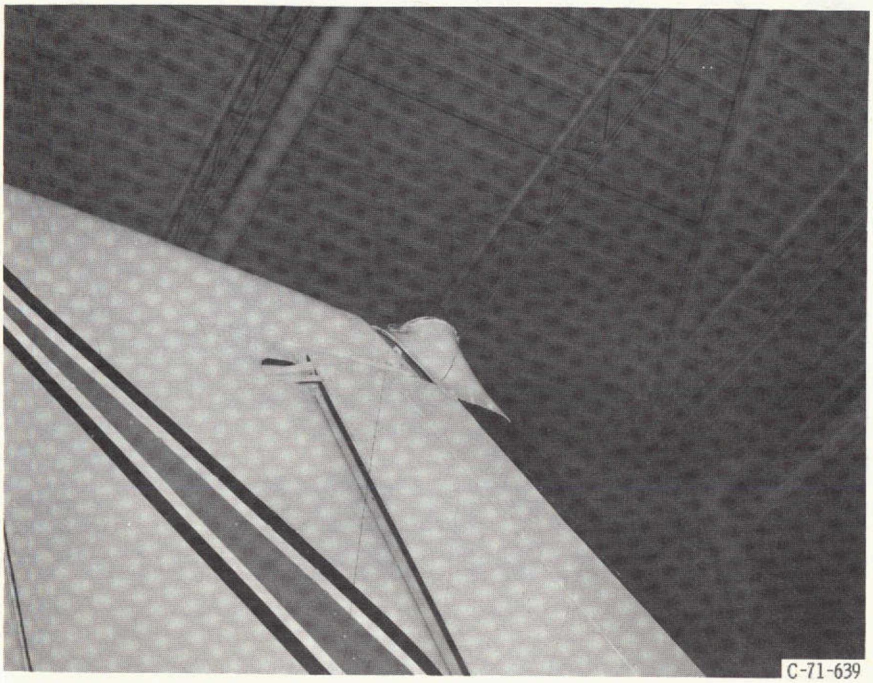


(d) Aft section of fin.

Figure 4. - Continued.

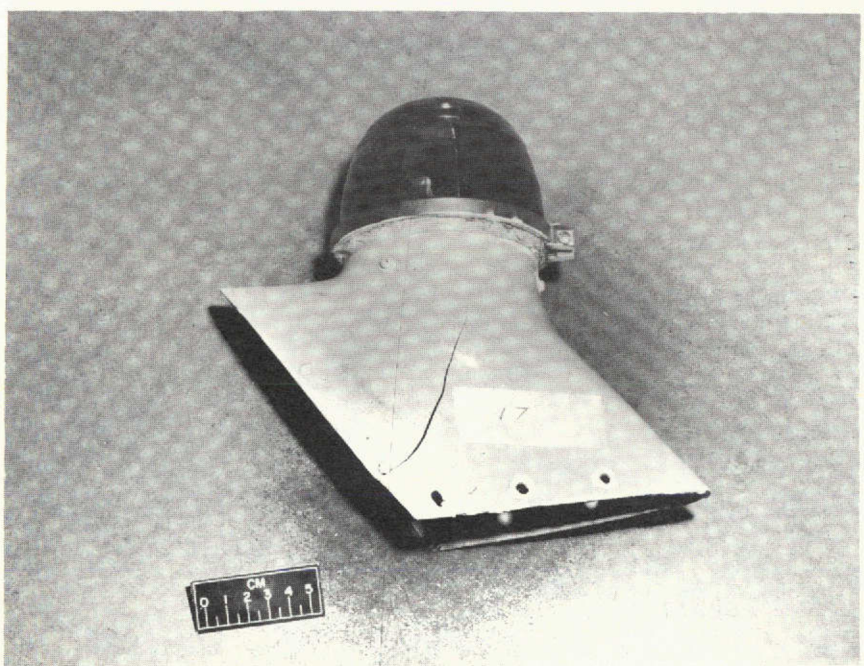


(e) Aft end of fin.
Figure 4. - Concluded.



C-71-639

(a) General view of light in place.



C-71-890

(b) Closeup of light removed from aircraft.

Figure 5. - Crack in plastic mount for navigation light located on top front of vertical stabilizer.

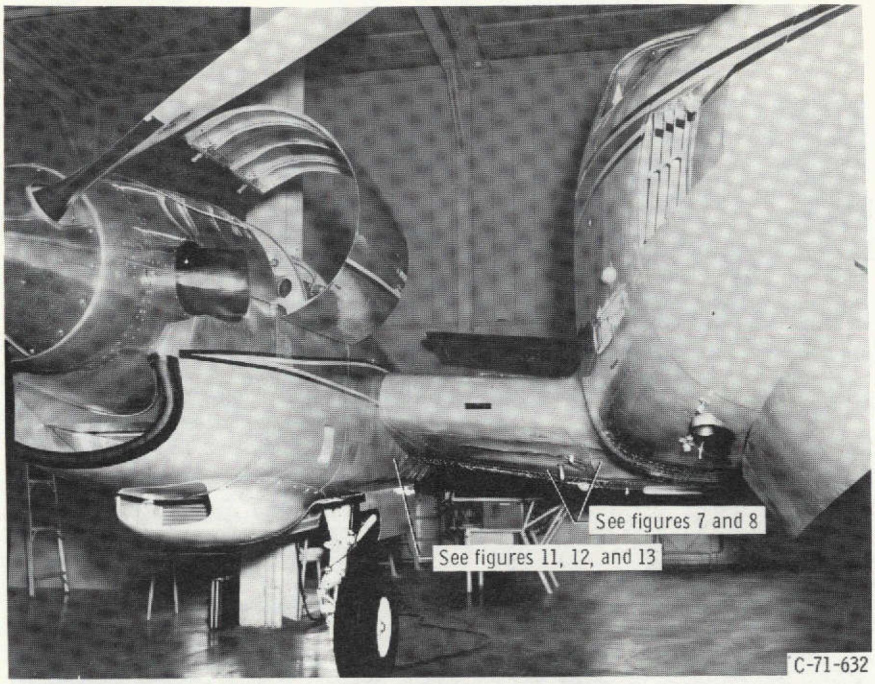


Figure 6. - General view of damage to lower surface of wing and inboard side of engine nacelle.

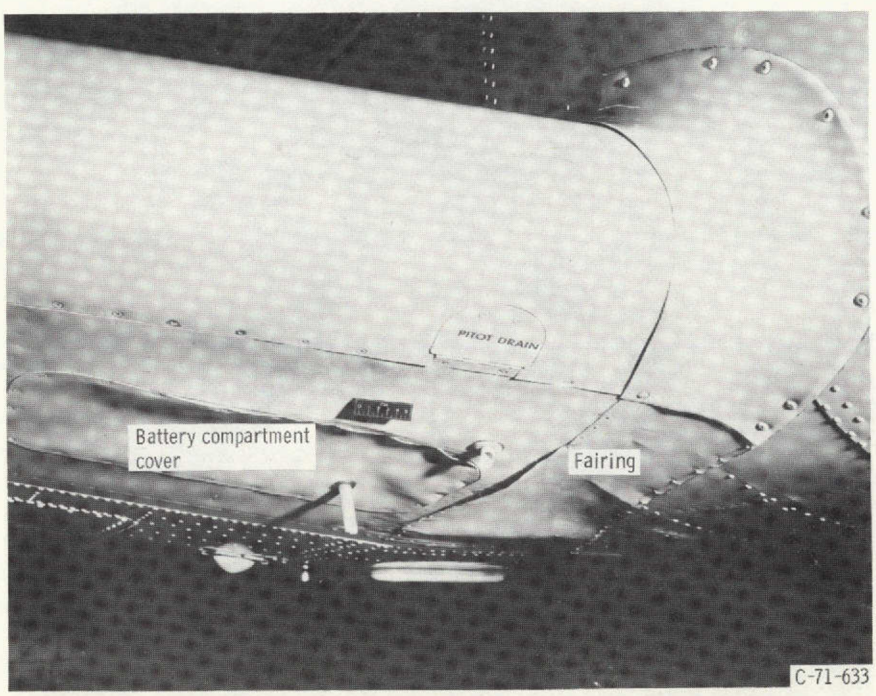


Figure 7. - Damage to battery compartment cover and wing-to-fuselage fairing.

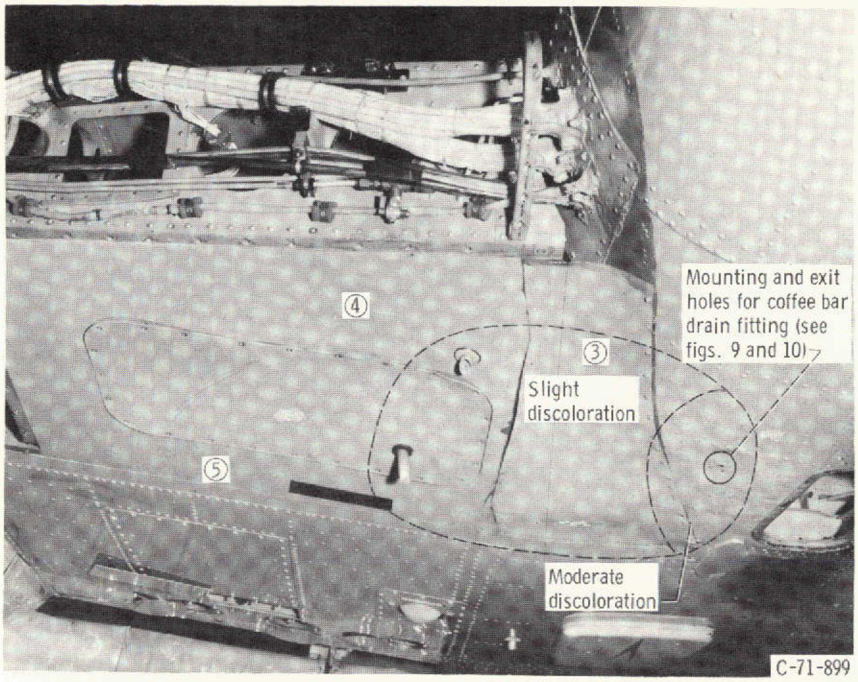


Figure 8. - Area of paint discoloration on wing and fuselage.

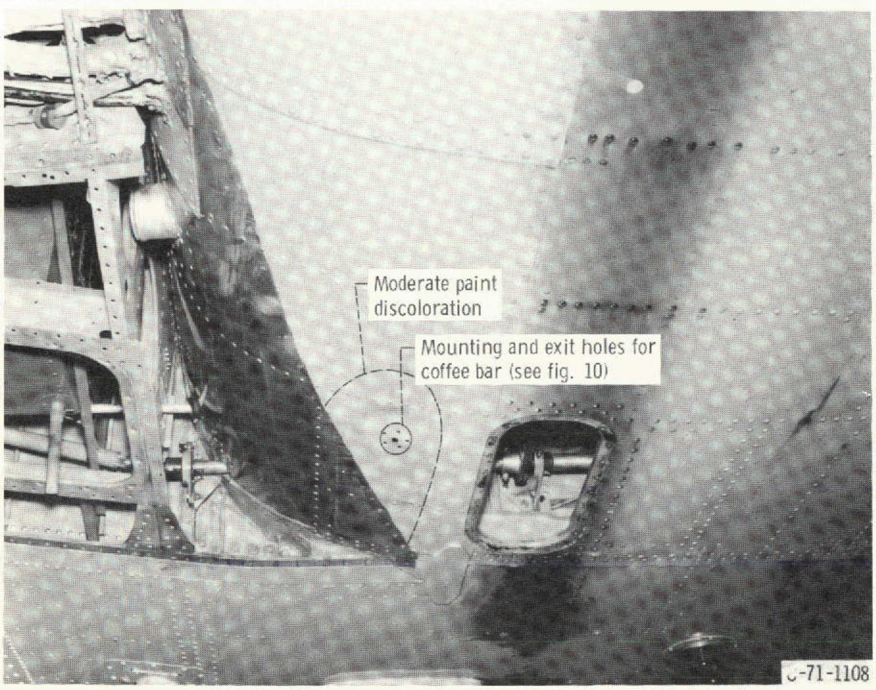
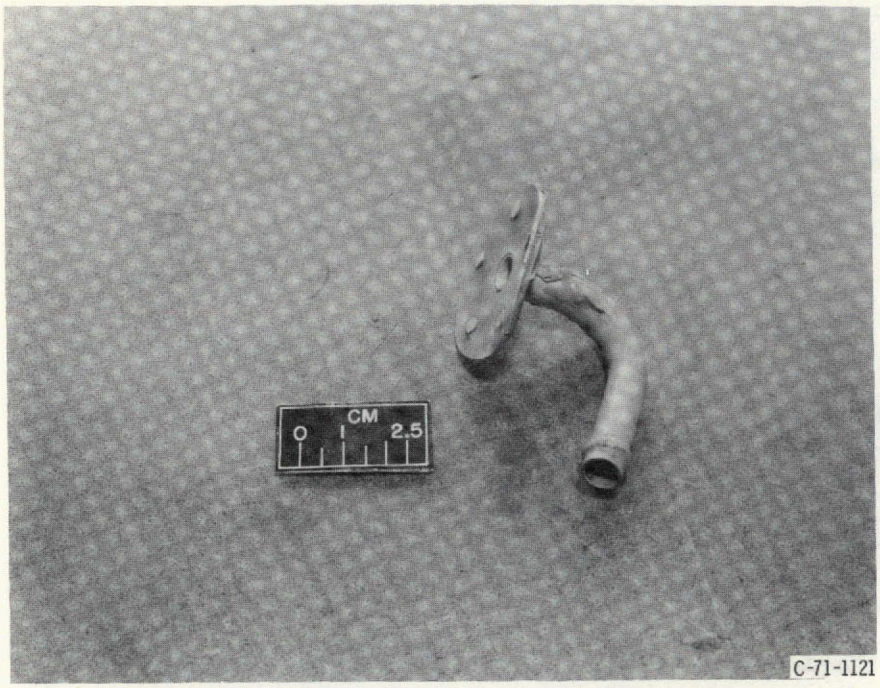
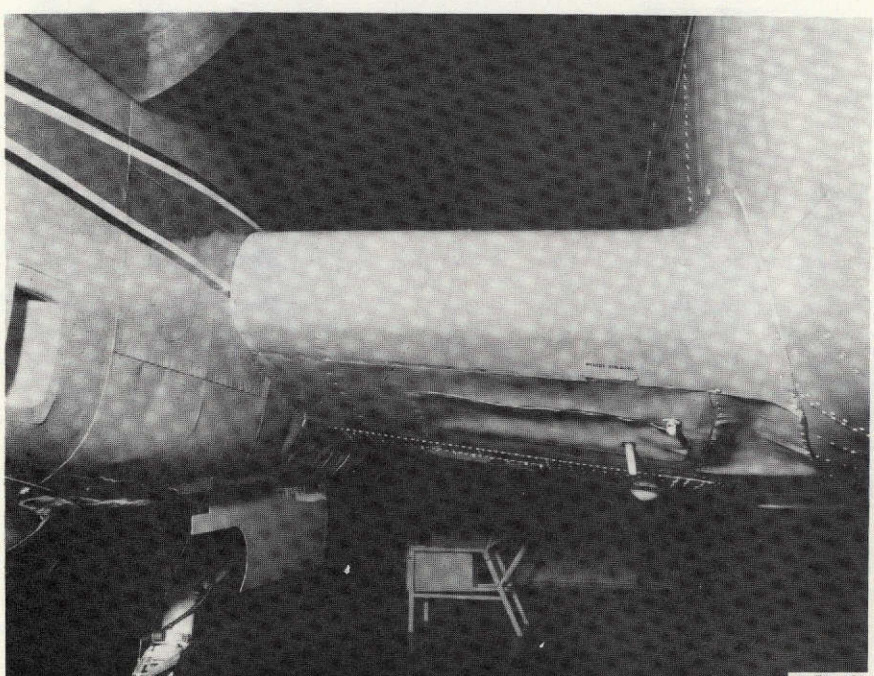


Figure 9. - Area of moderate paint discoloration around mounting and exit holes for coffee bar drain fitting on bottom of fuselage.



C-71-1121

Figure 10. - Coffee bar drain fitting. (See fig. 9 for location on bottom of fuselage.)



C-71-631

Figure 11. - Damage to lower inboard side of right engine nacelle and wing.

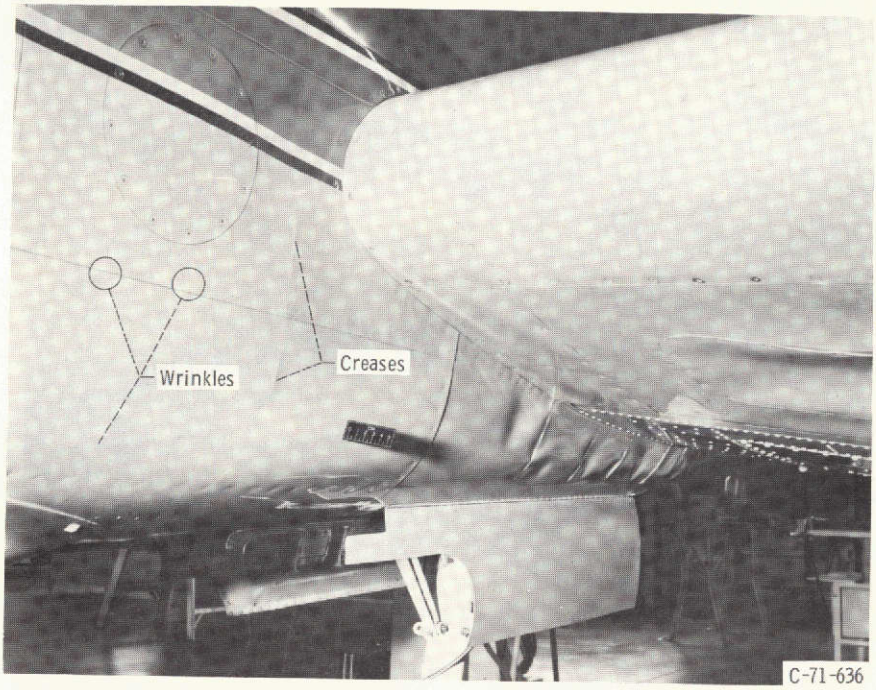


Figure 12. - Damage to lower inboard side of right engine nacelle.

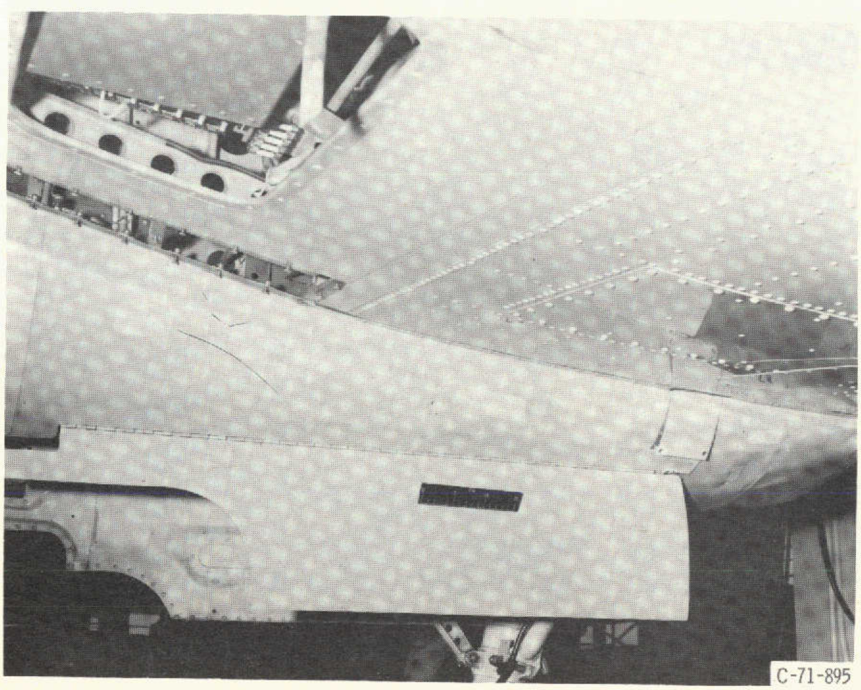


Figure 13. - Inboard view of damage at aft bottom of right engine nacelle. (See also figs. 15 and 16.)

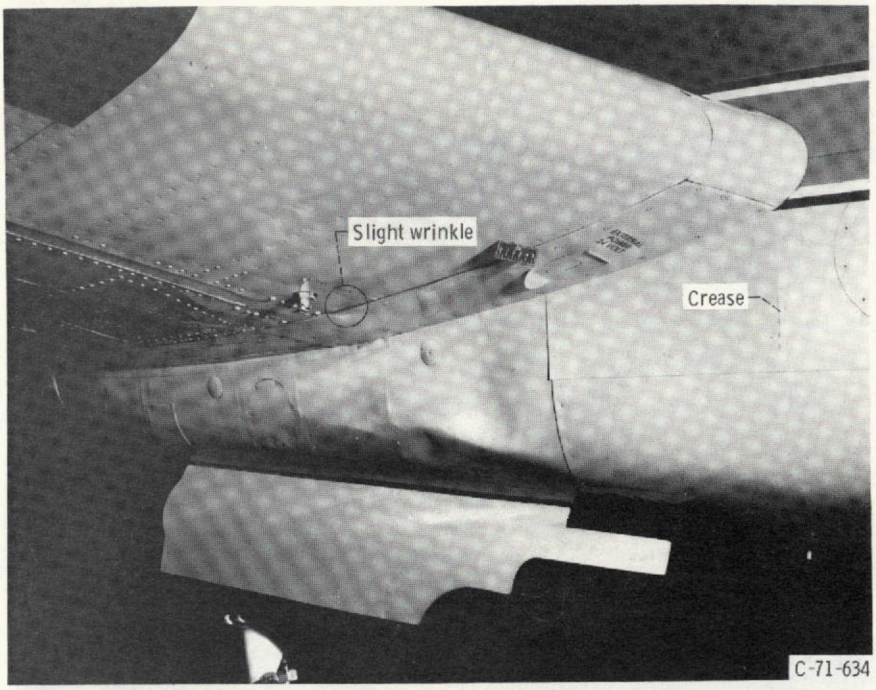


Figure 14. - Damage to outboard bottom side of right engine nacelle and lower wing surface.

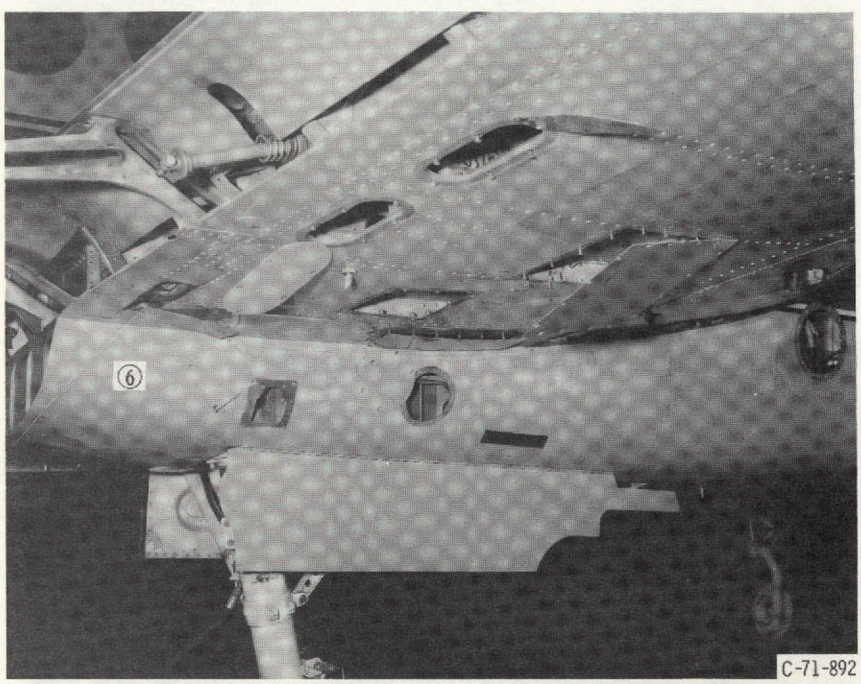


Figure 15. - Outboard view of damage at aft bottom of right engine nacelle. (See also figs. 13 and 16.)

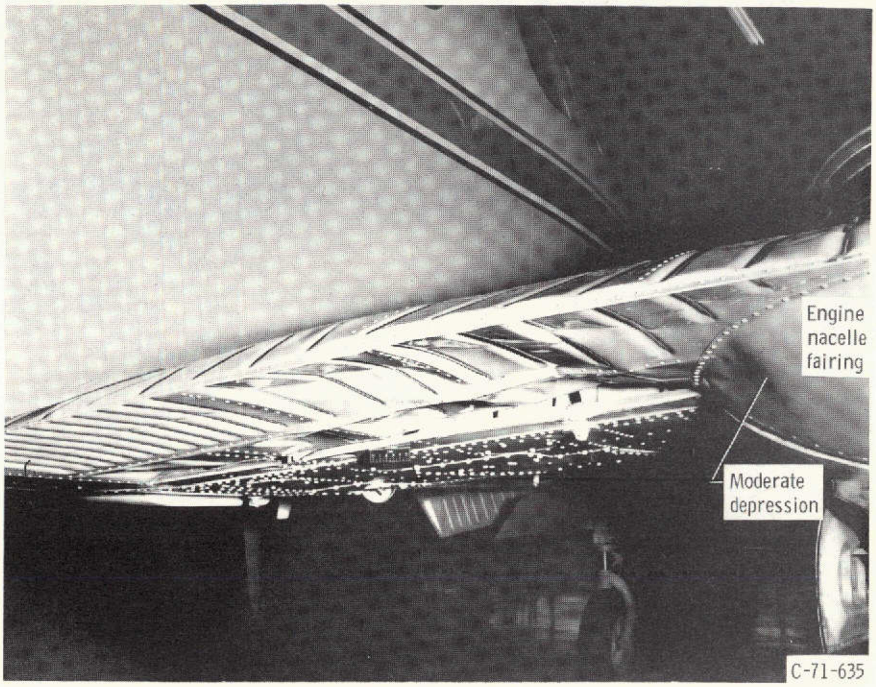


Figure 16. - Forward view of damage to lower surface of right inboard flap and engine nacelle fairing.

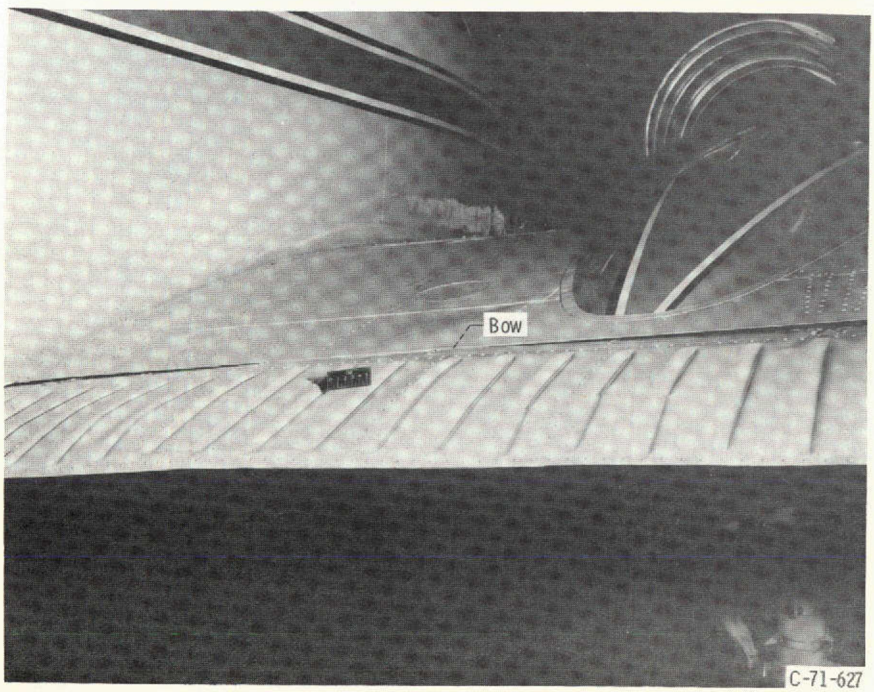


Figure 17. - Damage to top surface of right inboard flap.

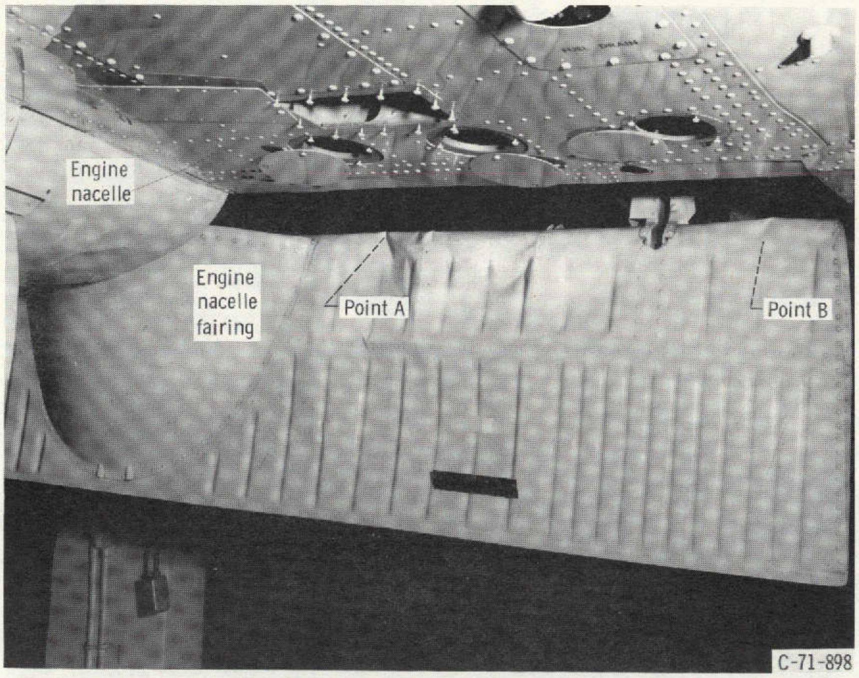


Figure 18. - Rearward view of damage to lower surface of right inboard flap and aft end of engine nacelle. Flap control rod disconnected with flap hanging from flap track. (See fig. 19.)

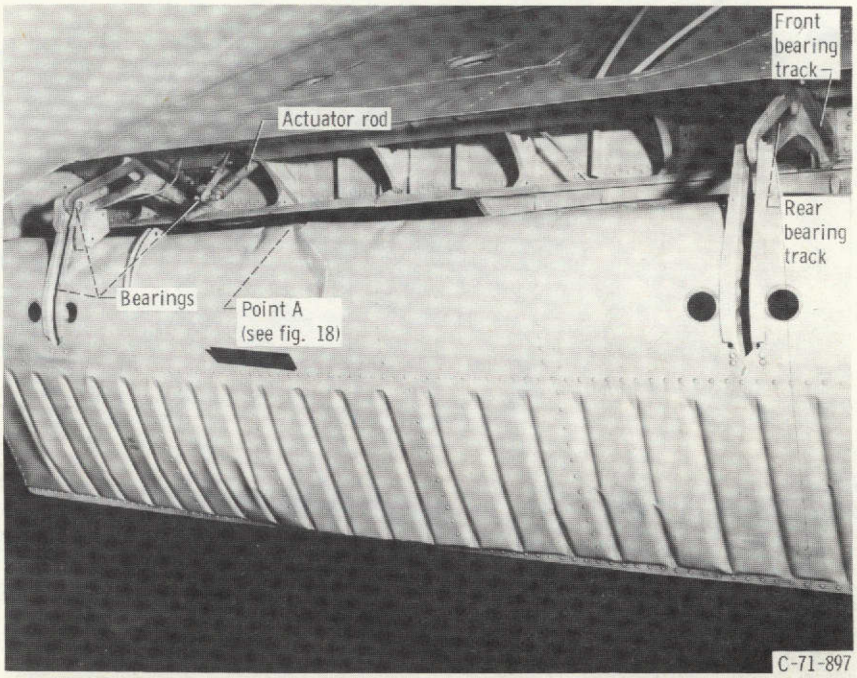


Figure 19. - Damage to top surface and leading edge of right inboard flap. Flap control rod disconnected with flap bearing normally in forward track supporting flap in rear track.

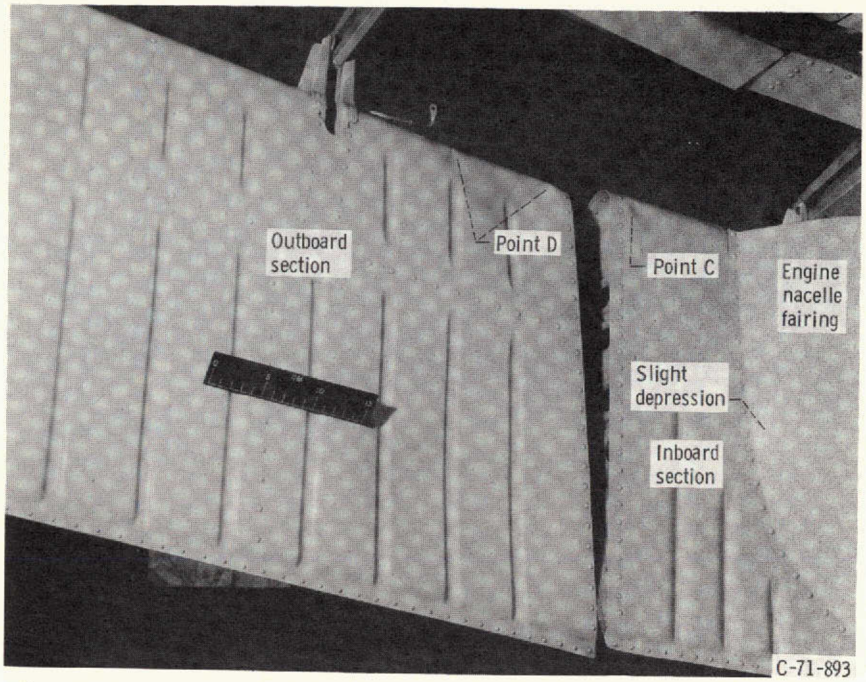


Figure 20. - Damage to lower surfaces of right inboard and outboard flaps. Flap control rod disconnected with flaps hanging from flap tracks.

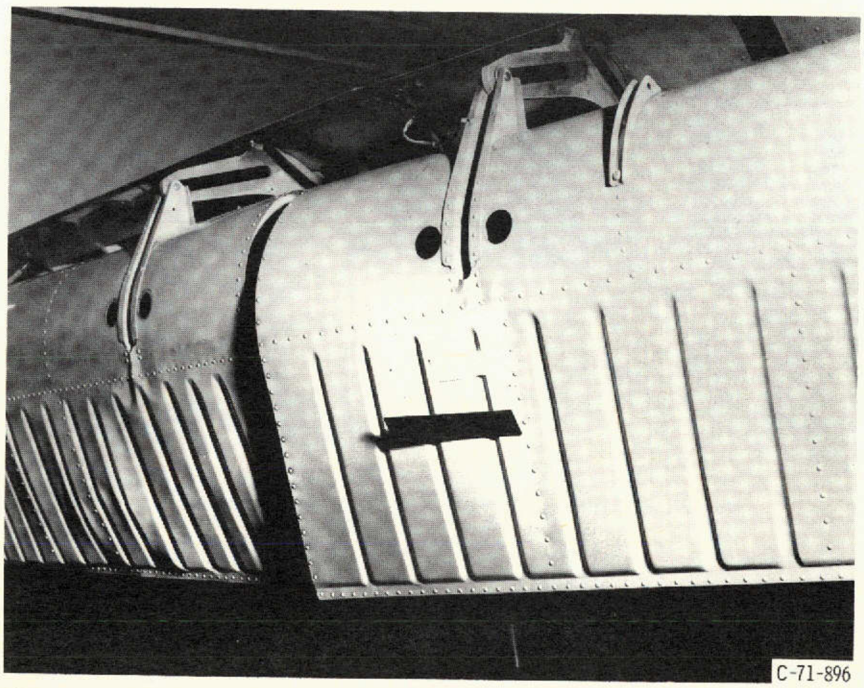


Figure 21. - Damage to upper surfaces of right inboard and outboard wing flaps. Flap control rods disconnected with flaps hanging from flap tracks.

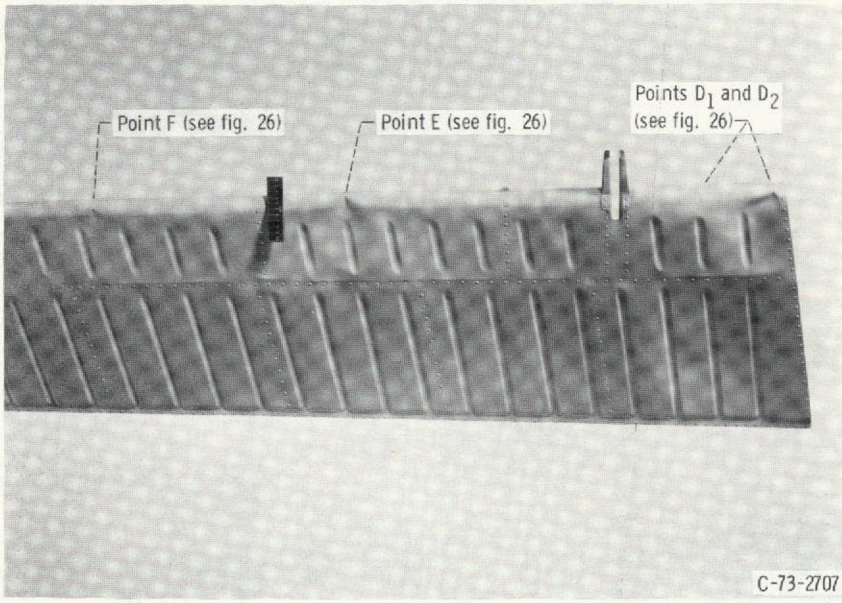


Figure 22. - Damage to lower-surface leading edge of right outboard flap.

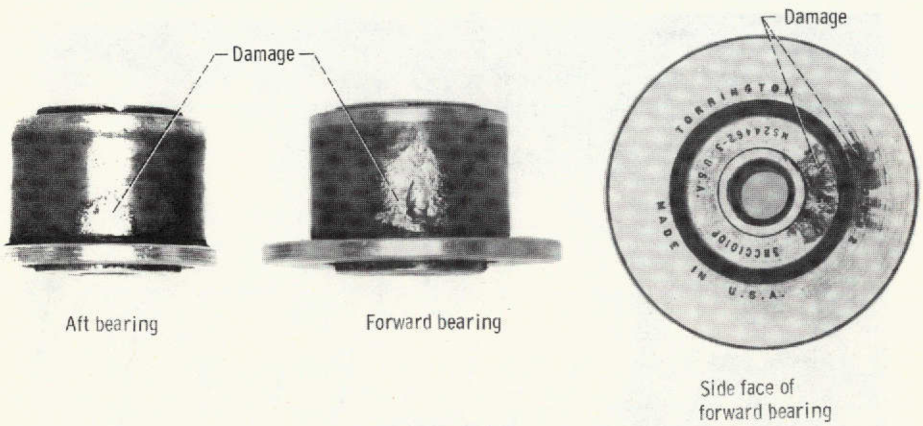


Figure 23. - Damage to outboard pair of bearings on left outboard flap.

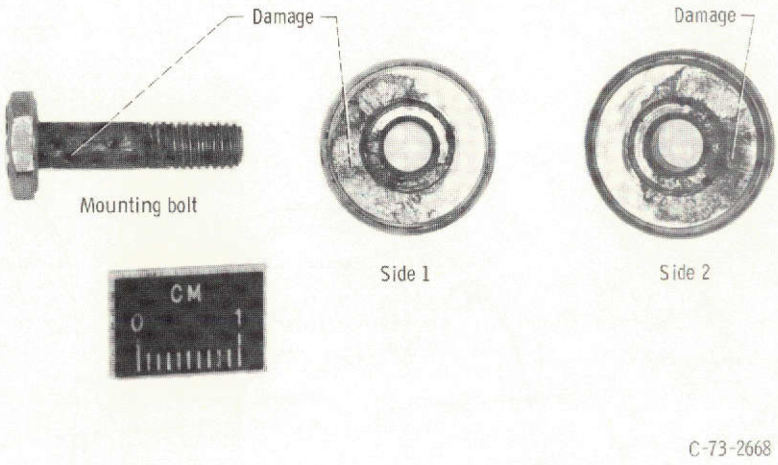


Figure 24. - Damage to flap control rod bearing on left outboard flap.

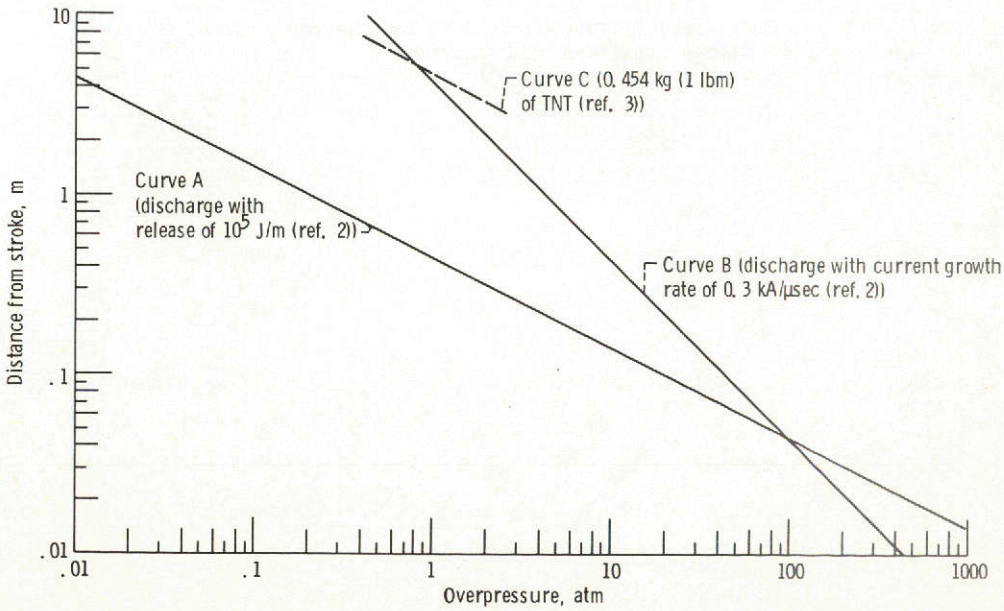


Figure 25. - Predicted shock wave overpressure generated by typical lightning discharge.

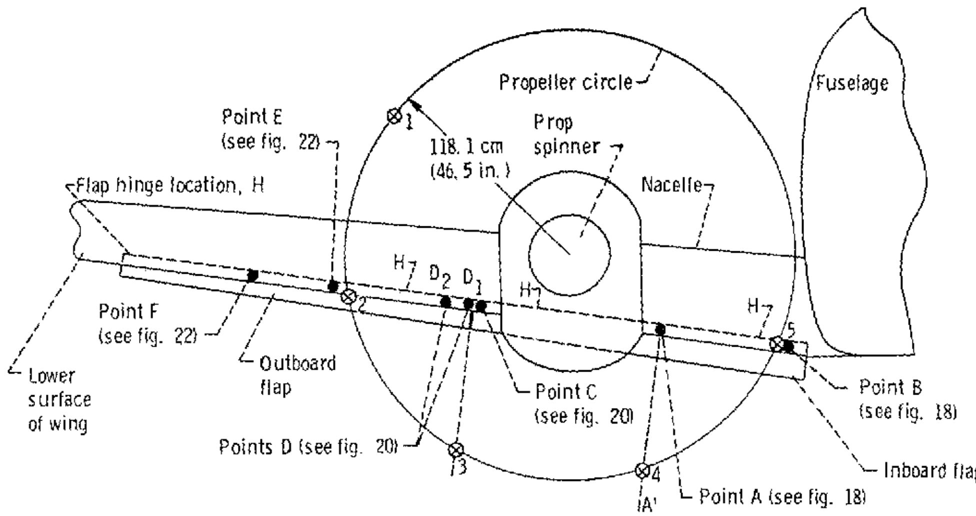
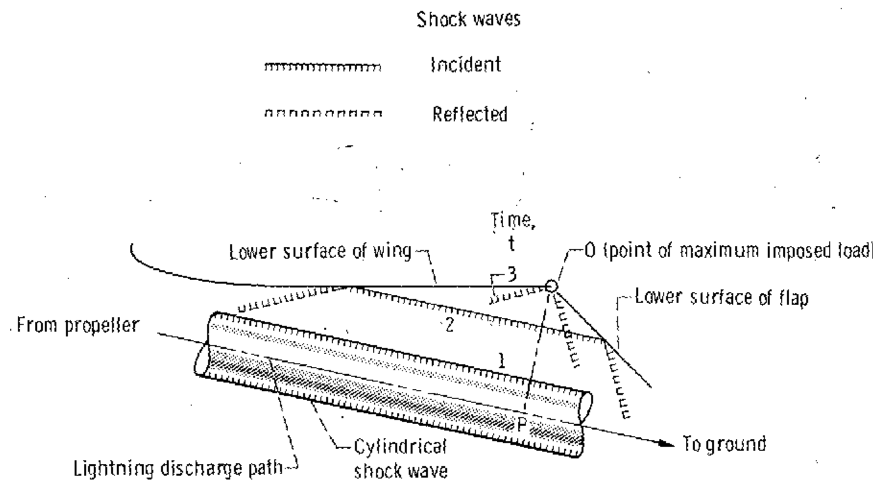
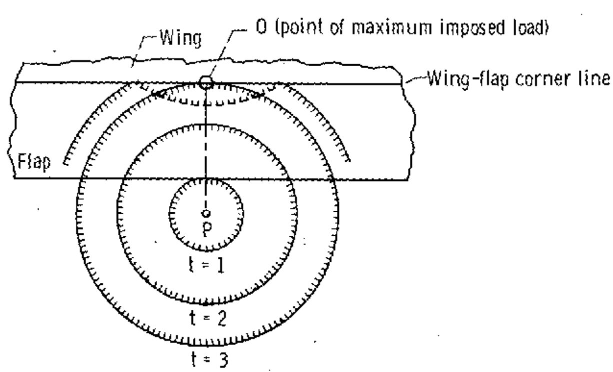


Figure 26. - Locations of sharp indentations (points A to F) on leading edge of flaps and estimated positions (1 to 5) of propeller tip at times strokes occurred.



(a) Chordwise direction.



(b) Spanwise direction - perpendicular to lightning path at point P of part (a).

Figure 27. - Orientation of lightning path and shock wave with respect to lower side of aircraft wing-flap combination.

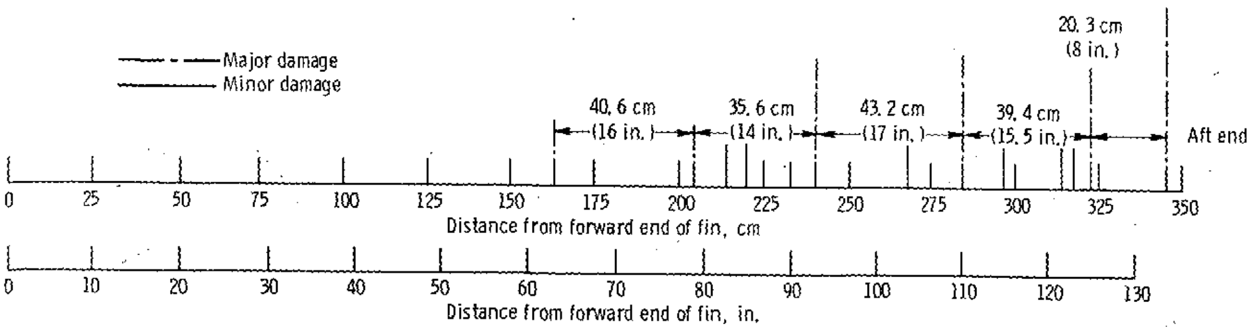


Figure 28. - Location of damage points along ventral fin due to swept stroke. (Length of line marking damage points indicates magnitude of damage.)

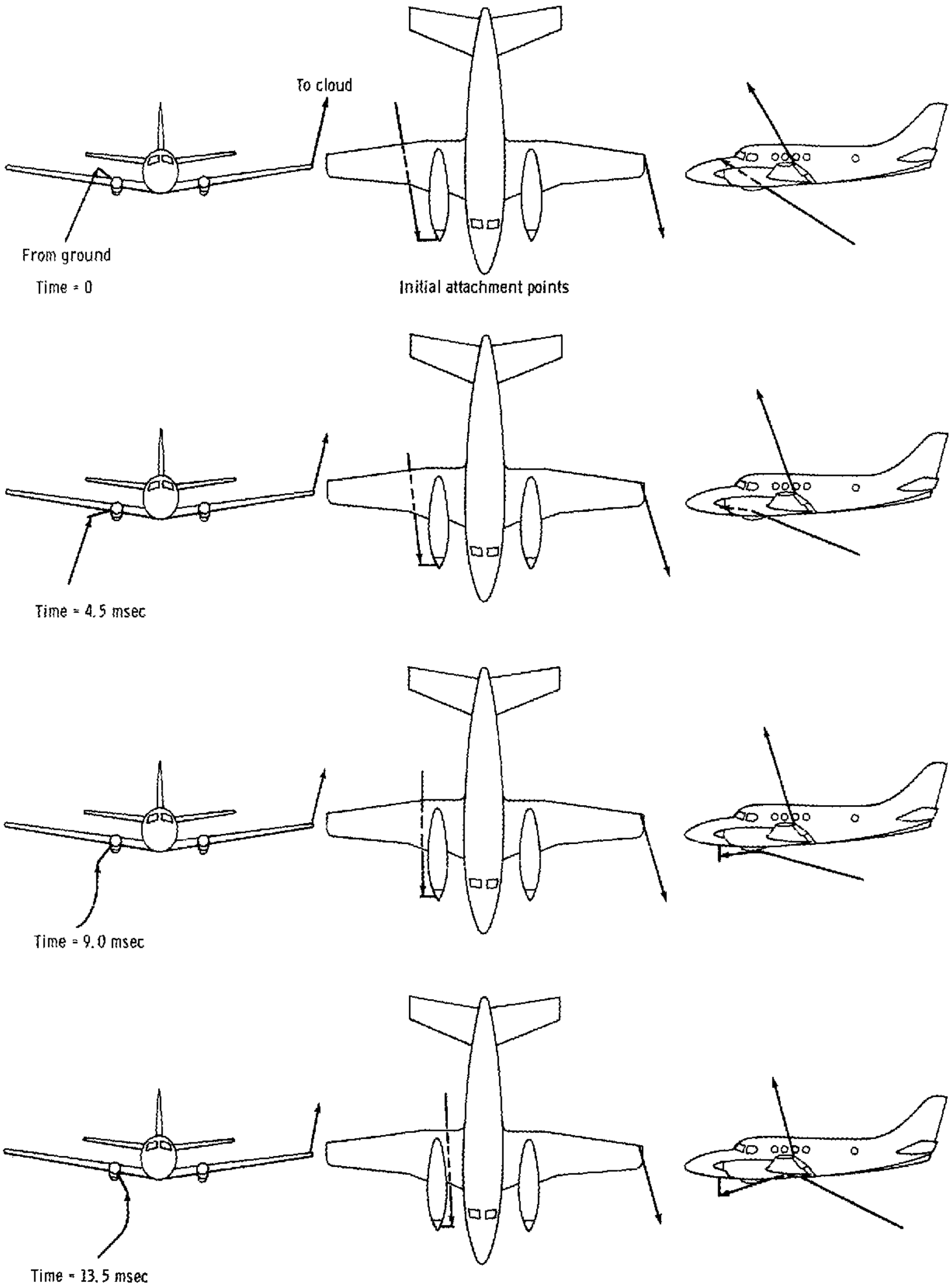
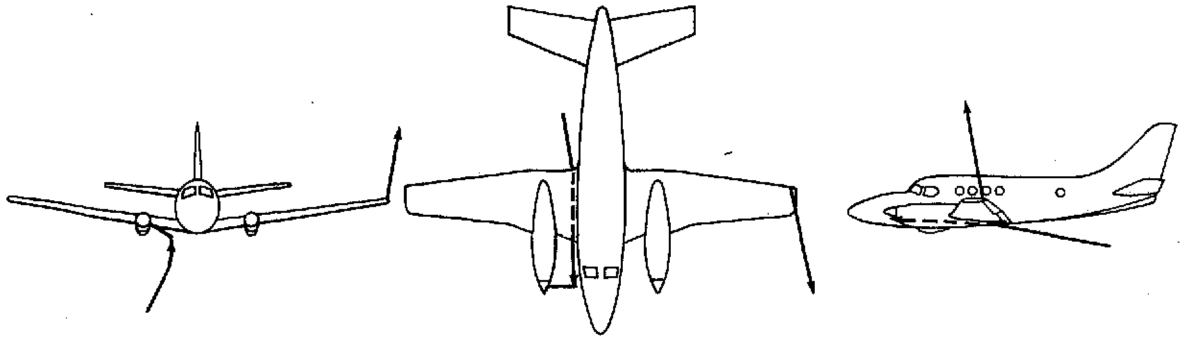
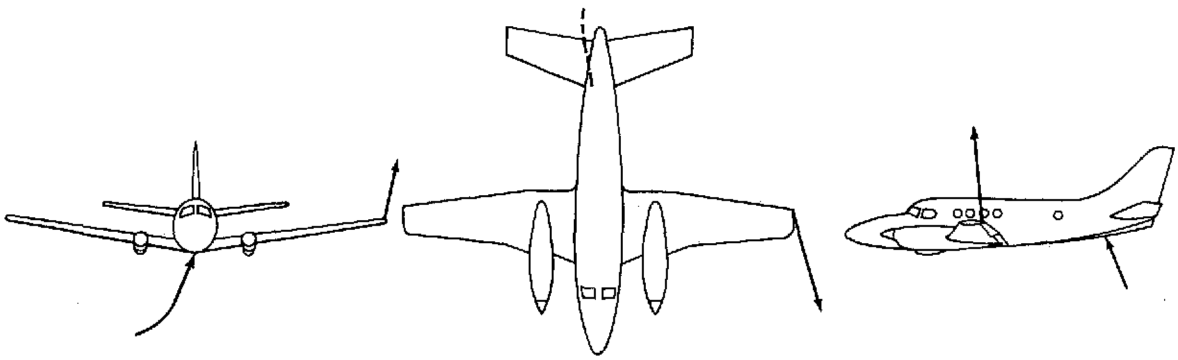


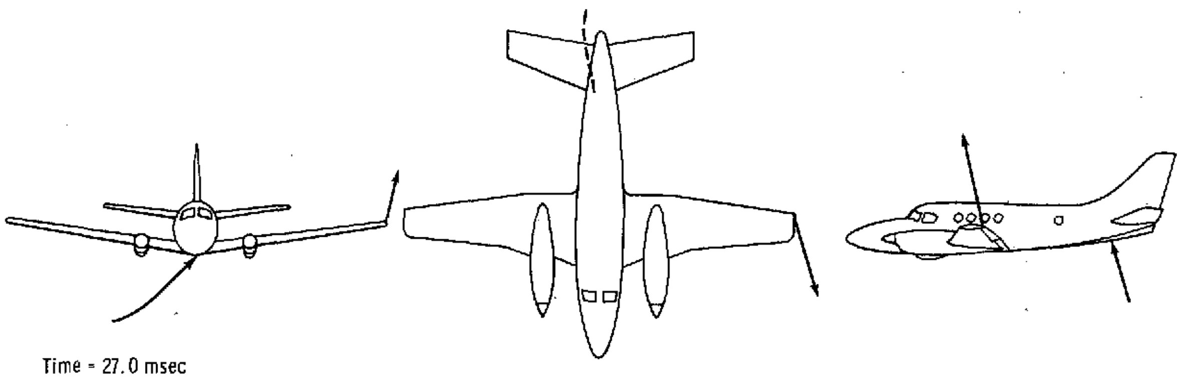
Figure 29. - Probable lightning path with respect to aircraft. (Indicated times are for high-current-stroke portions of discharge.)



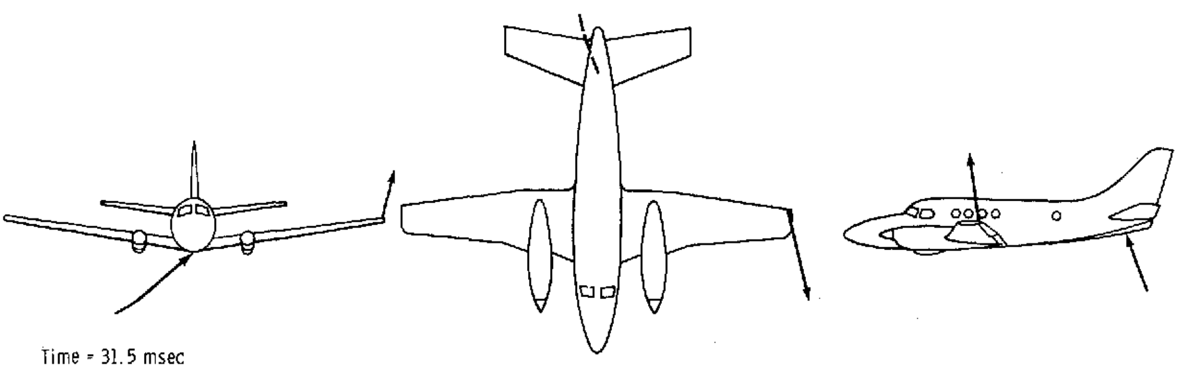
Time = 18.0 msec



Time = 22.5 msec

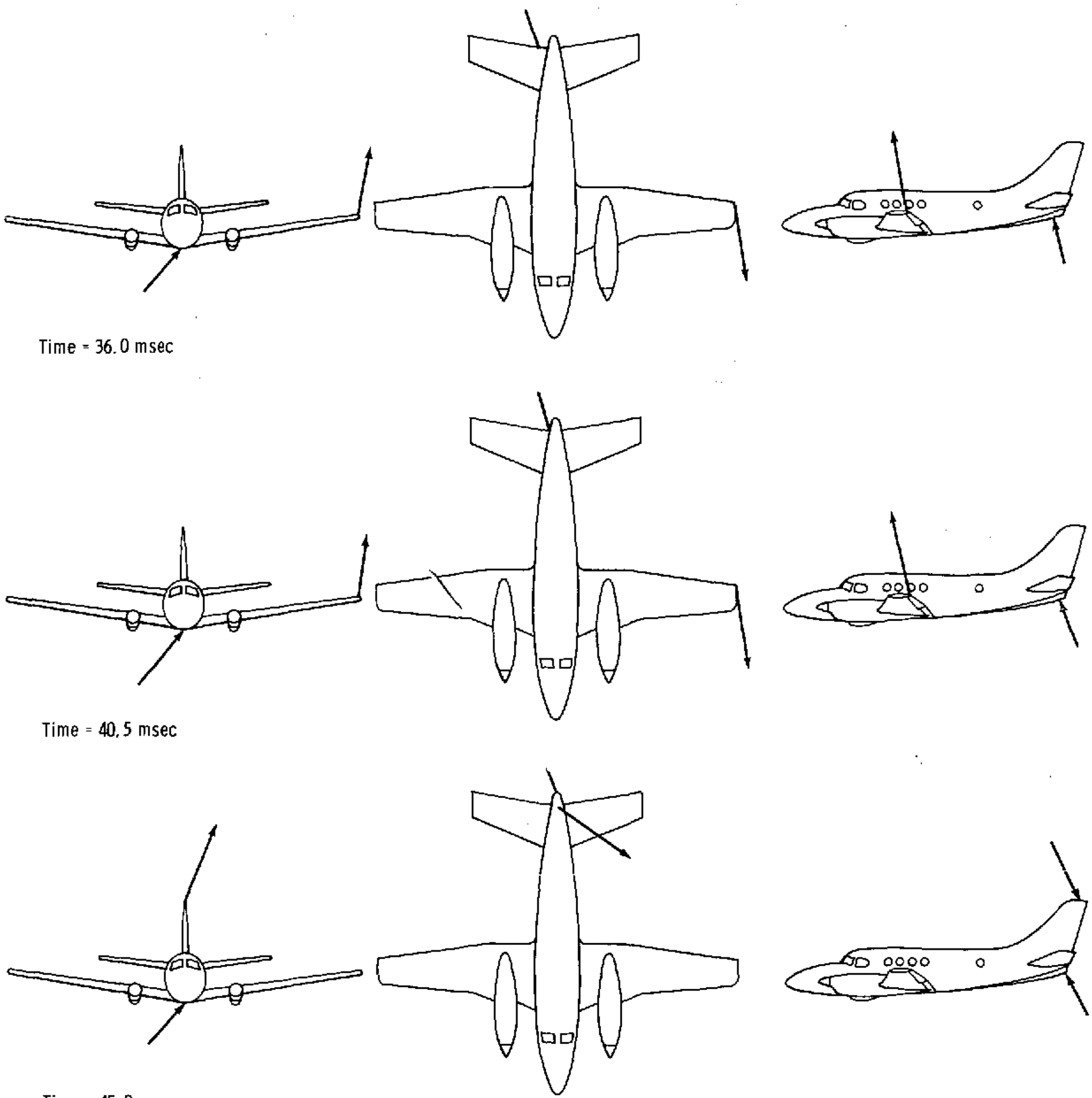


Time = 27.0 msec



Time = 31.5 msec

Figure 29. - Continued.



Final attachment points

Figure 29. - Concluded.

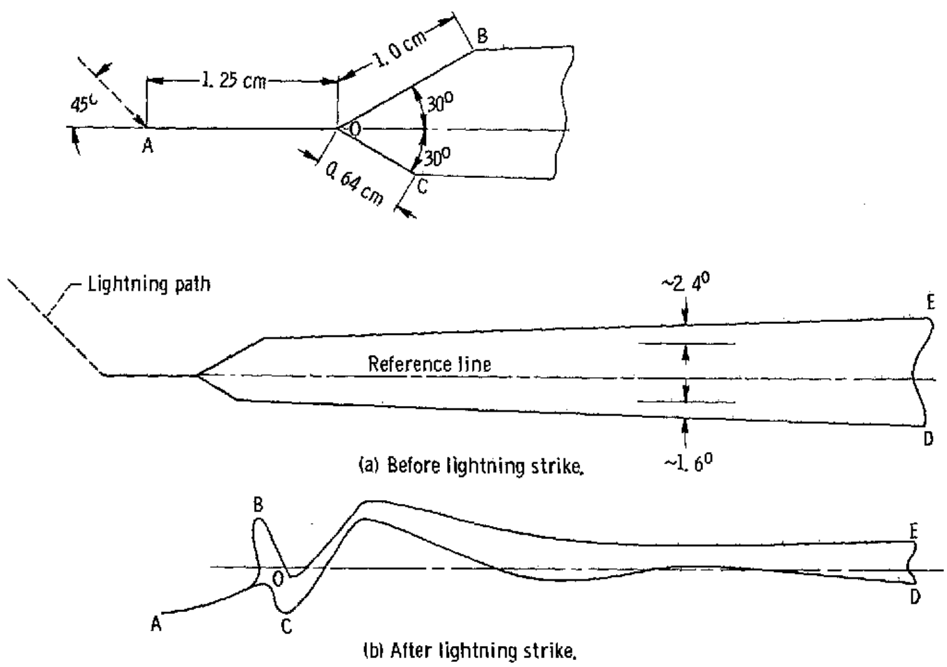


Figure 30. - Approximate geometry of chordwise cross section of wingtip trailing edge.

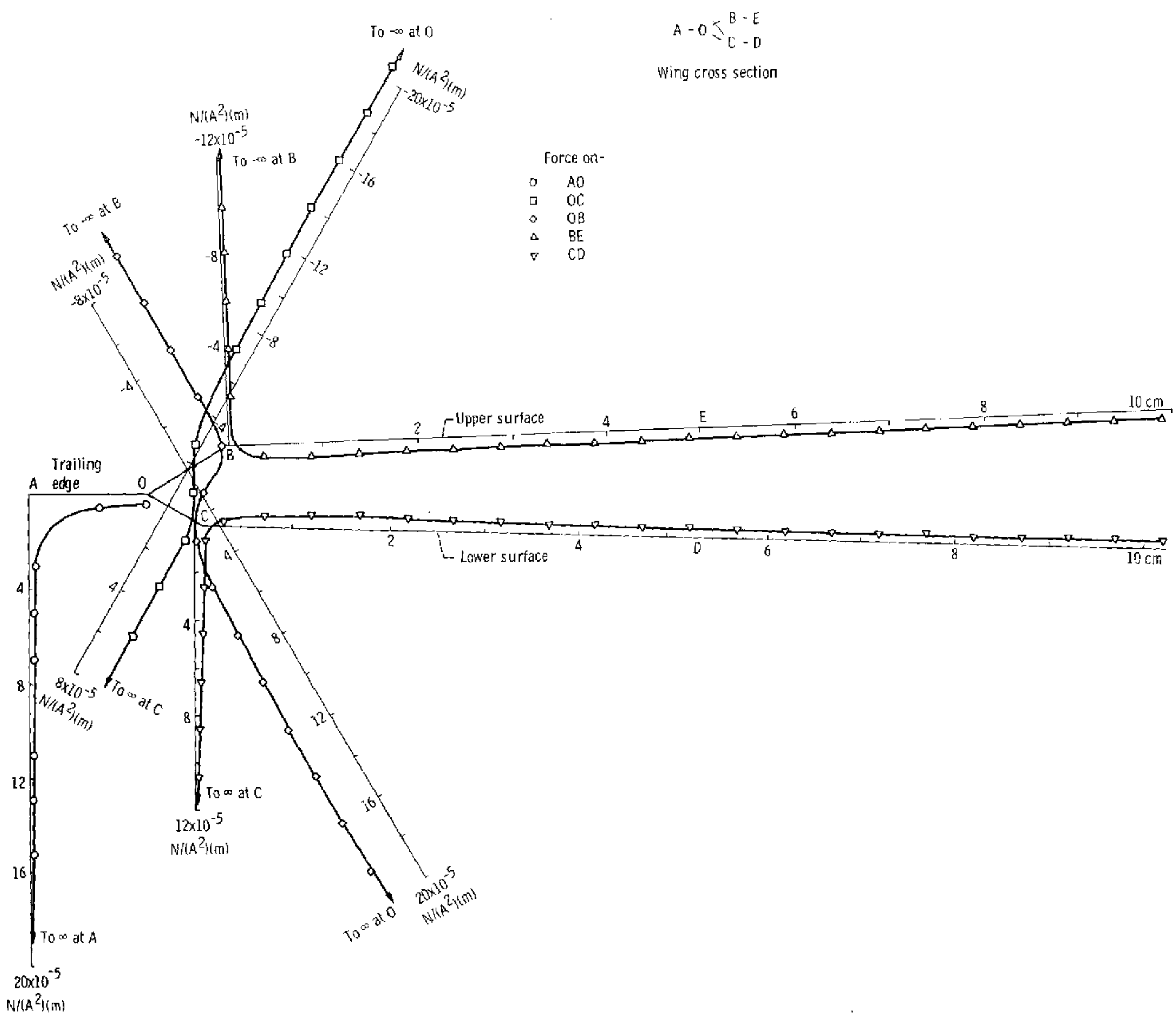
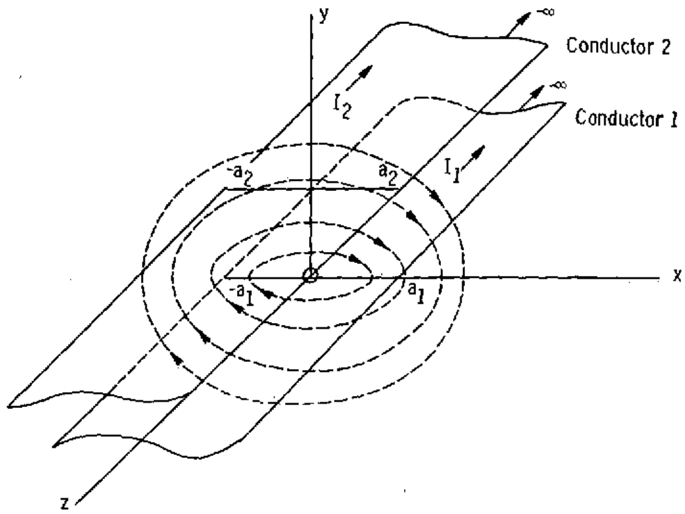
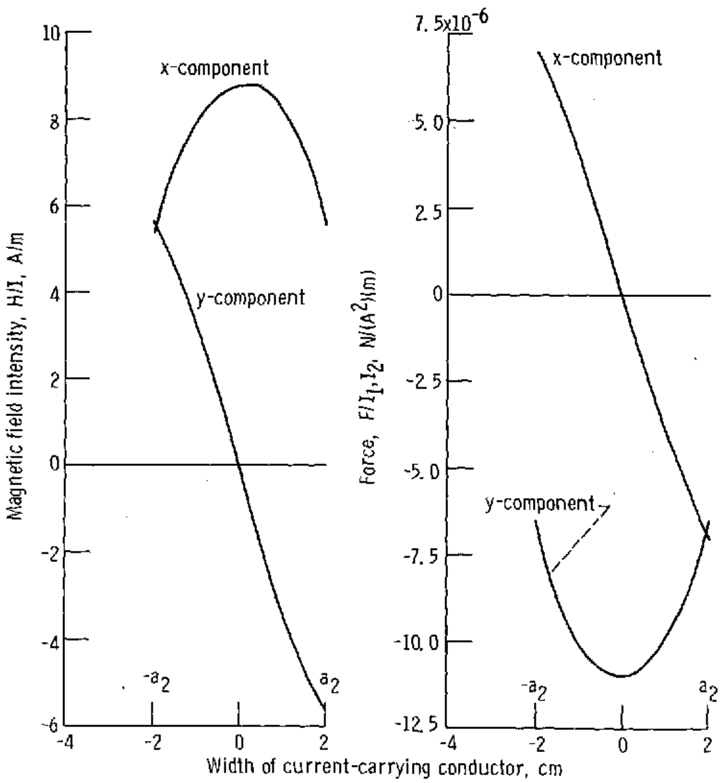


Figure 31. - Direction and magnitude of forces on trailing-edge surfaces of aircraft wing due to interaction of magnetic fields and electrical currents. (Force is in newtons per ampere squared of lightning current per meter of surface length of circuit.)



(a) Schematic of conductors and magnetic flux lines.



(b) Magnetic field intensity on conductor 2 per ampere of current in conductor 1.

(c) Force on conductor 1 per ampere of current in conductor 2 for magnetic field intensity shown in part (b).

Figure 32. - Magnetic fields and forces created by two infinitely long, 4-centimeter-wide, current-carrying conductors separated by 1 centimeter (assuming uniform current density in each conductor).

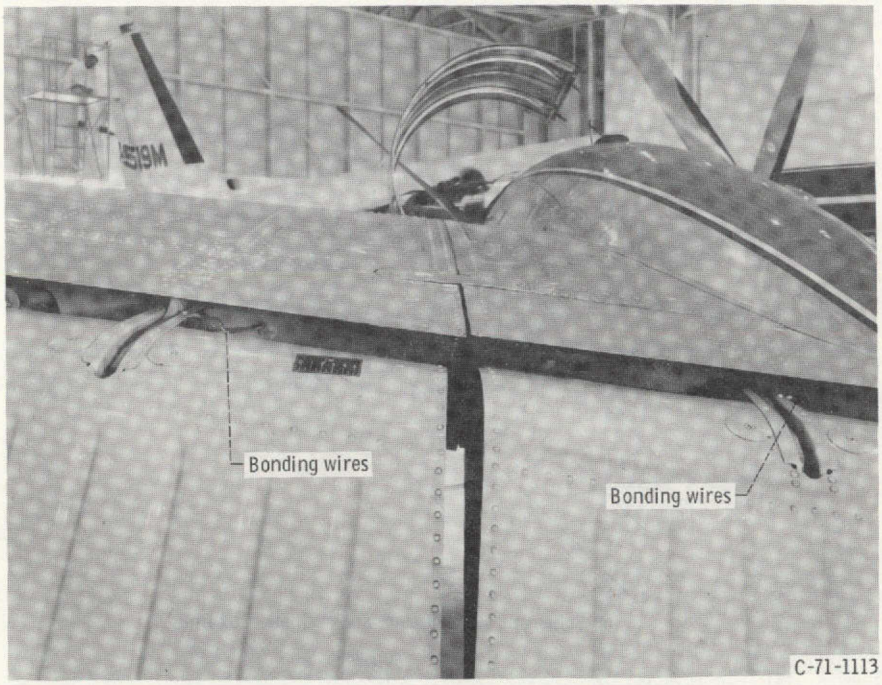


Figure 33. - Electrical bonding wires on left wing flaps.

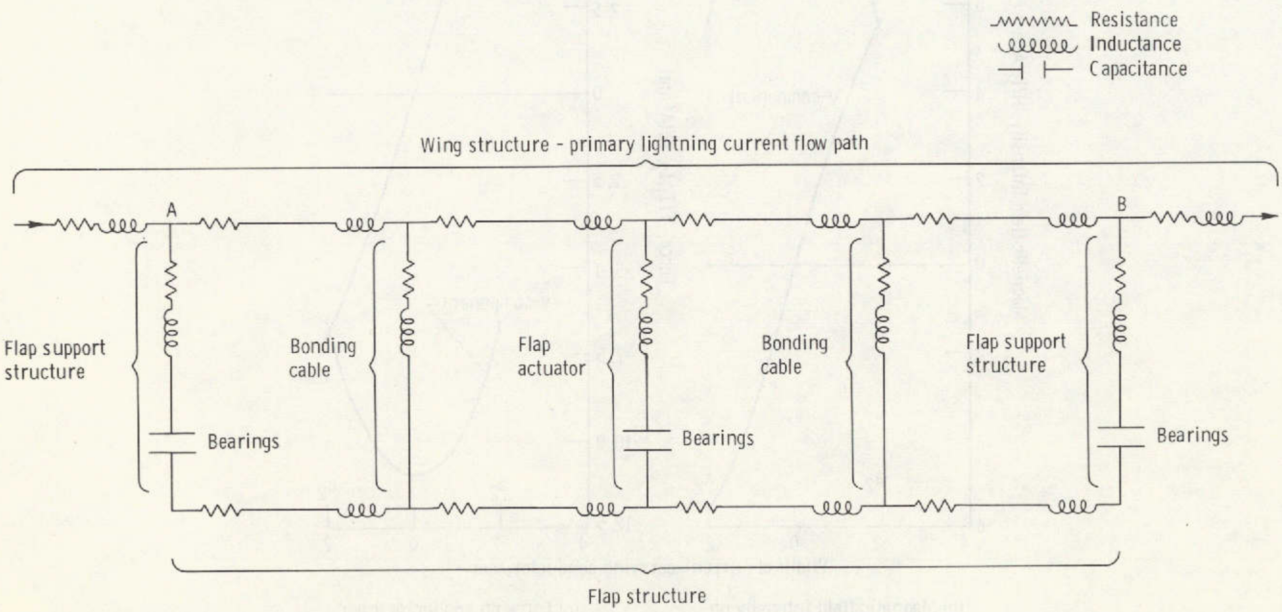


Figure 34. - Electrical circuit representation of wing-flap structure and interface attachments.

NASA-Langley, 1974 E-7967