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PRELIMINARY REPORT ON FLIGHT TESTS OF AN AIRPLANE HAVING EXHAUST-HEATED WINGS

By Lewis A. Rodert, William H. McAvoy, and
Lawrence A. Clousing

Ames Aeronautical Laboratory
Moffett Field, California

NACA

WASHINGTON

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SUMMARY

Flights have been made with an airplane in icing conditions in order to test the effect of exhaust heat applied to the wings as a means of preventing ice formations. Other ice-prevention equipment, including an exhaust gas-heated pitot-static head, hot-air-heated windshield, and an inflatable de-icer of recent design, were also tested.

Icing conditions were encountered in a range of air temperatures from -10° to $+32^{\circ}$ F, which in certain instances resulted in a high rate of ice formation. The use of exhaust heat on the airplane wing resulted in successful ice prevention during all tests, and it is concluded that this method represents a practical means of ice prevention. The use of exhaust heating on the pitot-static head prevented ice under all conditions and appears to be a satisfactory solution to the pitot-static head icing problem when applied jointly with exhaust wing heating. The air-heated windshield also gave complete protection against ice or snow on the outside of the windshield and frost on the inside, and is believed to represent a practical and satisfactory solution to the windshield-icing problem. Ice was removed from the horizontal stabilizer by the inflatable de-icer under certain icing conditions, although under other icing conditions the ice was only partially removed.

INTRODUCTION

Previous research on the prevention of ice on aircraft, references 1, 2, 3, and 4, and analytic studies of the possibilities of the application of exhaust heat as a means of preventing the formation of ice on vulnerable parts of airplanes, led the NACA to the conclusion that a full-scale test of exhaust-gas wing heating and other types of thermal ice-prevention equipment should be conducted in natural icing conditions. With the cooperation of the Matériel Division of the Army Air Corps, alterations were made on a Lockheed 12A transport airplane, which included provision for heating the wing with exhaust gas from the engines and for heating the windshield with hot air.

Inasmuch as the tests were to be made in natural icing conditions, ice-prevention equipment was provided for other vulnerable parts of the airplane. An exhaust-heated pitot-static head, alcohol-distributing apparatus for the propellers, air preheating for the engine carburetors, a windshield wiper, an electrically heated pitot-static head, and an inflatable de-icer on the horizontal stabilizer were installed.

The tests reported here were conducted along the Pacific Coast, in the regions of San Francisco, California, Medford, Oregon, and Tacoma, Washington. The total flying time of the airplane for the period covered by this report was 65 hours, of which 15 hours were in icing conditions. Successful searches for icing conditions in these areas resulted from cooperation with the Weather Bureau, the Meteorological Section of the Air Corps at Moffett Field, and Airline operators in the Northern Pacific Coastal region.

EQUIPMENT

The Lockheed 12A airplane (fig. 1), in which the research was conducted, was equipped with two Pratt and Whitney 450-horsepower Wasp Junior engines, and 8-foot 10-inch diameter constant-speed propellers. The wings were heated by passing all or part of the engines' exhaust gas through tubes along the inside of the wing leading edges. The quantity of exhaust gas passed through the wing was controlled from the pilots' cockpit. The exhaust gas was discharged from the wing tube at the wing-tip joint into a tip shroud, and from there to the atmosphere. Figures 2, 3, 4, 5, 6, and 7 show details of the exhaust heating system in the wing.

In order to assist the transfer of heat from the exhaust duct and the distribution of this heat over the surface of the wing, air was taken in through a port on the wing leading edge near the engine nacelle and passed along a circuitous route within the wing. After entering the leading-edge port, the air was passed along the space formed by the outside of the exhaust tube and the inside of the wing leading edge. After having been heated, as a result of passage along the leading edge of the wing, the air was run into the after-portion of the wing and finally discharged through louvers in the upper surface about 30 percent of the chord length ahead of the trailing edge. The quantity of air which was passed through the wing was controllable from the pilots' cockpit. Figures 8, 9, 10, and 11 show details of the air circulation system. The air-discharge louvers on the upper surface of the wing and the exhaust discharge at the wing tip are shown in figure 12. The heat was distributed over the span between the engine nacelles and the tips. Temperatures of the exhaust gas, gas duct, wing structure, wing skin, and circulated air were measured in flight by thermocouples. Pressures within the exhaust-duct system were measured at five points along the exhaust tube and manifold. Instruments and equipment for making the temperature and pressure measurements are shown in the airplane cabin in figure 13.

Heated air for the pilot's windshield was taken from the exhaust air heater of the right engine. The heated air was piped to a manifold at the windshield leading edge. Details of the air-duct system for the windshield are shown in figures 14 and 15. A control for the flow of heated air through the windshield was located in the pilots' cockpit. The windshield was composed of two panes of $\frac{3}{16}$-inch safety glass, spaced $\frac{1}{4}$ inch apart. Heated air flowing between the two glass panes was intended to prevent the formation of ice on the exterior and of frost on the interior. The exhaust-wing heating system and hot-air heating system for the windshield with the necessary test apparatus added about 150 pounds to the weight of the airplane.

Protection against the formation of ice on the propeller blades was provided by the distribution of alcohol from a tube on each blade extending from the hub along the blade leading edge. The tubes, which were made of rubber, were lashed to the propeller blade near the stagnation pressure line. The propeller anti-icing fluid tube and attachment are shown in figure 16.

Additional protection of the pilot's windshield was sought through the use of a rotating windshield wiper. Alcohol was discharged from the hub of the wiper which was intended to prevent the formation of ice over the disk swept by the rotating blade. A view of the windshield wiper is shown in figure 17.

Protection against ice on the pitot-static heads was obtained by electric heating on the service head and by exhaust heating on a head developed by the laboratory for use in these tests. The exhaust-heated head is shown attached to the wing tip in figure 18. The strut was $1\frac{1}{2}$ inches in diameter and 24 inches in length. Exhaust gas from the tip shroud was ducted through a tube along the center of the boom out and against the pitot-static head, then back along the annular space between the central and outer tubes to the wing-tip shroud. The power necessary for the exhaust circulation was obtained from the kinetic energy of the gas in the tip shroud.

The leading edge of the horizontal stabilizer was equipped with a Goodrich inflatable de-icer. The de-icer was a two-lobe type and was designed with a rubber flap extending from the de-icer to the rear edge of the fairing strips. The de-icer installation is shown in figure 19.

No provision was made for the prevention or removal of ice from the vertical fins, propeller spinner, copilot's windshield, antenna wires and struts, oil cooling air-inlet scoop, and the wing leading edge between the engine nacelles and the fuselage.

TESTING METHODS

On the basis of weather forecasts from the U. S. Weather Bureau and the Weather Station of the U. S. Air Corps at Moffett Field, California, flights were scheduled to coincide with atmospheric conditions in which ice would form. During the flights in icing conditions, notations based on visual observations and instrument readings were made. Attempts were made during each icing flight to maneuver the airplane out of the clouds in order that photographs of various parts of the airplane could be made.

The heating equipment for the wings, pitot-static head, and windshield was started prior to encountering ice during some flights, while in others heating was not started until after one-eighth inch or more had formed on the leading edge of exposed parts. A small telltale strut was mounted on the right wing on which ice was allowed to form. Photographs of the wing and of ice on the strut were made to show in a visual manner the ice protection which was provided for the wing by the heating system.

RESULTS AND DISCUSSION

The heat which was supplied to the wing by the exhaust duct along the leading edge successfully prevented the formation of ice on all flights. Figures 20, 21, and 22 show photographs of the wing which were made during icing flights. Data which describe the conditions encountered during the flights are shown with the photographs. When icing conditions were encountered with air temperatures below 0° F, a tendency for ice to form around the air intake on the wing leading edge was observed. Under similar conditions, or when the wing heating system was operated on less than full heating capacity, thin sheets of ice about 1/16 inch thick formed on the wing surface in the vicinity of the trailing edge. The nature of the formation of ice along the unprotected wing leading edge between the fuselage and engine nacelle is shown in figure 23.

The temperature rise of the wing resulting from the exhaust heating varied from about 100° F above the ambient air along the leading edge to 20° F above near the rear beam. The rear beam on the Lockheed 12A is located along the aileron and flap hinge line. The spanwise temperature distribution was satisfactorily uniform, varying approximately 10° F over the heated span. The wing-tip region was about 10° F hotter than equal chord points near the engine nacelle.

The temperature of the aluminum wing structure at critical points along the exhaust wing heating system was not above 200° F in any case, and not above 100° F in the case of the wing's primary structural parts, such as the main beam. The back pressure on the engine due to the flow of exhaust gas through the wing duct was less than 2 inches of water at all points in the exhaust manifold and collector ring. No effect on the performance due to the use of the exhaust wing heating system was observed.

Important factors in the design of exhaust-heating equipment, in addition to the degree of ice protection afforded, such as corrosion, thermal expansion, failures resulting from vibration, and increased weight and cost have been considered. After about 50 hours' flying time, an inspection of the airplane indicated that while the need for maintenance and repairs had been found, a remedy for each defect was not difficult to discover.

The temperature rise of the exhaust-heated pitot-static head above that of the ambient air was about 65°. The head position and strut shape employed were desirable from the viewpoint of position error. At air speeds in the vicinity of cruising - i.e., 140 miles per hour and above, the correction for this type of head located at the wing tip, is near zero. The prevention of ice on the head by the use of exhaust heating, was entirely satisfactory.

The prevention of ice on the pilot's windshield is illustrated in figure 24, in which the windshield is free of ice. During several flights, ice was allowed to form before the heat was turned on and it was found that ice could be removed as well as prevented. The windshield wiper was unsatisfactory because of ice formations on the blade, as seen through the windshield in figure 24, and because of uneven alcohol distribution over the swept disk of the wiper. The air stream lifted the wiper blade off the glass over a part of the arc of rotation, and ice formed on the glass over this region. It appears that the windshield heating as employed in these tests is adequate for protection against ice and frost.

Ice removal was only partially successful on the horizontal stabilizer on which the inflatable de-icer had been installed. It was observed that if the ice formation was hard and confined to the leading-edge region, upon inflation of the lobes of the de-icer the ice would break into many pieces and blow away. However, if the ice extended rearward over the surface or was inclined to have a soft consistency, the inflation of the lobes would break the ice only slightly and much of the ice would remain on the wing leading edge. Figures 25 and 26 show the ice accretion remaining on the leading edge of the stabilizer after the inflatable de-icer had been operated during one flight.

No preceptible propeller unbalance or loss in power was experienced during the icing flights. It should be noted that although anti-icing propeller equipment was provided, the speed of the propellers on the test airplane probably was sufficiently high that ice was thrown off either by centrifugal force or melted by aerodynamic heating.

The formation of ice on an antenna wire and insulator is shown in figure 27. Greater formations than those shown in figure 27 were observed on several flights without breakage of antenna wires or insulators. Stranded stainless-steel antenna wires and rubber strain insulators are used in the antenna system.

DISCUSSION OF TESTS IN ICING CONDITIONS

The meteorological conditions during the icing flights included various types of disturbances. Air temperatures ranging from -10° to +32° F were recorded, the most severe icing condition occuring at about 25° F. Rime and glaze ice were observed on the unprotected parts of the airplane, as well as combinations of rime and glaze ice, with the combinations made complex in some tests by the addition of snow.

Data taken during severe icing conditions have been confined to observations on the degree of ice protection afforded by the different components on the airplane. The severe icing encountered was accompanied by violent turbulence, snow-and-rain static which stopped radio communication, and occasional dangerous electrical discharges. On March 30, 1941, a series of cold and warm fronts crossed the Pacific Coast in the vicinity of northern California, which resulted in severe icing conditions. During this disturbance the cloud structure was unbroken and extended from 4000 feet to above 16,000 feet. Ice-prevention tests were made at an altitude of between 9000 and 10,000 feet, over which range the air temperature varied from 22° to 28° F. The icing rate and the violence of the turbulence increased steadily during the flight. About 5 minutes after severe icing conditions were encountered, the tests were terminated because of dangerous flight conditions. The airplane was struck by an electrical discharge which melted the trailing edge of one propeller blade and the edges of the airplane structure at several points. The length of time that the airplane was in the condition of most rapid icing was sufficient to observe that the wing and windshield heating system appeared to be adequate. In this particular storm the wing ice-prevention system was operating on about 50 percent of the maximum heating capacity available.

CONCLUSIONS

1. Under all conditions of icing encountered in the flight tests, satisfactory protection against the formation of ice on the wings of the Lockheed 12A airplane was obtained by the use of heat from the engine exhaust.

2. A consideration of the weight of exhaust wing-heating equipment, the effects of the equipment on the performance of the airplane, and the problem of maintenance of the equipment indicates that the use of exhaust-heated wings has immediate practical possibilities.

3. The use of air heating on the pilot's windshield and exhaust heating on the pitot-static head was found to provide satisfactory protection against ice on these parts.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, California.

REFERENCES

1. Theodorsen, Theodore, and Clay, William C.: Ice Prevention on Aircraft by Means of Engine Exhaust Heat and a Technical Study of Heat Transmission from a Clark Y Airfoil. Rep. No. 403, NACA, 1931.

2. Rodert, Lewis A.: A Preliminary Study of the Prevention of Ice on Aircraft by the Use of Engine-Exhaust Heat. T.N. No. 712, NACA, 1939.

3. Rodert, Lewis A., and Jones, Alun R.: A Flight Investigation of Exhaust Heat De-icing. T.N. No. 783, NACA, 1940.

4. Rodert, Lewis A.: An Investigation of the Prevention of Ice on the Airplane Windshield. T.N. No. 754, NACA, 1940.

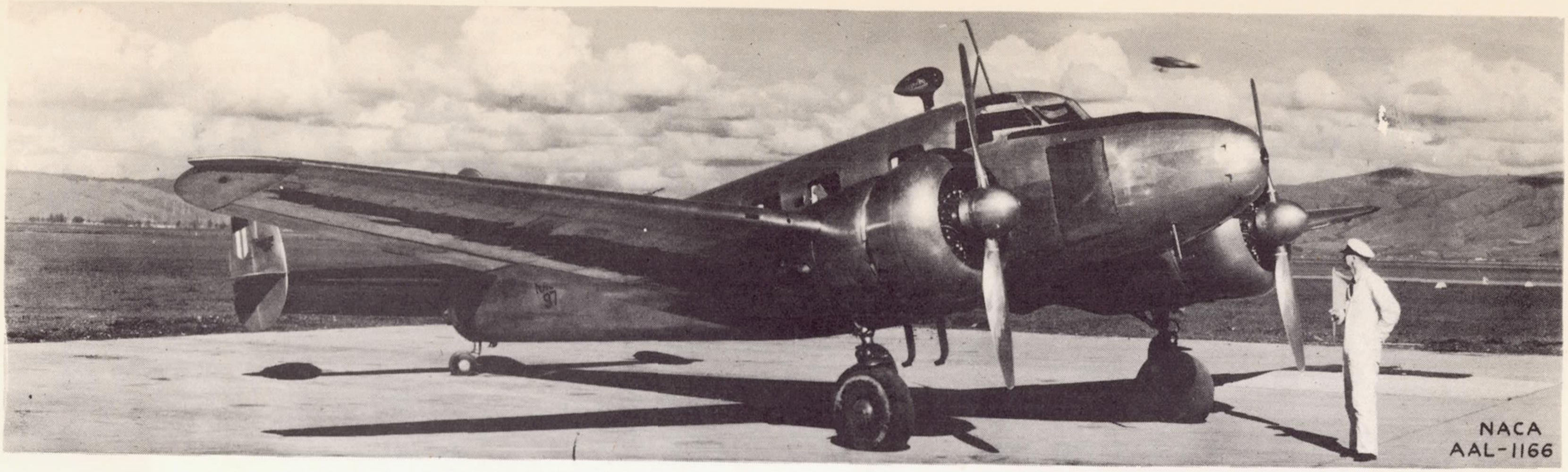

Figure 1. - Lockheed 12-A airplane. Alterations were made to a standard commercial model which include provisions for heating the wings with exhaust gas, and the windshield with heated air.

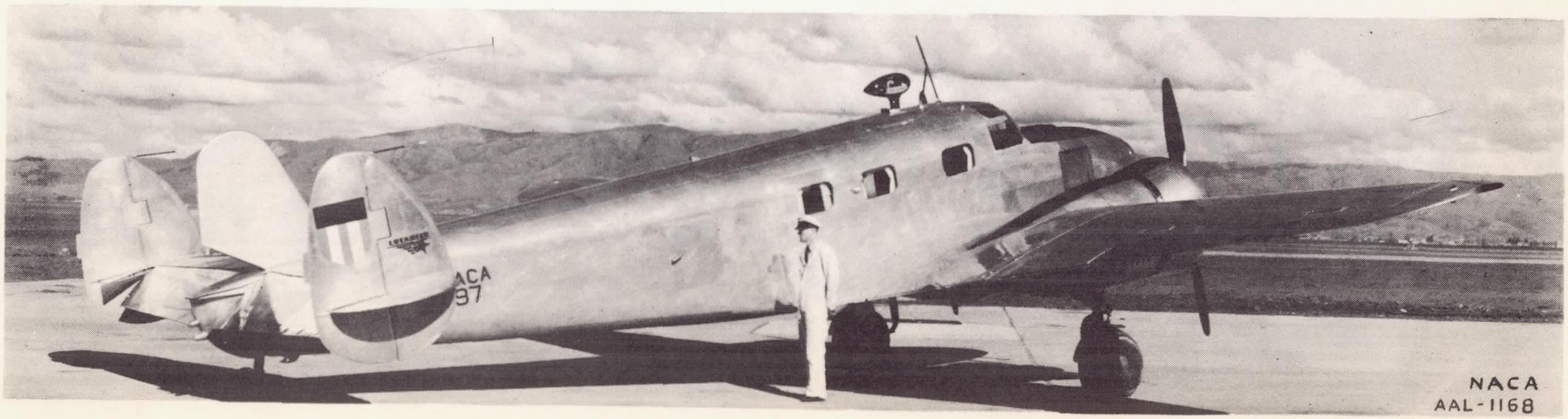

Figure 12. - Three-quarter rear view of airplane, showing location of air discharge louvers in the wing upper surface and exhaust discharge at the wing tip.

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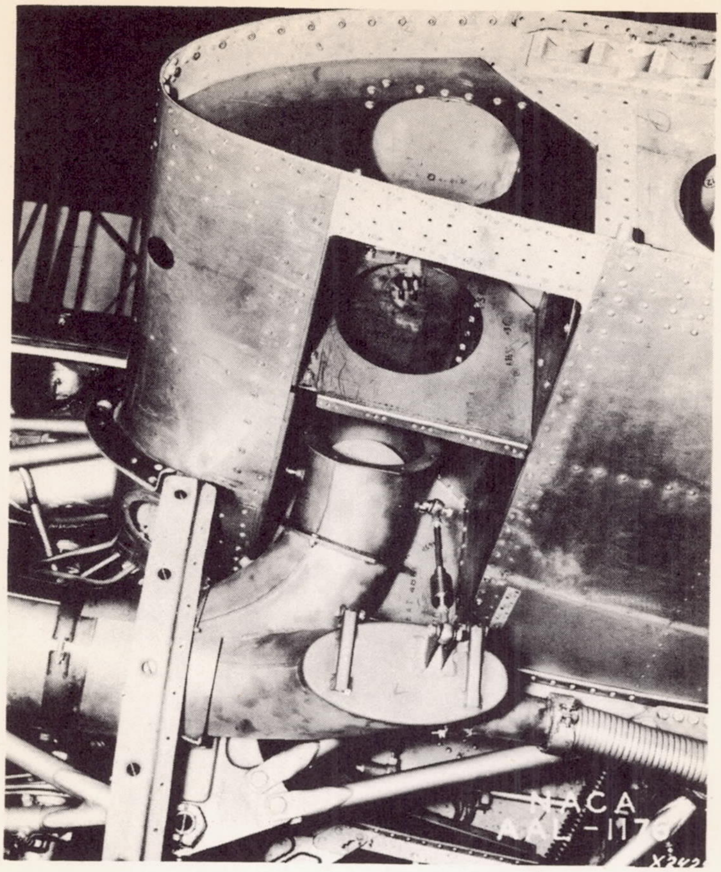

Figure 2. - Exhaust tail pipe showing "Y" and valve systems. When the valve over the normal discharge opening closes, a butterfly valve in the elbow opens permitting the exhaust gas to pass through the wing heating tube.

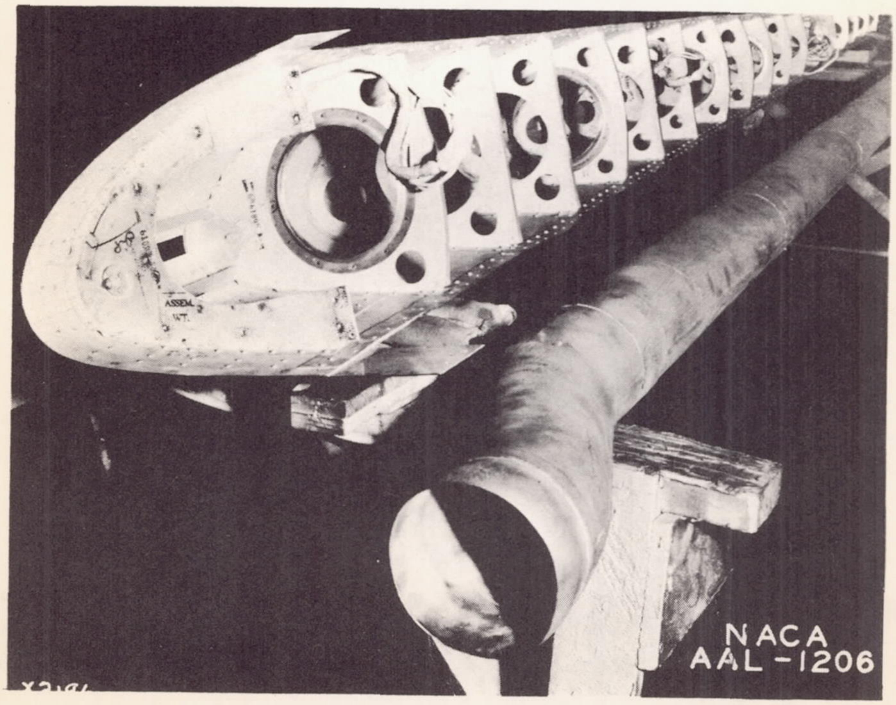

Figure 3. - Exhaust wing heating tube and wing leading edge shown disassembled.

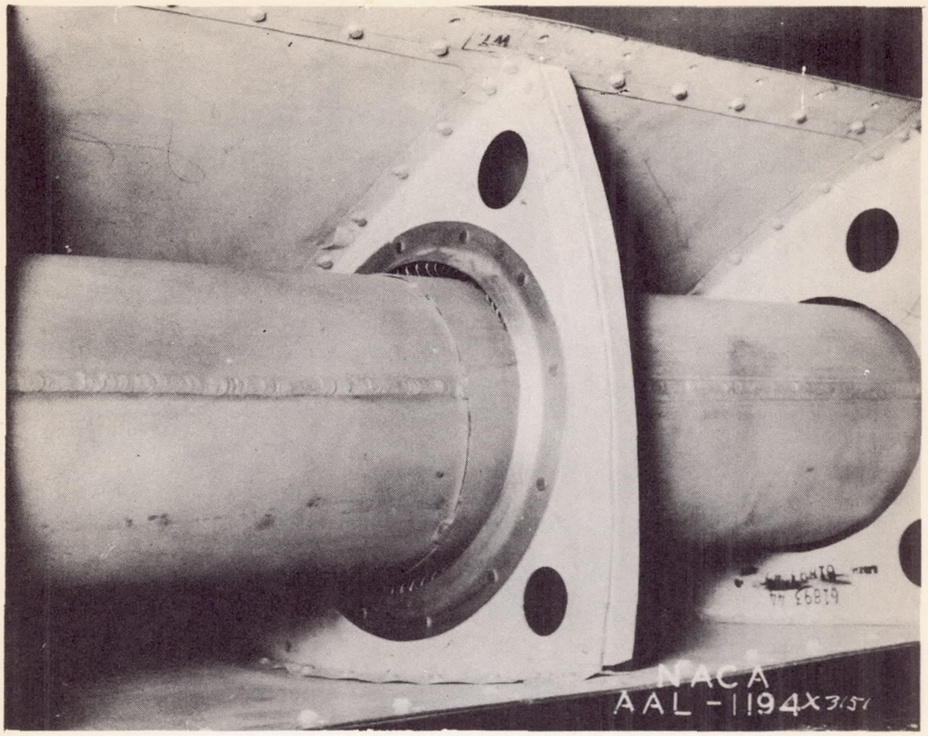

Figure 4. -
Exhaust wing heating tube in leading edge showing mounting ring and spring.

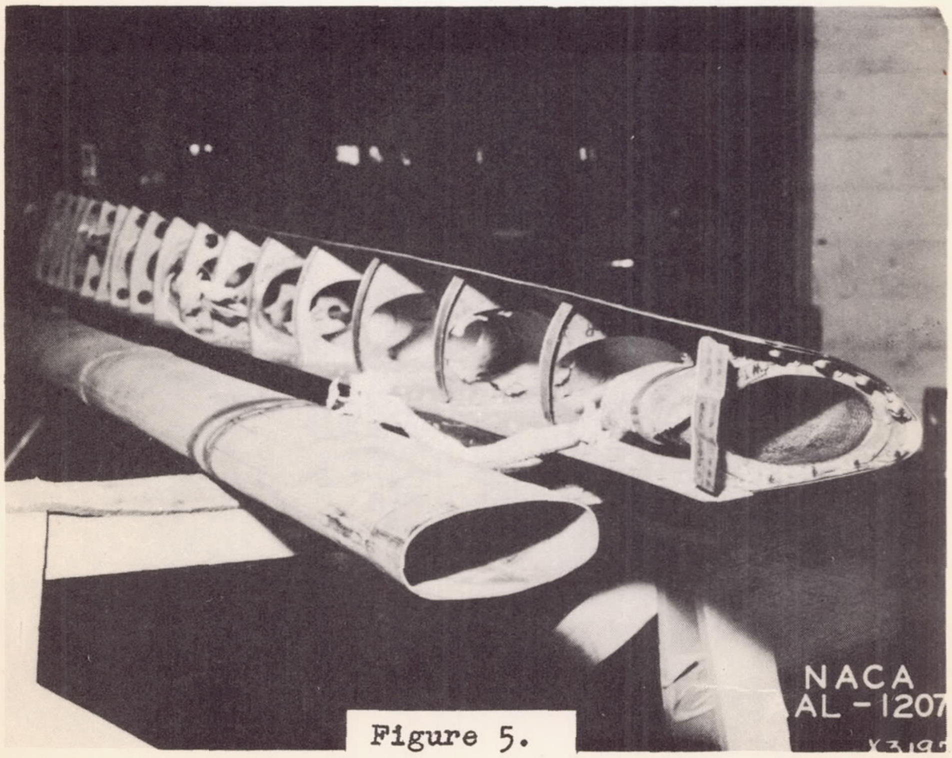

Figure 5.
Tip end of wing heating tube, shown disassembled with the leading edge.

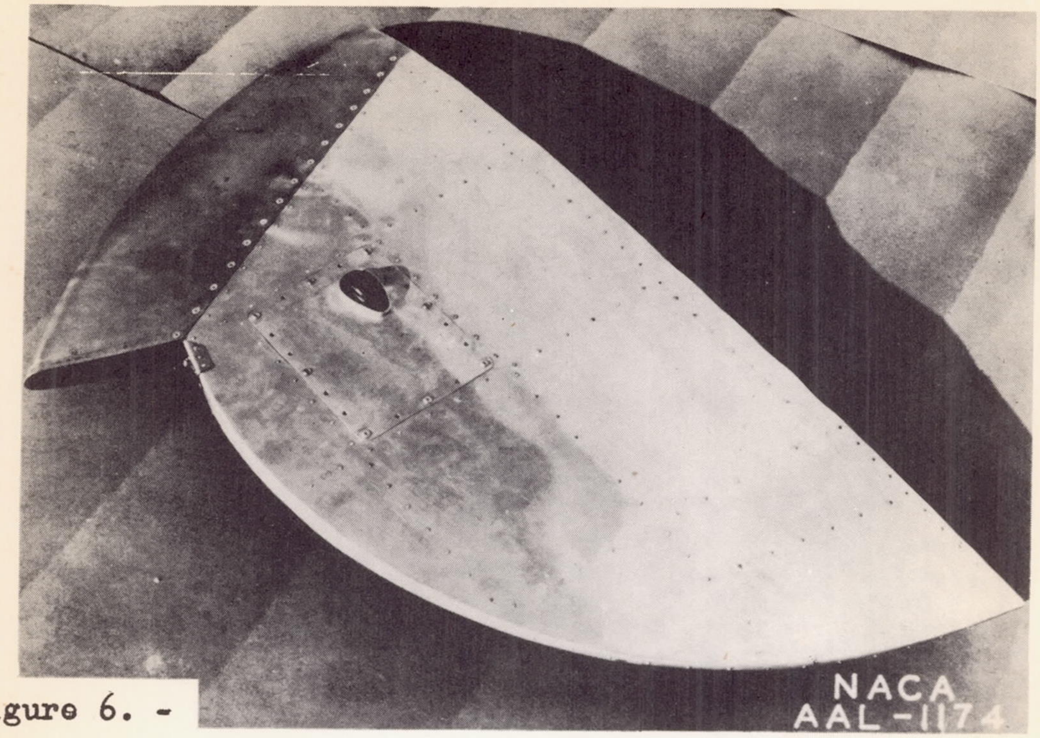

Figure 6. - The wing tip and tip shroud. The exhaust discharges from the opening at the left.

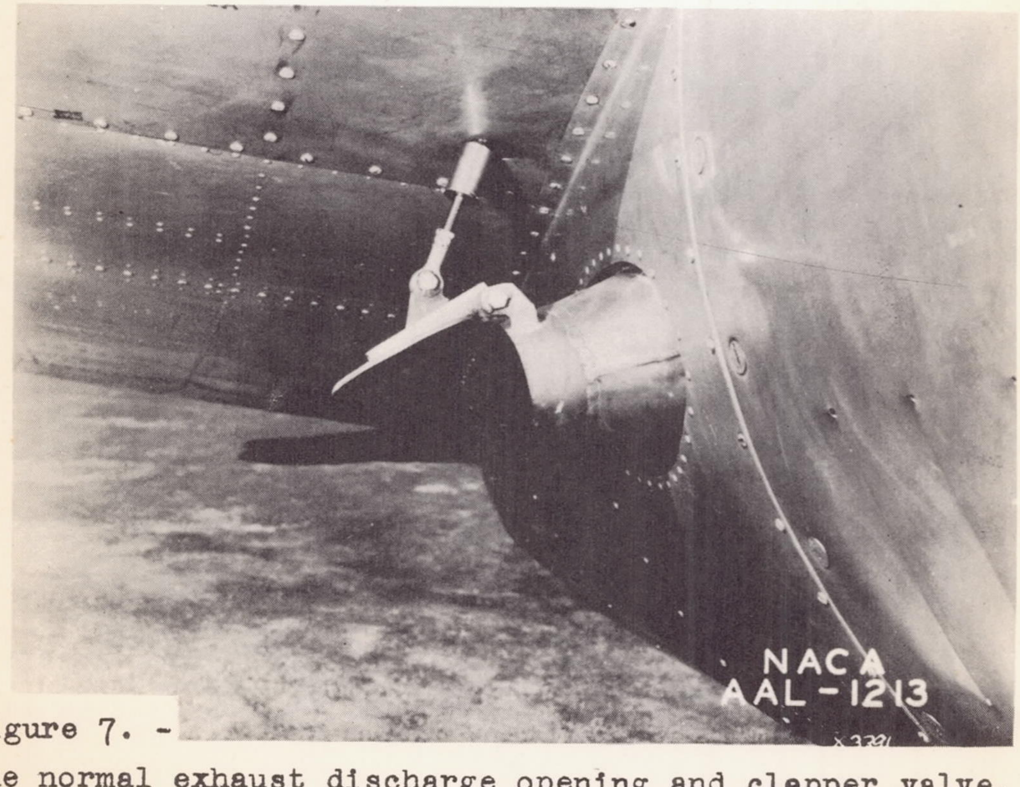

Figure 7. - The normal exhaust discharge opening and clapper valve. This valve is closed in varying degrees, depending on the amount of wing heating desired.

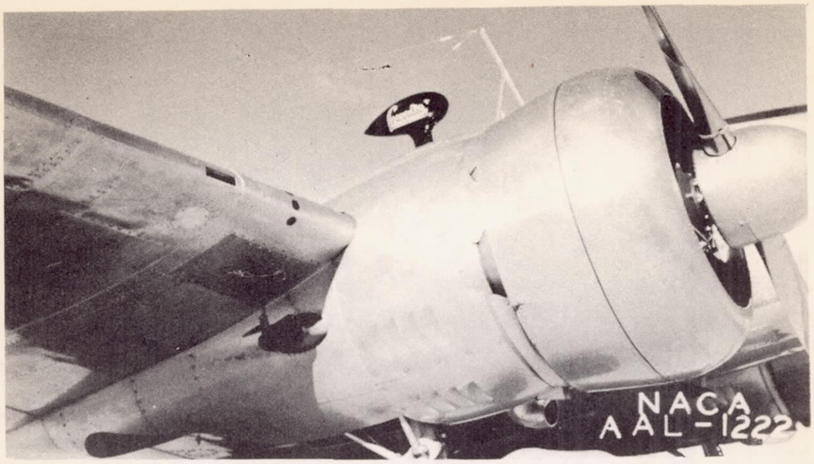

Figure 8. - A view of the wing leading edge showing the air intake port. The opening area of this port could be varied during flight by a control located in the pilot's cockpit.

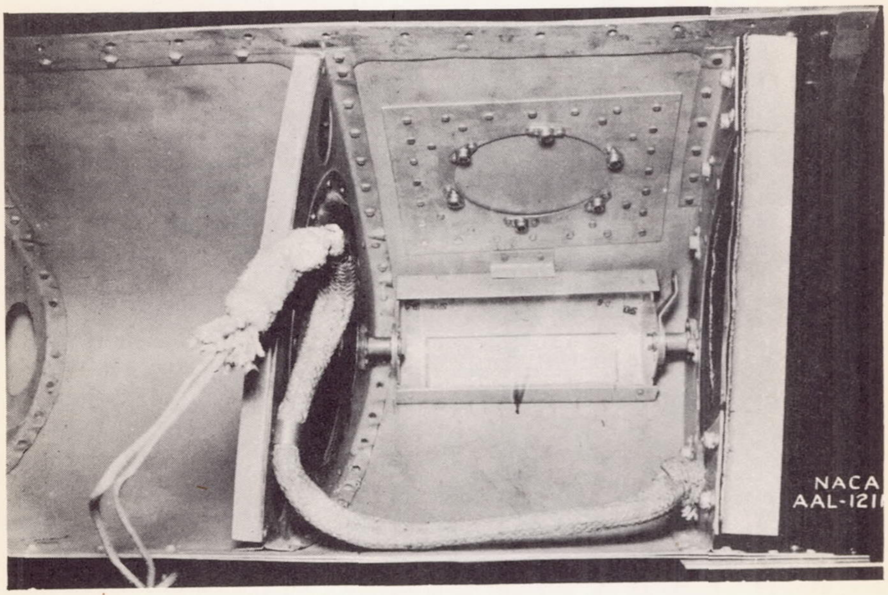

Figure 9. - Interior view of wing leading edge air intake port.

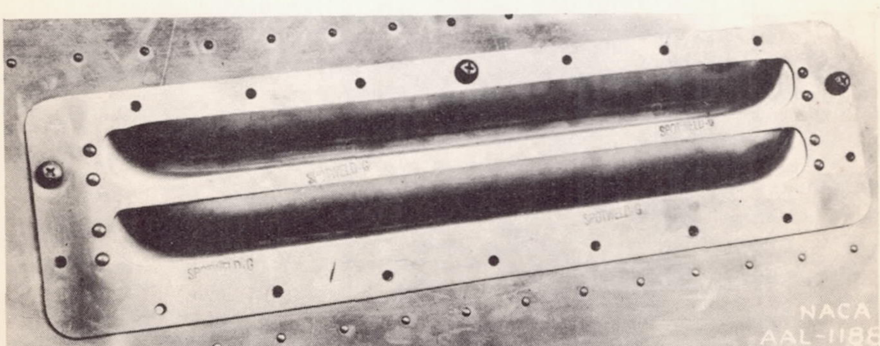

Figure 10. - Air outlet louvers, located on the upper wing surface. Two were employed on each wing, each located about 5 inches ahead of the rear wing beam.

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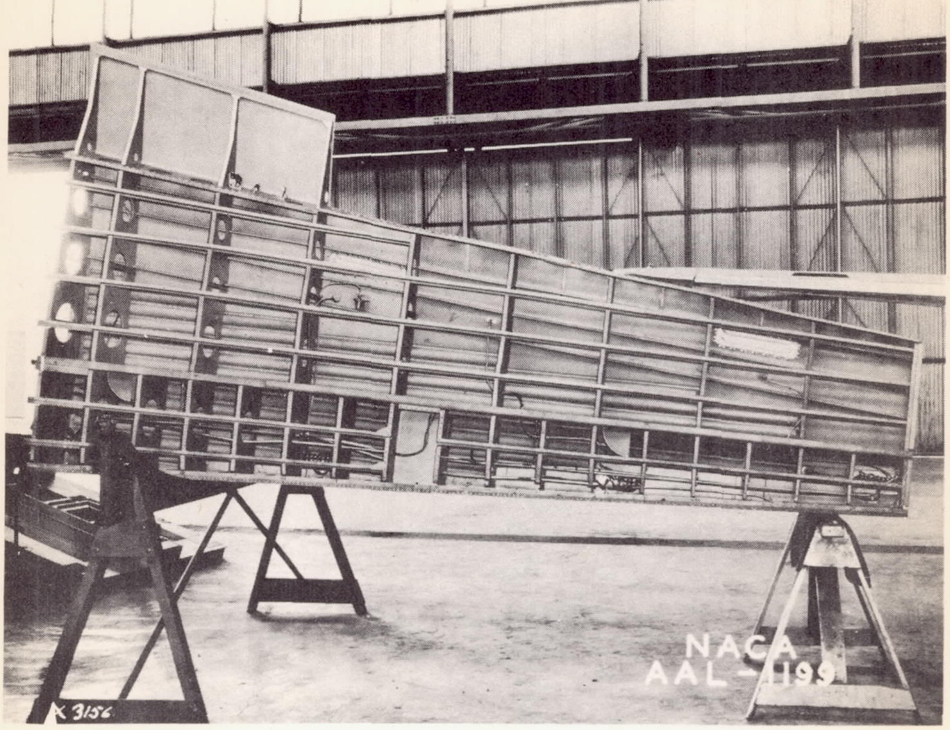


Figure 11.

Interior view of wing during construction. The position of the air discharge louvers are seen on the wing skin attached to the back side as shown in this photograph.

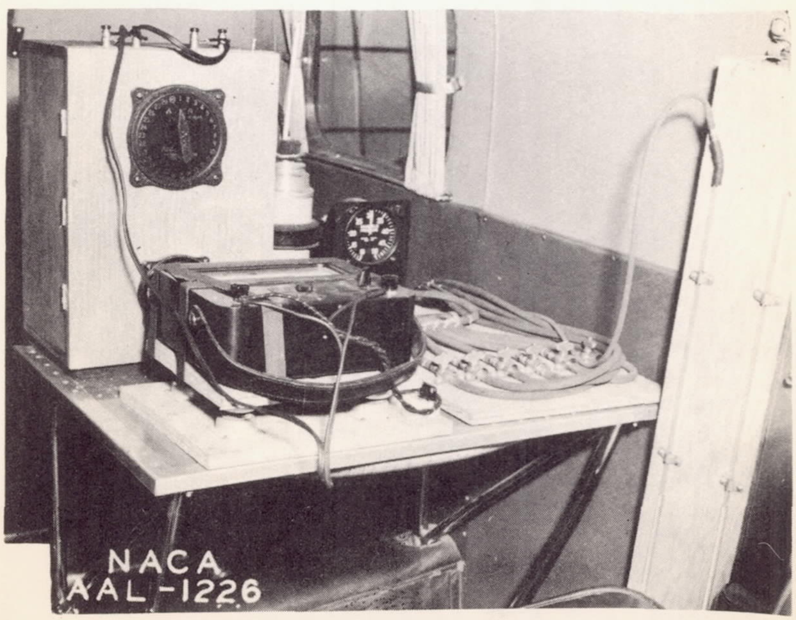


Figure 13.

Temperature and pressure measuring equipment in Lockheed 12-A airplane.

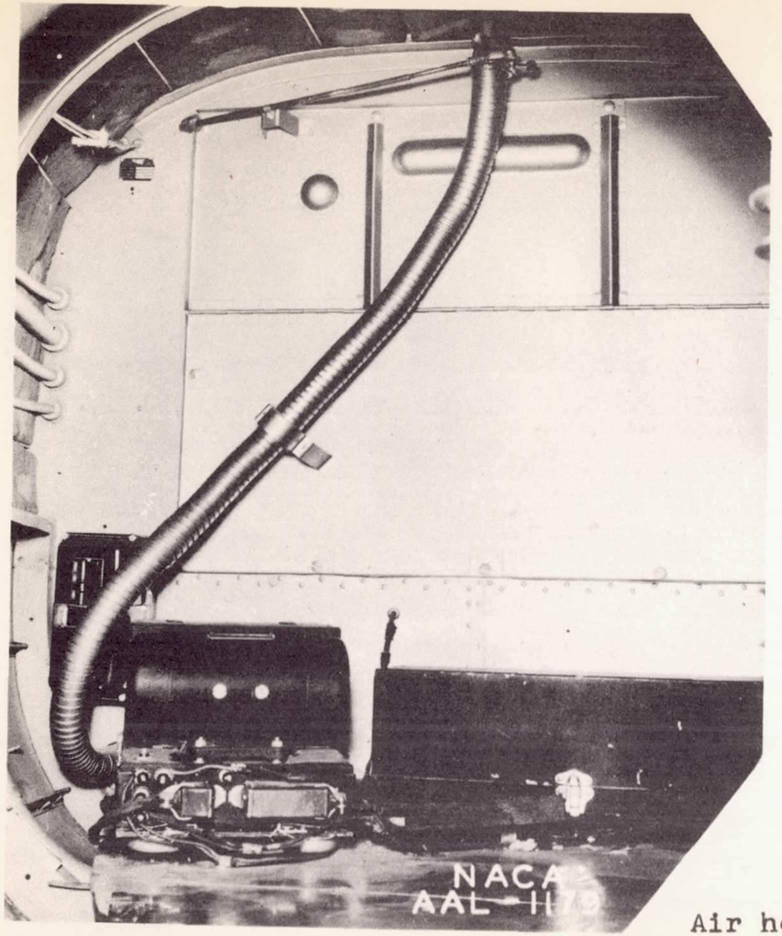


Figure 14.

Air duct and valve leading to the windshield hot-air manifold. This view is from the front end of the fuselage at the baggage door.

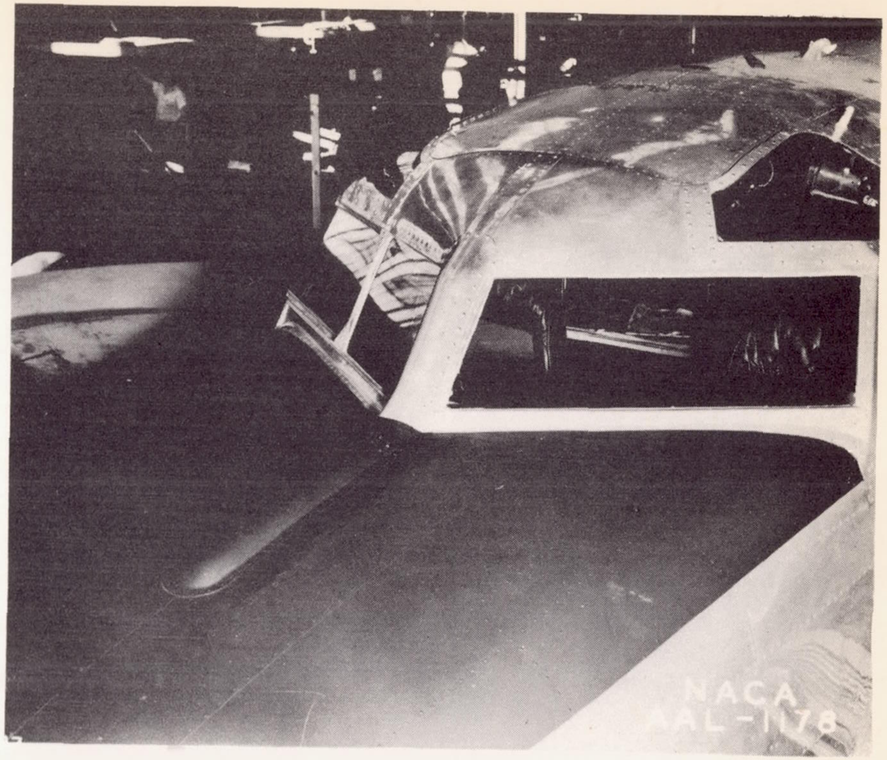


Figure 15. -

Air heated pilot's windshield showing the hot air manifold along the top of the fuselage and the leading edge of the windshield.

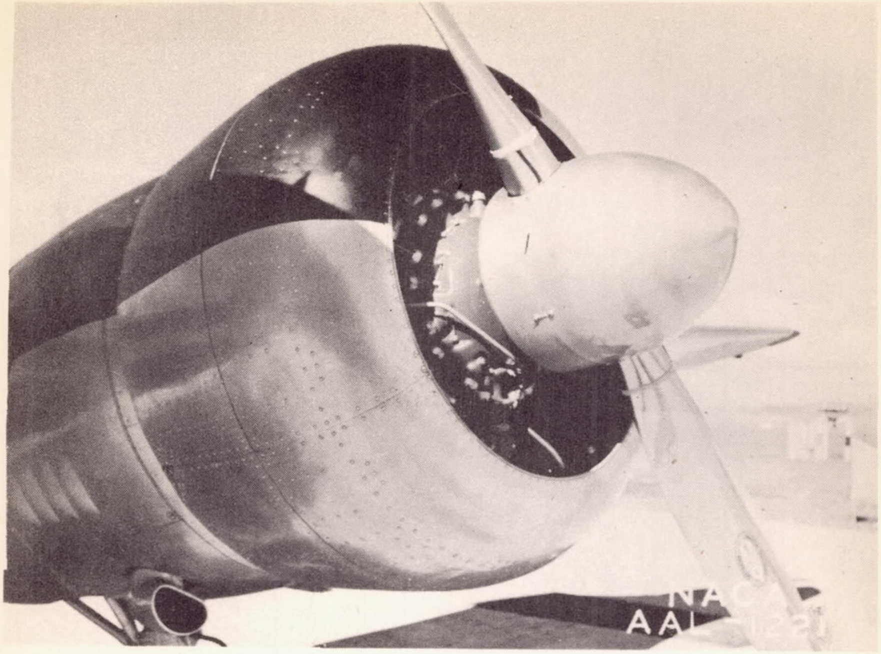


Figure 16.

Propeller anti-icing equipment. A rubber tube, conducting alcohol, discharges on the blade near the stagnation pressure line.

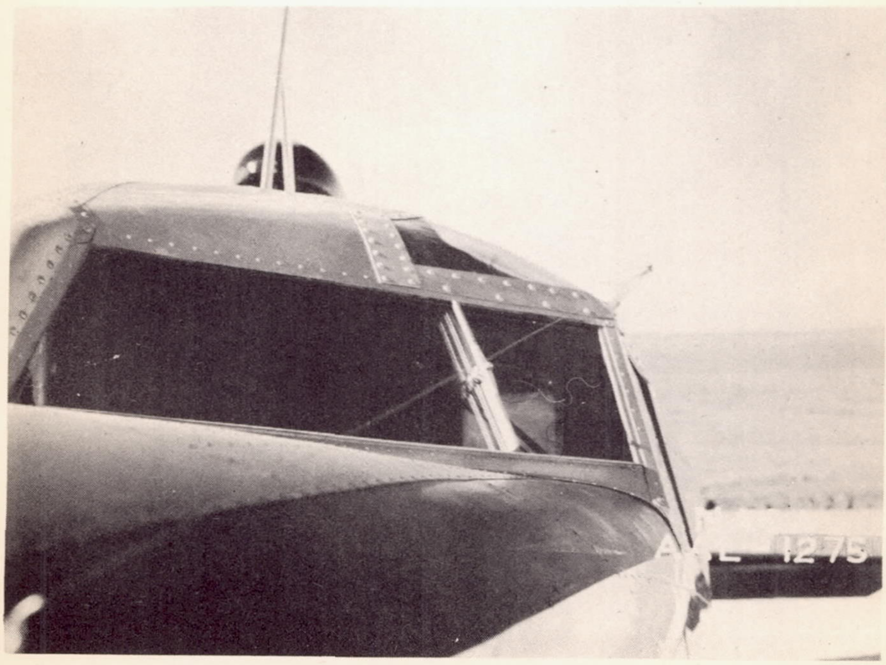


Figure 17.

Rotating windshield wiper mounted on pilot's windshield.

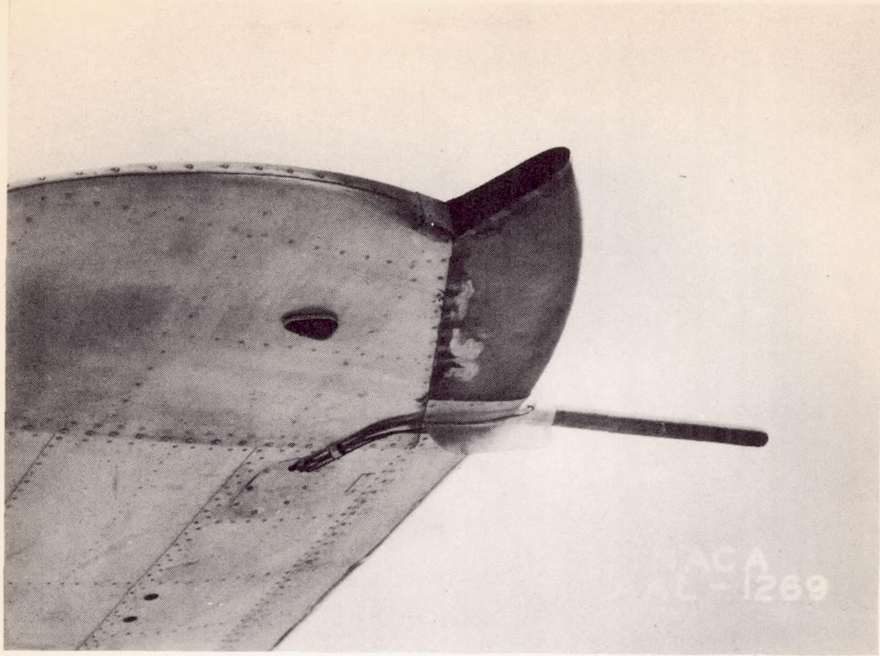


Figure 18. -

The exhaust heated pitot static head.

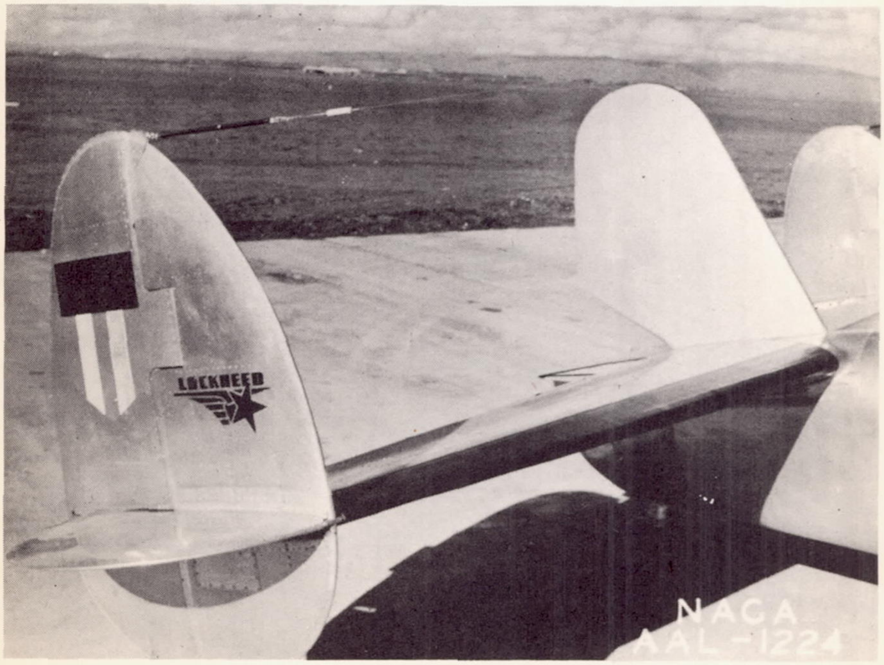
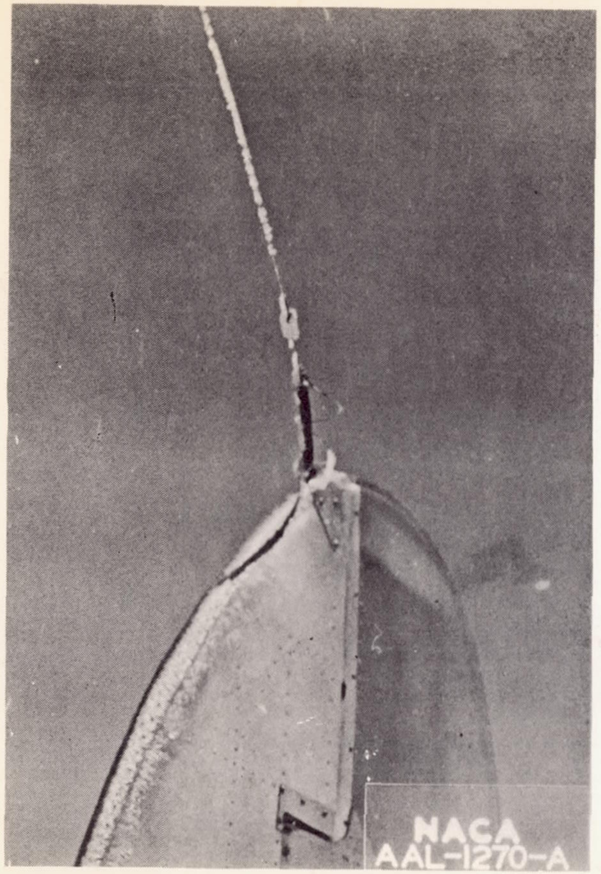


Figure 19. -

Goodrich inflatable de-icers on the Lockheed 12-A tail surfaces.



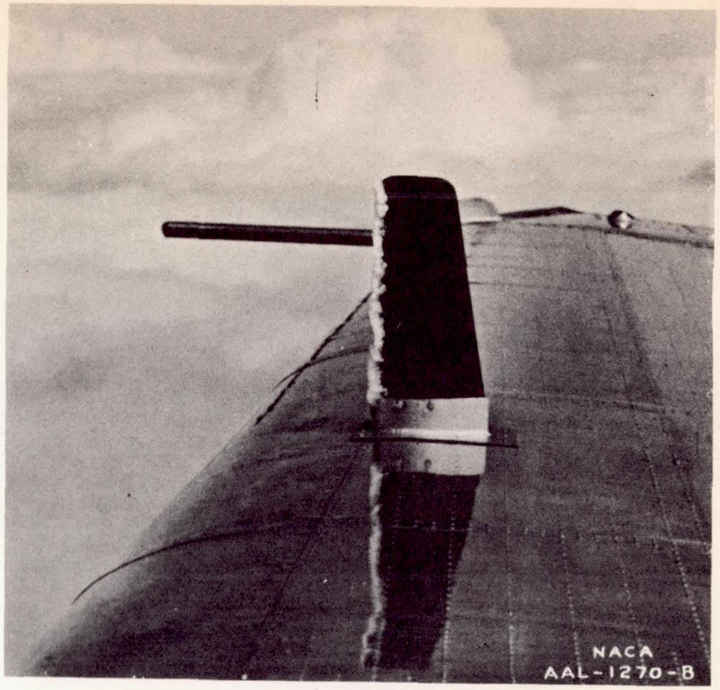


Figure 20. -

Ice formation on the tell-tale strut; wing and pitot-static head protected from ice formation by the use of exhaust heating.

Data: Airspeed, 140 m. p. h.; altitude, 10,000 to 12,000 feet; Cumulus clouds; air temperature, 20° to 26° F.; air, moderately rough; rime ice formation; estimated rate of icing, 7 inches/hour. The flight was made in the vicinity of Moffett Field, Calif.

Figure 27. -

A view of the Lockheed tail surface and radio antenna showing a formation on the wire resulting from a light rime icing condition.

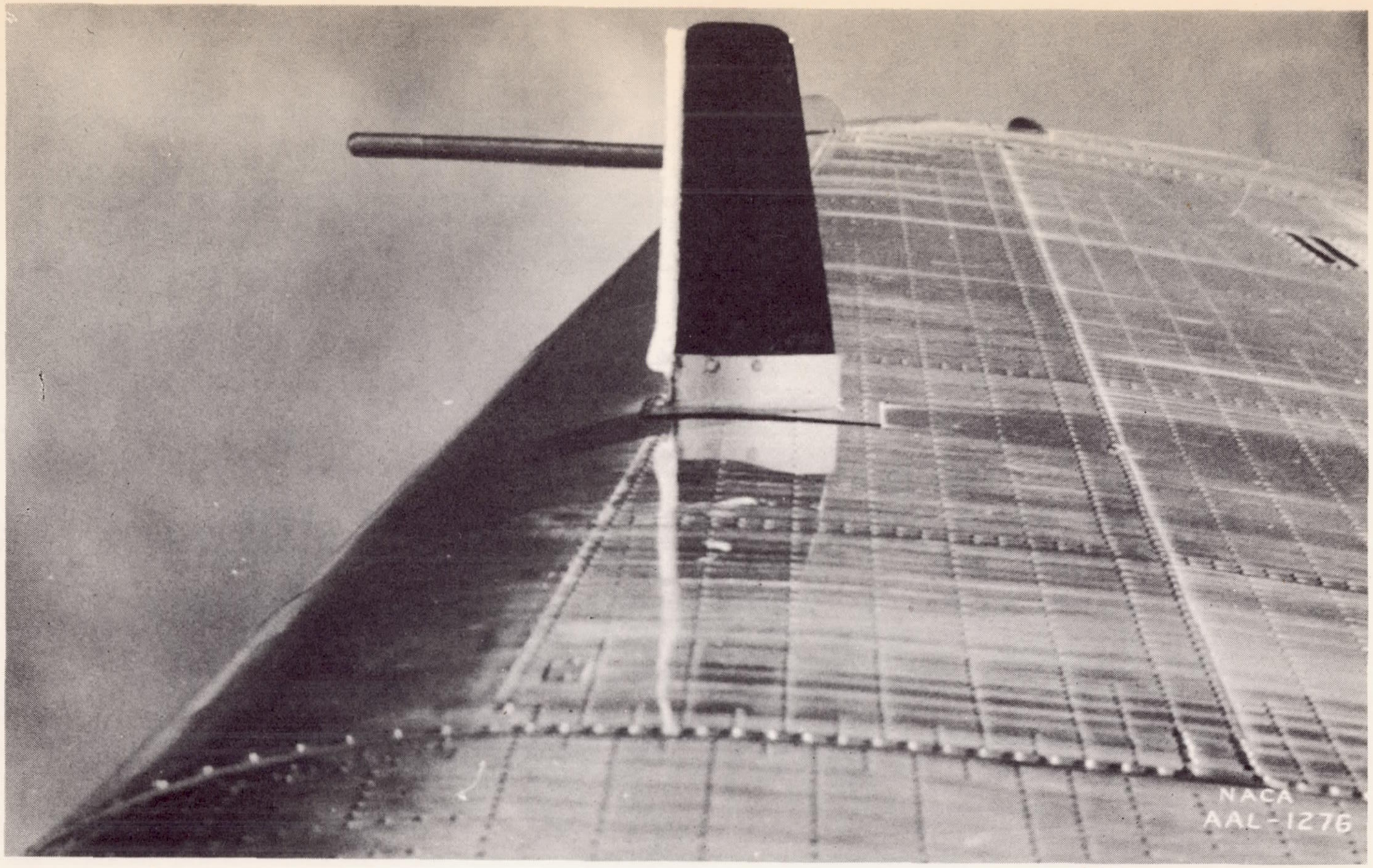


Figure 21.

A photograph taken on an icing flight during which ice was prevented on the airplane wing and pitot-static head by the use of exhaust heating. Ice on the tell-tale strut gives an indication of the nature of the icing conditions.
Data: Airspeed, 140 m. p. h.; altitude, 8,000 to 13,500 feet; Cumulus-Nimbus clouds; air temperature -10° to 22° F.; air, moderately to severely rough; types of ice, rime, glaze, and snow slush; estimated rate of icing, 6 to 7 inches per hour. The flight was made between Tacoma, Washington, and the Pacific Coast.

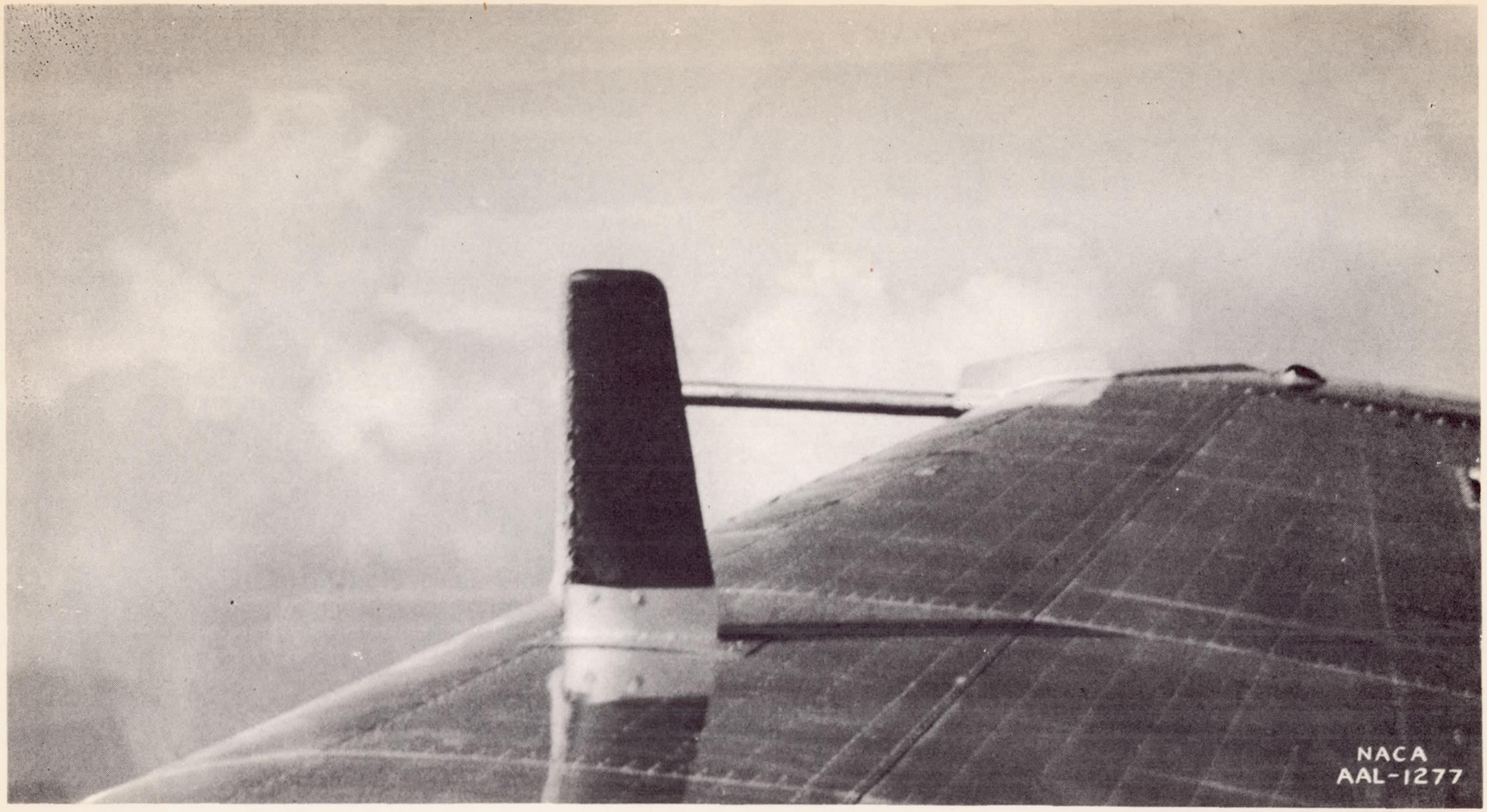


Figure 22. -

Ice prevention on the wing of the Lockheed 12-A airplane by the use of heat from the engine exhaust. The formation of ice on the strut in the foreground indicates the type of ice encountered.

Data: Airspeed, 140 m.p.h.; altitude, 8,000 to 8,500 feet; cumulus and cumulus stratus clouds; air temperature, 25° F.; air, very rough; types of ice, glaze and rime; rate of icing, undetermined. The flight was made in the vicinity of Medford, Oregon, over the Coast Range Mountains.

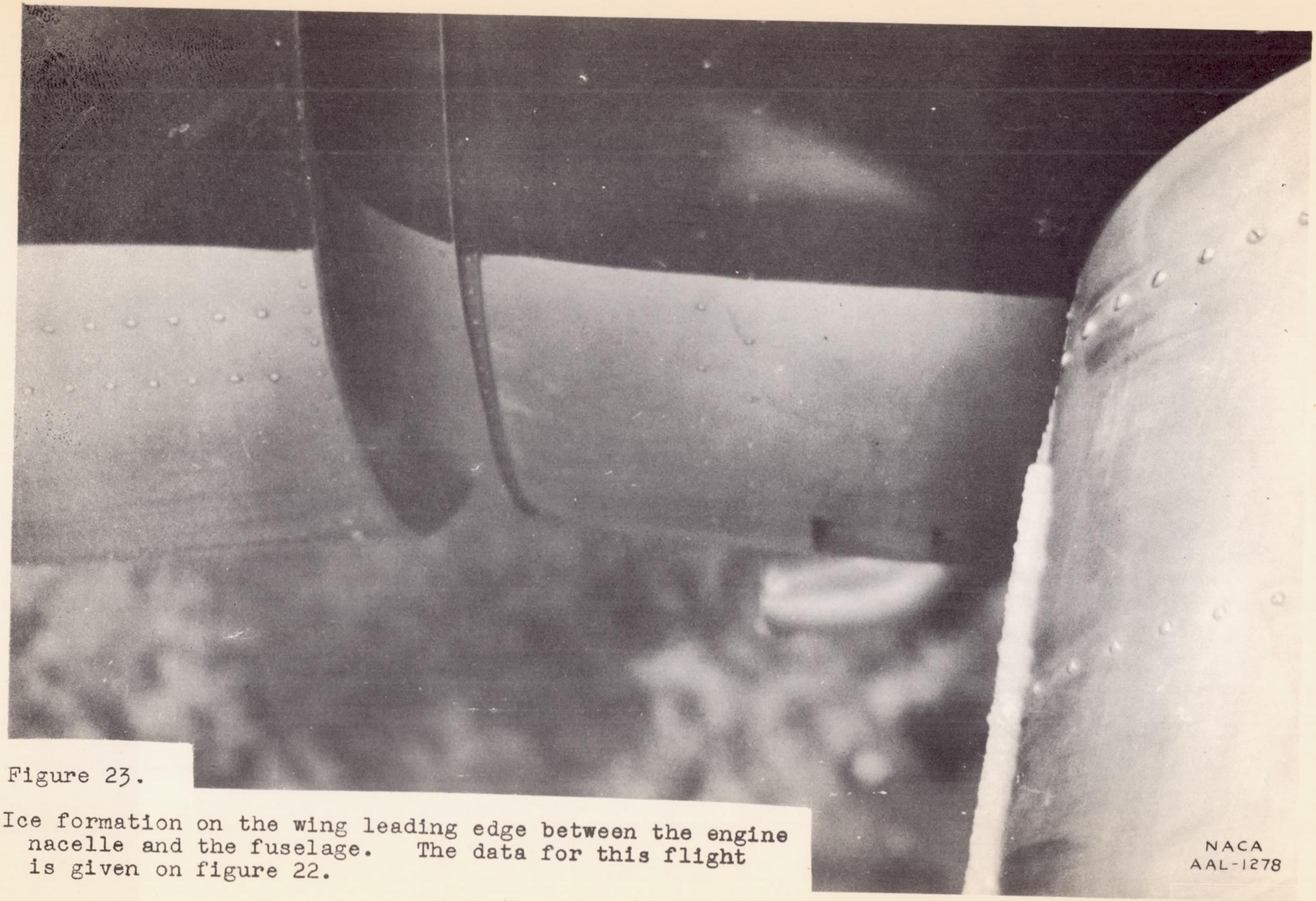


Figure 23.

Ice formation on the wing leading edge between the engine nacelle and the fuselage. The data for this flight is given on figure 22.

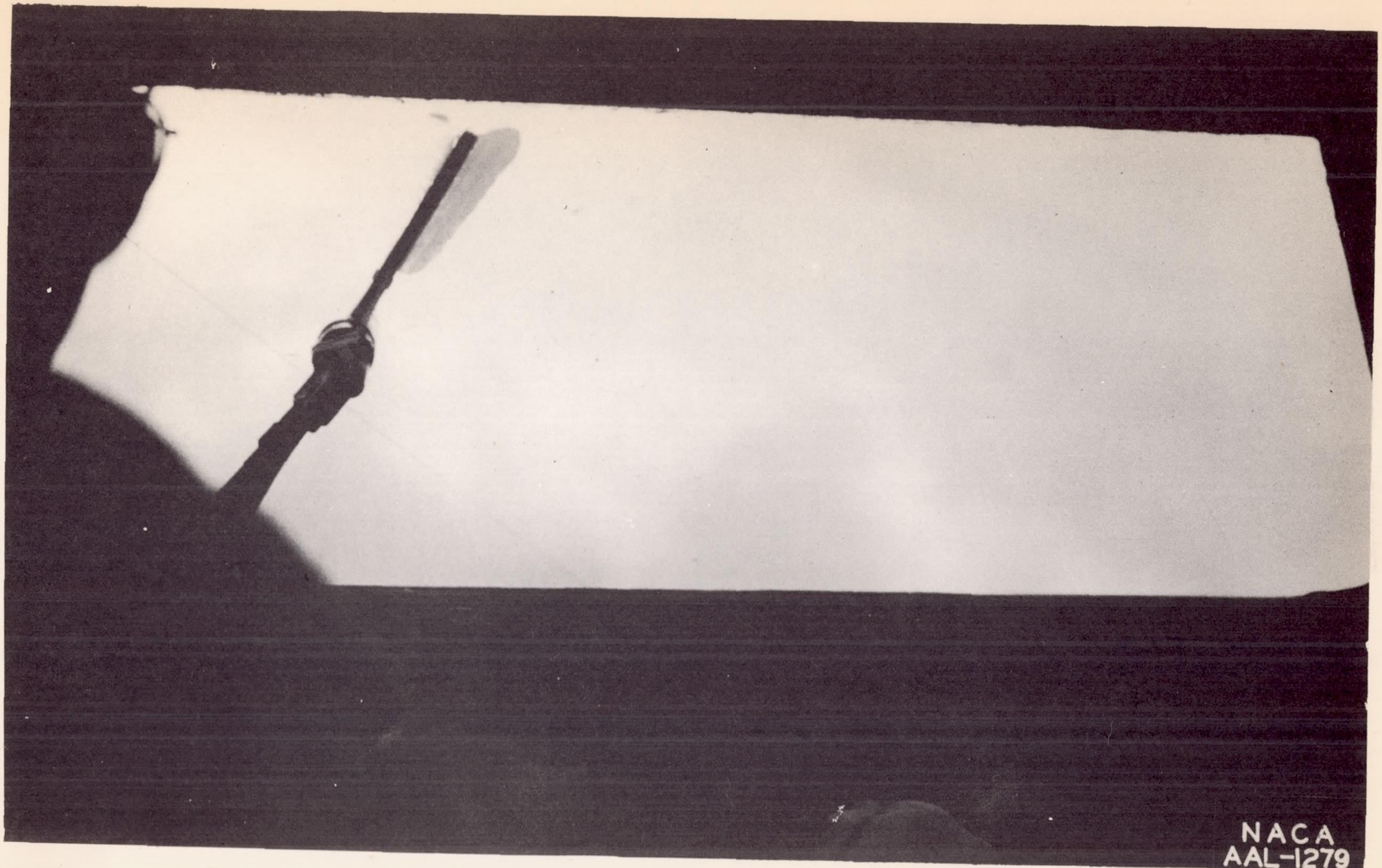


Figure 24. - A view through the pilot's windshield during an icing flight. The glass is free from ice on the exterior and frost on the interior. The data for the flight is given on figure 21. The low air temperatures produced frost on the co-pilot's windshield interior; ice forming on the exterior. Ice is seen on the windshield wiper blade protruding to windward about an inch.

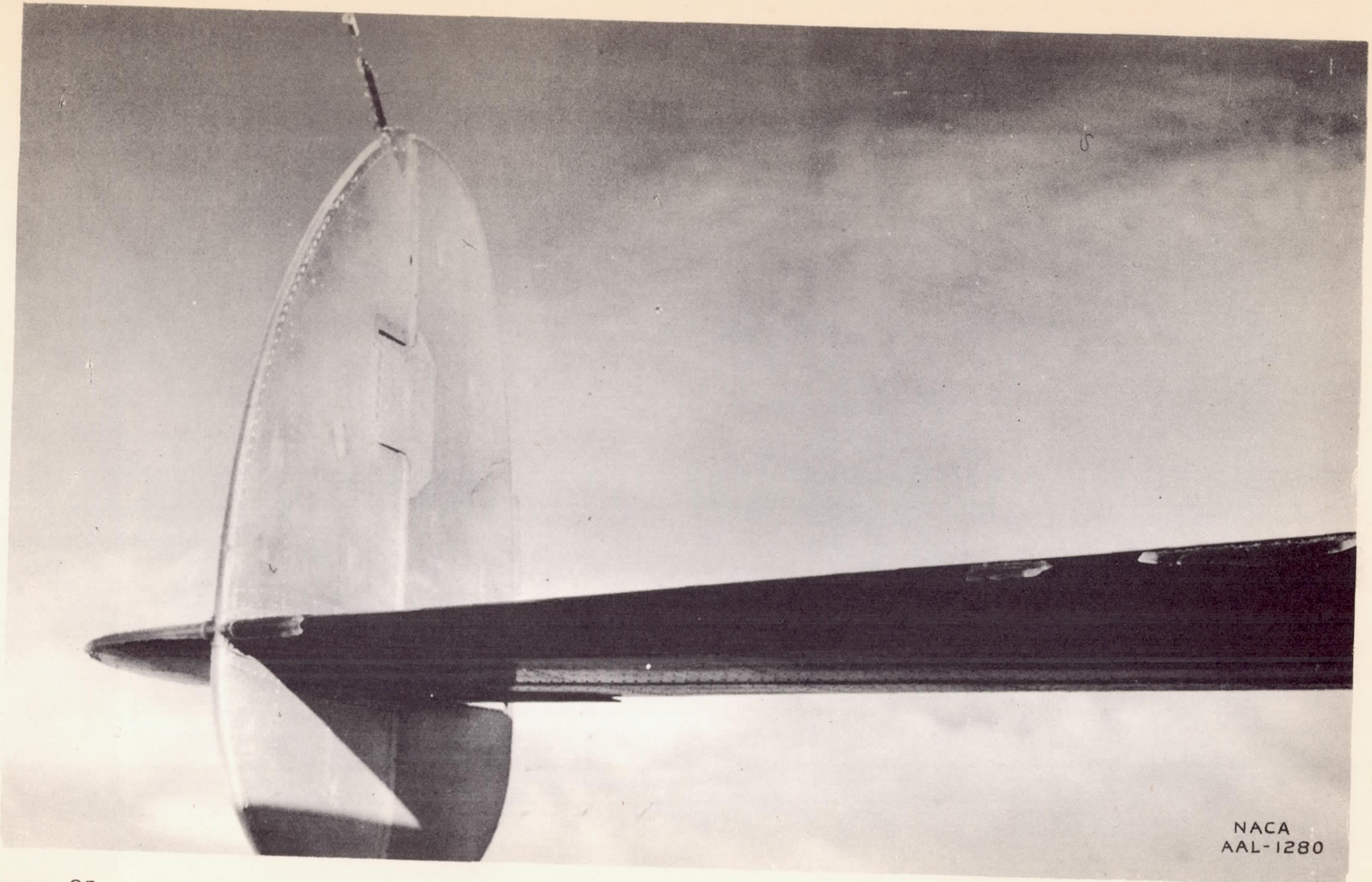


Figure 25. - The inflatable de-icer on the horizontal stabilizer of the Lockheed airplane after having been placed in operation. The data for this flight is found on figure 21. The photograph was taken during the early part of the flight.

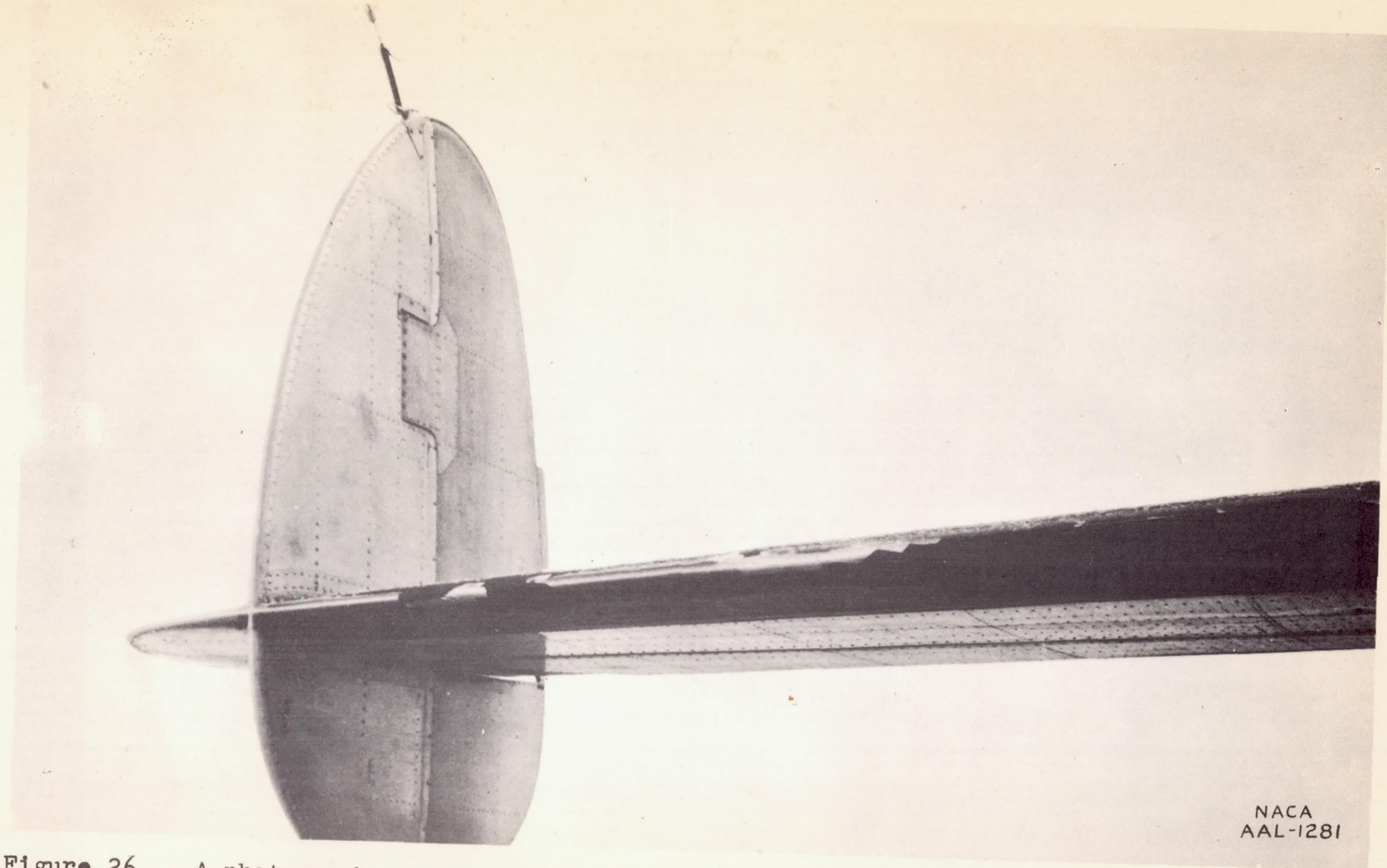


Figure 26. - A photograph of the de-icer on the Lockheed tail which was taken a few minutes after the photograph shown in figure 25. Residual ice remained on the stabilizer leading edge throughout the flight.