NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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WIND-TUNNEL INVESTIGATION OF ICING OF AN ENGINE COOLING-FAN INSTALLATION

By James P. Lewis

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Cleveland, Ohio

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SUMMARY

An investigation was made of the icing characteristics and means of ice protection of a typical radial-engine cooling-fan installation. The investigation was made at various icing and performance conditions in the icing research tunnel of the NACA Cleveland laboratory.

The icing of the unprotected cooling-fan installation was found to present a serious operational problem. Reduction in air flow below the minimum value required for engine cooling occurred within 2 minutes and complete stoppage of the cooling-air flow through the fan assembly occurred in as little as 5 minutes under normal icing conditions.

Steam de-icing was found to be effective for the cowling lip and inlet duct. Alcohol de-icing of the fan blades and stator vanes was found to be unsatisfactory. Electrical heat de-icing of the fan blades was found to be effective but de-icing of the stator vanes was not completely effective at the power densities investigated.

INTRODUCTION

Inadequate engine cooling at high gross weights necessitated the use of engine cooling fans on a large twin-engine airplane. Because of the expected loss in cooling-air flow under icing conditions, an investigation of the de-icing of a typical radial-engine cooling fan was deemed advisable. The trend toward the use of engine cooling fans on large high-performance aircraft makes such an investigation of general interest.

An investigation to determine the icing characteristics of the fan-assembly components, to evaluate the effect of icing on fan performance at various icing and fan-performance conditions, and to investigate and evaluate the effectiveness of several systems of ice protection of the cooling-fan assembly was conducted in the icing research tunnel of the NACA Cleveland laboratory.

APPARATUS

The investigation was conducted in the diffuser section of the icing research tunnel. The cooling-fan assembly was mounted on the modified nose section of an airplane fuselage installed in the tunnel. The installation consisted of a typical propeller-speed engine cooling fan, a stator-vane and diffuser assembly, a baffle plate located in a constant-area annular duct downstream of the fan to simulate the pressure drop across the engine, a standard radial-engine cowling, a three-blade propeller and spinner, and necessary instrumentation. (See fig. 1.)

Cooling fan. - The cooling-fan assembly was designed to be mounted at the front face of a radial engine and enclosed by the engine cowling with the fan rotor attached to the rear of the propeller hub and the stator-vane assembly attached to the reduction-gear housing. The front fairing of the fan disk was of the "dish-pan" type with a large forward bulge at the outer diameter of the dishpan. The fan had 72 cambered sheet-metal blades with a tip diameter of 43 inches and a tip clearance of three-sixteenths inch. As part of the cooling-fan assembly, 49 cambered sheet-metal stator vanes were located behind the fan to remove the rotational component of the flow. A clearance of seven-eighths inch existed between the fan blades and stator vanes. (See fig. 1.)

Instrumentation. - Total pressure in front of the fan and total and static pressure behind the stator vanes were measured by pressure-tube rakes (fig. 2). Four equally spaced rakes of shielded total-pressure tubes were located at the lip of the engine cowling between the fan and propeller. These rakes were unheated because of the extreme difficulty in heating small shielded total-pressure tubes and hence were used only on nonicing pressure-distribution studies. Electrically heated rakes consisting of four total-pressure tubes and one static-pressure tube were installed behind the stator vanes at four equally spaced positions corresponding to the positions of the front rakes. In addition, static pressures were measured on the inner wall of the diffuser in the plane of the rear rakes. All the pressures were indicated on a multiple-tube manometer and were photographically recorded.

The tunnel ambient-air temperature was measured by two shielded thermocouples located approximately 15 feet downstream of the cooling fan. The tunnel air velocity was determined from the static-pressure drop through the contraction section of the tunnel. The propeller and engine operating conditions were indicated by standard aircraft instruments located on the control desk. A battery of four stroboscopic flash lamps permitted observations of the fan while operating.

Steam-heat installation. - In order to investigate the elimination of ice on the engine-cowling lip and the consequent scraping of the fan-blade tips, one steam line with jets 0.10-inch in diameter and spaced 1/2 inch apart was placed inside the cowling lip and another was located outside the inlet duct 2 inches behind the first line (fig. 3). These lines were of 3/8-inch copper tubing and extended approximately 40° on each side of the center line in the lower half of the cowling. Steam heating was confined to the lower quarter of the cowling because of time limitations and also to provide an unheated area for comparison.

Alcohol de-icing installation. - In the investigation of the use of isopropyl alcohol for de-icing, spray nozzle bars were mounted radially in front of the fan blades and also between the fan blades and the stator vanes (fig. 4). The spray nozzle bars, consisting of tubes having six small jets each 0.070 inch in diameter, were mounted to spray the alcohol forward in an attempt to obtain a good spray dispersion and at the same time to keep the spray tubes de-iced. For the first installation a single nozzle bar was mounted horizontally in front of the fan blades and one in a corresponding position was mounted at the leading edge of the stator vanes. For the second installation two spray nozzle bars located approximately 45° apart were similarly mounted in front of the fan blades and two spray nozzle bars were also mounted at the leading edge of the stator vanes. This second configuration was used to obtain a greater coverage of alcohol on the stator vanes and to accommodate greater flows. A variable-control alcohol pump provided flow rates up to 2.3 pounds per minute.

Electrical-heat de-icing installation. - The use of electric heaters for de-icing was confined to the fan blades and stator vanes, as shown in figure 5. Because of the large number of blades and the anticipated large power requirements, only a few of the blades were so heated. The blade heaters were similar to propeller-blade de-icing heaters and consisted of parallel chordwise

electrical resistance wires enclosed between two layers of neoprene cemented to cover the entire chord of both blade faces. Because the heaters were rectangular, they did not fully protect the inner ends of the fan-blade leading edges. Heaters were applied to twelve of the 72 fan blades, arranged in two groups of six consecutive blades diametrically opposite and to six consecutive stator vanes. The heated area on each fan blade was 21.3 square inches with a resistance of 12 ohms per blade; the heated area on a stator vane was 39 square inches with a resistance of 16 ohms per vane.

The power density of the heaters was uniform. The twelve heaters on the fan blades were connected in series in one circuit and the six heaters on the stator vanes were also series-connected in a second circuit. Power to the blade heaters was metered through a variable resistance and transmitted to the fan through a slip ring mounted on the propeller hub behind the fan. An electronic cycle timer permitted the cyclical application of power to the blade heaters.

CONDITIONS AND PROCEDURE

The investigation was conducted in three parts to determine: (1) fan performance in clear air, (2) effect of icing on fan performance, and (3) effectiveness of several icing protection systems.

Speed and performance conditions. - The investigation was made at fan speeds and airspeeds corresponding to rated power, cruise power, and rated-power climb conditions of the airplane for which this particular fan was designed. Because of the slow response of the available propeller governor, the entire program was made in fixed propeller pitch with manual throttle speed control. The tunnel airspeeds were the highest that could be obtained in the diffuser section of the icing research tunnel but in some cases were slightly less than the corresponding flight airspeeds. In addition, it was impossible to maintain a constant airspeed for all icing conditions because of icing of the tunnel. Baffle plates of three different sizes were used to obtain the required pressure drop and cooling-air flow for each of the power conditions tested. The airplane thrust axis was at an angle of attack of 0° for the entire investigation.

Calibration of tunnel-icing conditions. - The icing conditions were defined by the ambient-air temperature and liquid-water content of the air. Figure 6 presents the variation of liquid-water content

with air temperature at the face of the cooling fan as determined by a survey conducted in the diffuser section of the icing research tunnel and a comparison of these conditions with the values recommended by the NACA Subcommittee on De-Icing Problems and by the Mt. Washington Weather Bureau meeting on June 19, 1945. The subcommittee values are one-half of the recommended maximum values and are for average or typical icing. Vertical cylinders rotating about their axes were installed in the diffuser section and, from measurements of the local velocity and the ice accumulation per unit time on these cylinders, the average liquid-water content in grams per cubic meter for each condition of tunnel air velocity, ambient-air temperature, and spray-water input pressure was computed by the method of Langmuir of the General Electric Company. Droplet size was also measured but no consistent correlation with air temperature was obtained. An average droplet size of 55 microns was obtained in the icing research tunnel for the range of air temperature of 0° to 32° F as compared with the recommended averages of 10 and 30 microns, respectively, at these temperatures. This variation in droplet size was not considered important, however, because the collection efficiency of small objects such as the thin fan blades and stator vanes is known to be very close to 100 percent. Although the liquid-water concentrations are slightly less than the recommended values for most of the temperature range, the experimental values are nevertheless representative of moderate-to-light icing conditions encountered in the United States. This survey was made approximately 3 months before the cooling-fan investigation. Although time limitations prevented any extensive checks of the liquid-water content and distribution, visual observations of the spray cloud and icing of the installation and tunnel, together with readings of spray-water input pressures, indicated that the icing conditions were fairly constant and in fairly close agreement with the indicated values for the cooling-fan investigation. A velocity survey made after this investigation indicated, however, that the icing of the contraction section of the tunnel resulted in an increase in the thickness of the tunnel boundary layer with a corresponding increase in the velocity at the center of the tunnel. In addition to the change in velocity distribution, this increase in boundary layer also caused some changes in liquid-water content and distribution.

Clear-air calibration of fan. - Because of the difficulty of heating the shielded total-pressure tubes in front of the fan during the icing investigation, a calibration was made under nonicing conditions to determine the variation in air-flow total pressure at the fan inlet with tunnel airspeed, fan speed, and baffle pressure drop.

Subsequent icing studies were then made without the fan-inlet total-pressure tubes. As indicated in the discussion of the tunnel-icing calibration, the icing of the tunnel throat caused a change in the air flow at the face of the fan and hence the calibrated values of inlet total pressure were somewhat different from those that actually occurred under icing conditions. From subsequent measurements, it is estimated, however, that the variation in total pressure with icing in the area of the cooling fan was not more than 3 percent, which would result in an error of 15 to 20 percent in the measured pressure differential through the fan.

Icing. - The general procedure for the icing investigation was as follows: After stabilizing the air temperature, tunnel airspeed, and fan speed at the desired conditions, the icing spray was started. All data were recorded at 1-minute intervals and visual observations of the icing were continuously made using the stroboscopic light system. The length of each icing experiment was determined by the severity of the icing of the cooling-fan assembly and the drop-off in the tunnel-air velocity due to icing. Upon completion of each experiment, photographs were taken of the residual ice formation on the component parts of the fan assembly. A summary of the conditions for the icing investigation is given in table I. The conditions of air temperature, liquid-water content, fan speed, and tunnel airspeed are mean values.

Steam heating. - The procedure for the investigation using steam jets in the cowling lip was much the same as for icing. The effectiveness of both ice prevention and de-icing was investigated. In the first case, the steam and icing sprays were turned on at the same time and the effectiveness of ice prevention in the heated area was noted. During de-icing the fan assembly was allowed to ice for 5 minutes before application of the steam. The first configuration utilized a single steam line at the outside of the inlet duct and the second had an additional steam line inside the cowling lip. The steam-heating conditions were: tunnel airspeed, 214 feet per second; air temperature, 14° F; liquid-water content, 0.5 gram per cubic meter; fan speed, 900 rpm; icing time, 5 minutes; steam pressure, 3 pounds per square inch.

Alcohol de-icing. - For alcohol de-icing protection, the icing sprays and alcohol sprays were started simultaneously and the alcohol was turned off 30 seconds after the icing sprays. The investigation was made under various icing and performance conditions for different alcohol flows and spray configurations. Because only a part of the stator blades were de-iced, no pressure measurements were made. A summary of the conditions is given in table II.

Electrical-heat de-icing. - With the electric blade heaters, only cyclical de-icing was investigated with heat-on and heat-off periods of 30 seconds. Because of the anticipated large power requirements and the limitations of present aircraft generators, cyclical heating seemed to be the most practical method of electrical heating for investigation in the limited time available. With cyclical heating, several groups of blades can be successively heated and the generator capacity is considerably less than when simultaneously heating all the blades. No pressure measurements were made because only a few of the blades were heated. The icing sprays and heat were simultaneously started. A summary of the conditions for this investigation is given in table III.

RESULTS AND DISCUSSION

The results of the investigation are presented in terms of the fan-performance coefficients C_P and C_Q and by photographs of icing and de-icing. The fan-pressure coefficient is defined as $C_P = \frac{\Delta P}{\frac{\rho}{2}(\pi\ nd)^2}$ and the air-flow coefficient as $C_Q = \frac{Q}{nd^3}$

where

d fan-tip diameter, feet

n fan speed, rps

ΔP pressure rise through fan assembly $(P_2 - P_1)$, pounds per square foot

P_1 total pressure at front of fan, pounds per square foot

P_2 total pressure at rear of fan assembly, pounds per square foot

Q cooling-air flow, cubic feet per second

ρ cooling-air mass density, slugs per cubic foot

Icing. - Photographs showing typical icing of the fan assembly at the conditions tested are shown in figures 7 to 12. The effects of icing on fan performance are shown in figures 13 and 14 where the ratios of the air flow and fan pressure of the iced fan to that

of the fan before icing $\frac{C_Q}{C_{Q,0}}$ and $\frac{C_P}{C_{P,0}}$, respectively, are plotted against icing time. Although insufficient data were available to compare the effects of icing at all icing and performance conditions, the results shown in figures 13 and 14 are complete enough to define the effects of icing on fan performance throughout the normal range of icing and performance conditions. The minimum air flow required for adequate engine cooling is indicated in figure 13 as computed from data supplied by the engine manufacturer.

The only condition at which the air-flow coefficient ratio did not markedly decrease was at an air temperature of 2° F, liquid-water content of 0.3 gram per cubic meter, and fan speed of 872 rpm (fig. 13). Photographs of icing at these conditions (fig. 7) show only a negligible ice build-up on both the fan blades and stator vanes. At 16° F, 0.5 gram per cubic meter, and 897 rpm, the air-flow coefficient ratio decreased, approaching the minimum required value in 5 minutes; whereas at 14° F, 0.5 gram per cubic meter, and 1060 rpm the flow-coefficient ratio fell to the minimum required value in $3\frac{3}{4}$ minutes, continued to decrease, and reached a fairly stable value after 6 minutes. Photographs of typical icing at these two conditions (figs. 8 and 9) show relatively light icing of the stator vanes at both speeds with most of the ice on the leading edge and concave face of the fan blades and extremely large formations at the higher fan speed. At approximately the same fan speeds, as the experiments at 897 and 1060 rpm, and at 23° F, and 0.9 gram per cubic meter, the cooling-air-flow coefficient fell off sharply, reaching the minimum required value in 2 to 3 minutes, and continued to decline with a complete stoppage of the flow occurring in 5 to 6 minutes. Photographs of typical icing at these conditions (figs. 10 and 11) show relatively little ice on the fan blades with the stator vanes completely blocked by very heavy formations.

The variation in the pressure-coefficient ratio at the same speed and icing conditions (fig. 14) exhibited similar trends. At 14° and 16° F (figs. 8, 9, and 14), the decrease in pressure coefficient was primarily due to icing of the fan blades.

Although no performance data were obtained at 17° F and 0.7 gram per cubic meter, visual observations revealed serious icing at this condition. As shown by the photographs in figure 12, heavy icing of the fan blades was obtained with medium formations

on the thrust face and leading edge of the stator vanes. At one time during this run, stroboscopic observations showed the fan blades to be fully bridged over but much of this ice was later thrown off.

In addition to the fan and stator blades, several other components of the fan assembly were subject to icing. As shown in the icing photographs, the fan-disk dishpan accumulated ice in varying degrees. For most conditions, this icing was fairly light, never exceeding three-eighths inch in thickness. With the exception of runs at an air temperature below 5° F, this ice was periodically thrown off in irregular patterns. Although the dishpan is of small diameter, this irregular throw-off of ice could contribute to propeller unbalance in icing conditions particularly at higher fan speeds. Heavy icing of the engine cowling lip and the inlet duct at the fan-blade tips was obtained at several icing conditions (figs. 10 and 11). Icing of the dishpan, cowling lip, and inlet duct had no noticeable effect on the fan performance.

Steam-heat de-icing. - The results of a brief qualitative investigation of the use of steam for de-icing the cowling lip and inlet duct are shown in figure 15. Figure 15(a) shows the results of de-icing with a single steam line placed outside the inlet duct at the tip of the fan blades. The heated area started to throw off ice 50 seconds after the steam was turned on and all the ice was removed within 2 minutes with the heated area remaining clear thereafter. In a delayed de-icing run with the same configuration, steam was turned on after 5 minutes of icing and the ice in the heated area was thrown off within 30 seconds. With the double steam line installed (fig. 15(b)), a slightly greater area including the lip of the engine cowling was de-iced in the same time. From these results, it appears that the de-icing of these areas by means of hot gases is entirely feasible.

Alcohol de-icing. - The results of the use of alcohol sprays are shown in figures 16 to 20. At an alcohol flow of 0.5 pound per minute and with the initial spray configurations, fairly good de-icing of the fan blades was obtained at an air temperature of 13° F and liquid-water content of 0.4 gram per cubic meter (fig. 16). A fairly heavy accumulation of slush was retained, however, on several stator vanes that were concave upward. At a higher air temperature and water content and with the same alcohol flow (fig. 17), the fan blades were only partly de-iced and all the stator vanes were partly blocked by similar deposits of slush. When the alcohol flow was increased to 1.2 pounds per minute at

approximately the same icing and speed conditions and with the second spray configuration, no improvement in de-icing was apparent (fig. 18). Although the convex face of the fan blades was almost completely clear of ice, heavy deposits of slush were as much as three-fourths inch thick at the concave-face trailing edge. The stator vanes again had large formations of wet ice and were approximately 50-percent blocked. At a medium icing condition (air temperature, 14° F and liquid-water content, 0.5 gram/cu m) and an alcohol flow of 1.5 pounds per minute, the fan blades were almost fully de-iced. (See fig. 19.) Medium formations of wet ice were found on the stator vanes immediately behind the spray tubes and only a thin coating of ice was found on the rest of the stator blades. When the alcohol flow was increased to 2.3 pounds per minute, the fan blades were again almost completely de-iced (fig. 20). Large deposits accumulated, however, on all the stator vanes. As shown by the photographs of all the alcohol de-icing (figs. 16 to 20), the alcohol-diluted ice thrown off the fan blades impinged on the stator vanes where it remained and refroze. For all conditions, configurations, and flows investigated, the use of alcohol as a de-icing agent proved ineffective because of the marginal de-icing of the fan blades and the large ice deposits obtained on the stator vanes. It is estimated that no practical amount of alcohol would satisfactorily preserve fan performance under all icing conditions.

Electrical heat de-icing. - Photographs showing the results of the use of electric blade heaters are presented in figures 21 to 25. As only a few of the fan blades and stator vanes were heated, no fan-performance data were obtained. With an air temperature of 15° F, liquid-water content of 0.5 gram per cubic meter, fan speed of 954 rpm, and a power density of 5 watts per square inch, fairly complete de-icing of the heated fan blades resulted. (See fig. 21.) The small amount of ice at the root of the leading edge was caused by ice bridging over from an unheated part of the blade. It should be noted that the group of heated fan blades behind propeller blade 1 were partly shielded from icing by the blade shank. The de-icing of the stator vanes was only marginal with rough ice building up near the trailing edge. When the power density was increased to 6 watts per square inch (fig. 22), some improvement in the de-icing of the stator vanes resulted but rough ice still collected at the trailing edge. At a higher temperature and liquid-water content (fig. 23), complete de-icing of the heated fan blades was obtained after 5 minutes of icing. The de-icing of the stator vanes was again marginal. The effects of electrical heating at two icing conditions, each of 10-minute duration, are shown in figures 24 and 25. Both

experiments were made at power densities of 6 watts per square inch with the fan blades almost completely de-iced. At the lower temperature, the de-icing of the stator vanes was marginal and at the higher temperature and liquid-water content, the de-icing of the stator vanes was completely ineffective.

The investigation of the use of blade heaters at other power densities, heat-on and cycle times was prevented by electrical failures and time limitations. The electrical heat de-icing tests indicated that 6 watts per square inch should be the minimum power density for the fan blades. From observations of the ice throw-off time, it is estimated that the heat-on time for the fan blades might be slightly reduced. Continuous anti-icing would probably provide the best means of protection for the stator vanes. The accumulation of rough ice at the trailing edge of the stator vanes indicates the occurrence of runback caused by the melted ice flowing toward the rear of the vanes and then refreezing during the heat-off period. Power requirements for the stator vanes may be even higher than indicated by this investigation as only one sixth of the fan blades were heated, thus reducing the amount of ice that would be caught by the stator vanes with full protection of the fan blades. Power economies might be affected by increasing the cycle time for the whole assembly but the icing runs indicate that a heat-off time of more than 2 minutes would result in a serious loss in fan performance for the range of icing conditions investigated.

SUMMARY OF RESULTS

The results of an icing investigation of a conventional radial-engine cooling-fan installation in the icing research tunnel indicate that:

1. The icing of the unprotected installation presents a serious operational problem. Reduction in air flow below the minimum value required for adequate engine cooling occurred within 2 minutes and complete stoppage of the cooling-air flow through the fan assembly occurred within 5 minutes under normal icing conditions.

2. Steam de-icing of the cowling lip and inlet duct showed the feasibility of hot gas de-icing for this portion of the assembly.

3. Alcohol de-icing of the fan proved to be ineffective and, in some cases, increased the icing problem by causing large formations on the stator vanes.

4. Electrical heat de-icing was the most promising method of de-icing the blades. The fan blades required a minimum power density of 6 watts per square inch but for the stator vanes this power density proved insufficient.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 10, 1947.

TABLE I - CONDITIONS FOR ICING INVESTIGATION

OF AN ENGINE COOLING FAN

Figure	Tunnel air-speed (ft/sec)	Tunnel air temper-ature (°F)	Fan speed (rpm)	Nominal cooling-air flow (cu ft/min)	Liquid-water content (gram/cu m)	Icing time (min)
7	210	2	872	54,000	0.3	5
8	220	16	897	22,000	.5	5
9	217	14	1060	30,000	.5	10
10	222	23	872	21,000	.9	5
11	222	23	1065	22,000	.9	7
12	213	17	872	22,000	.7	5
------	214	13	874	21,000	.4	5
------	220	14	905	20,000	.5	5
------	220	16	917	23,000	.5	5
------	220	17	892	20,000	.6	5
------	217	25	852	23,000	1.0	5
------	219	26	872	22,000	1.1	5

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TABLE II - CONDITIONS FOR ALCOHOL DE-ICING INVESTIGATION

OF AN ENGINE COOLING FAN

Figure	Tunnel air-speed (ft/sec)	Tunnel air temper-ature (°F)	Fan speed (rpm)	Nominal cooling-air flow (cu ft/min)	Liquid-water content (gram/cu m)	Icing time (min)	Alcohol flow (lb/min)
16	218.5	13	895	23,000	0.4	5	0.5
17	217	25	875	23,000	1.0	5	.5
18	219	24	950	23,000	1.0	5	1.2
19	218.5	14	952	23,000	.5	5	1.5
20	218.5	13	950	23,000	.5	5	2.3

TABLE III - CONDITIONS FOR ELECTRICAL-HEAT DE-ICING

INVESTIGATION OF AN ENGINE COOLING FAN

Fig-ure	Tunnel air-speed (ft/sec)	Tunnel air temper-ature (°F)	Fan speed (rpm)	Liquid-water content (gram/cu m)	Icing time (min)	Power density (watt/sq in.)	Heat-on time (sec)	Cycle time (sec)	Nominal cooling-air flow (cu ft/min)
21	218	15	954	0.5	5	5	30	60	23,000
22	218	16	950	.6	5	6	30	60	23,000
23	221	28	950	1.2	5	6	30	60	23,000
24	216	14	950	.5	10	6	30	60	23,000
25	221	22	952	1.0	10	6	30	60	23,000

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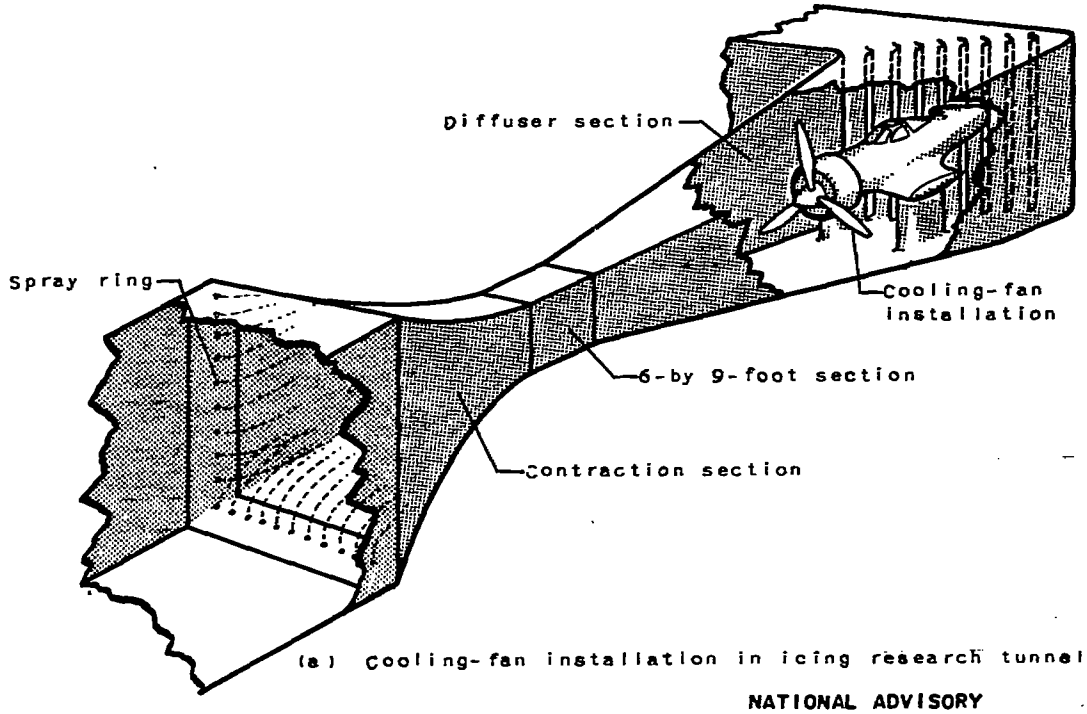

(a) Cooling-fan installation in icing research tunnel.

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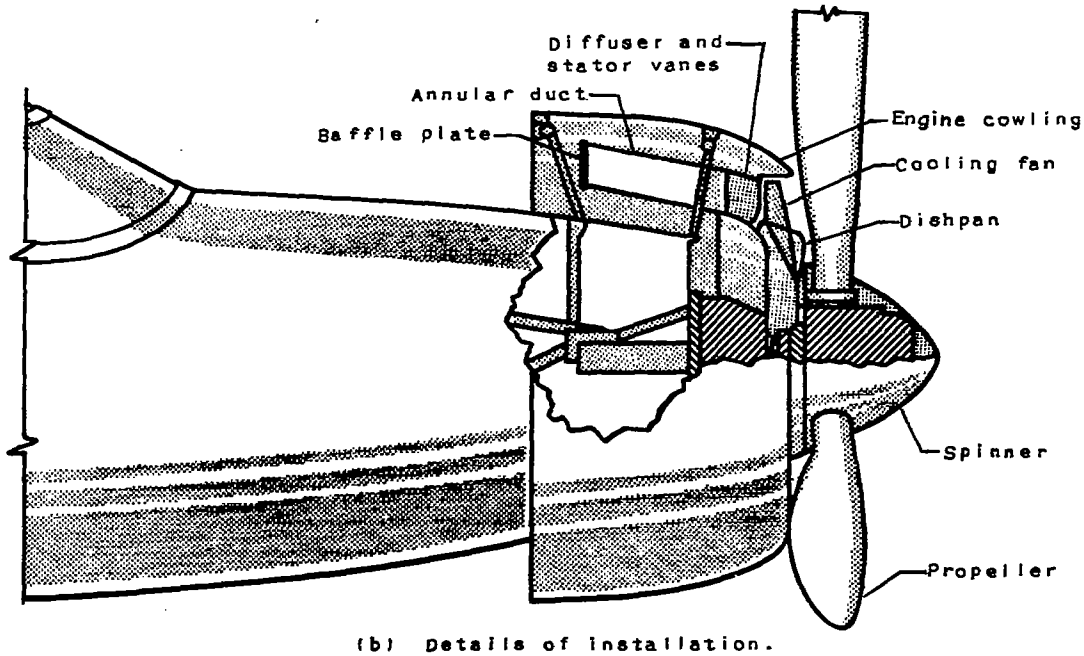

(b) Details of installation.

Figure 1. - Engine cooling-fan installation.

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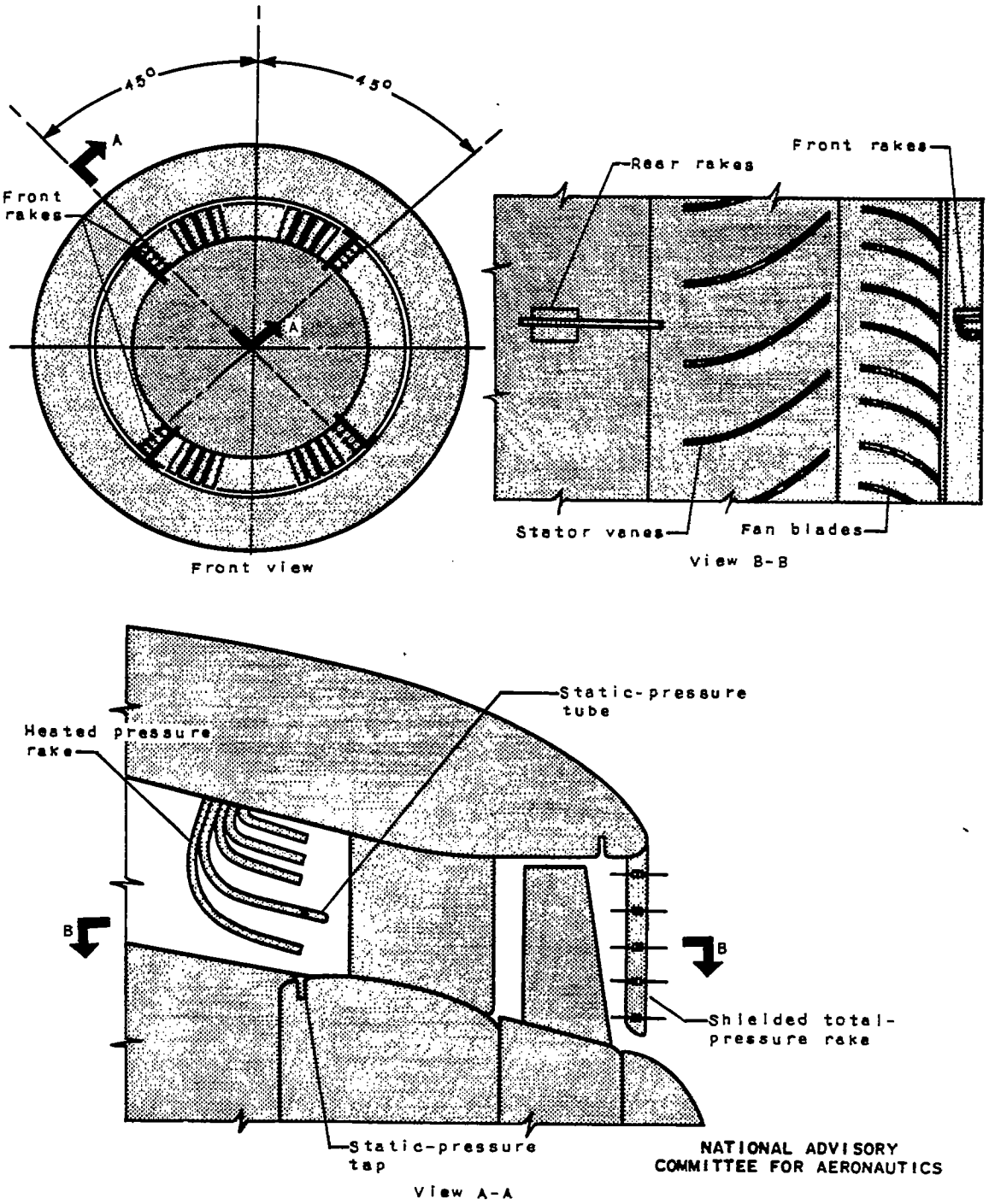

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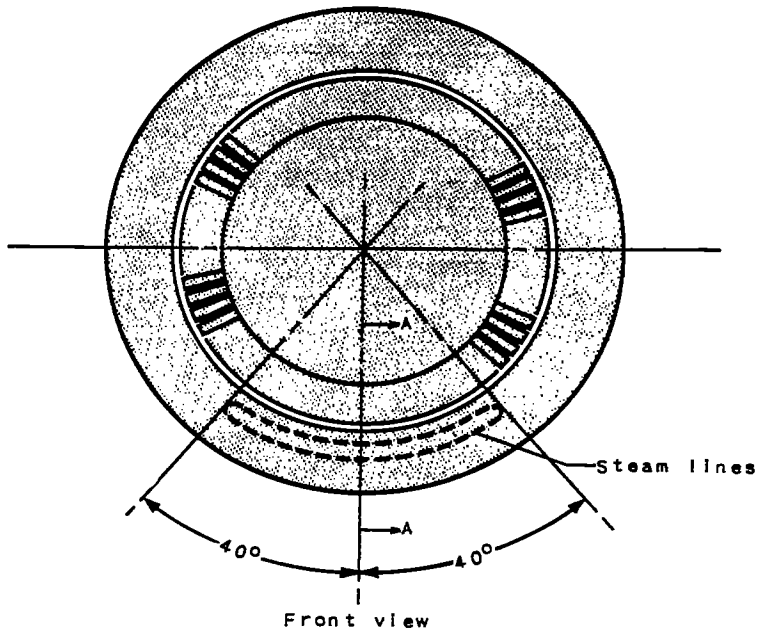
Figure 2. - Location of pressure-tube rakes in cooling-fan installation.



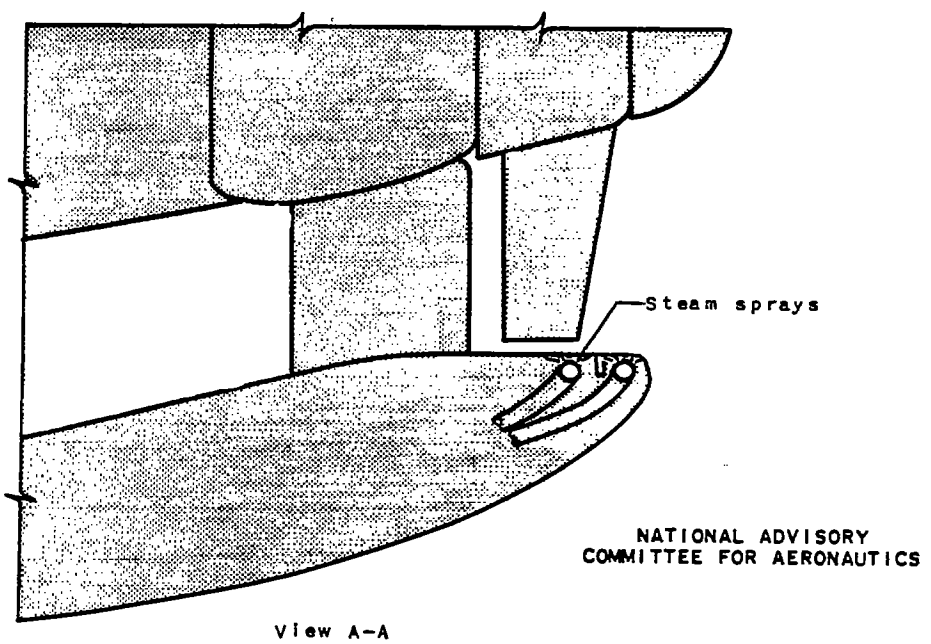


Figure 3. - Location of steam lines in cooling-fan installation.

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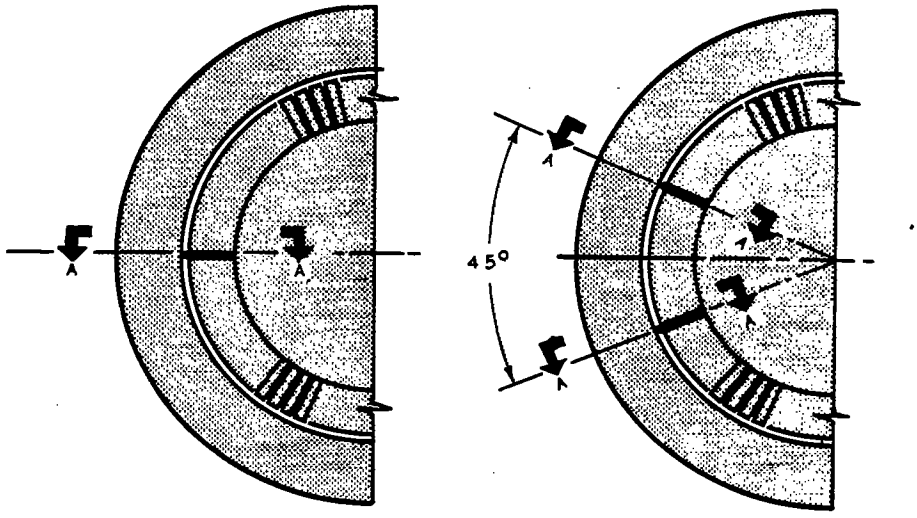

First spray-nozzle-bar installation

Second spray-nozzle-bar installation

Front view

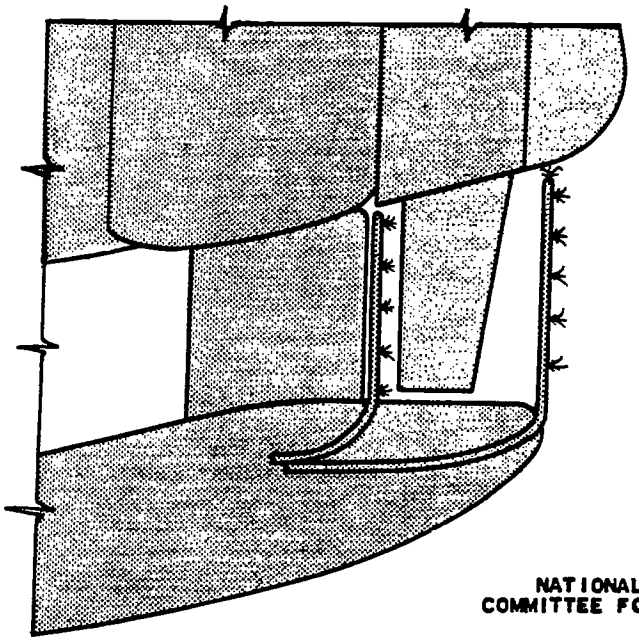

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Figure 4. - Location of alcohol spray nozzle bars in cooling-fan installation.

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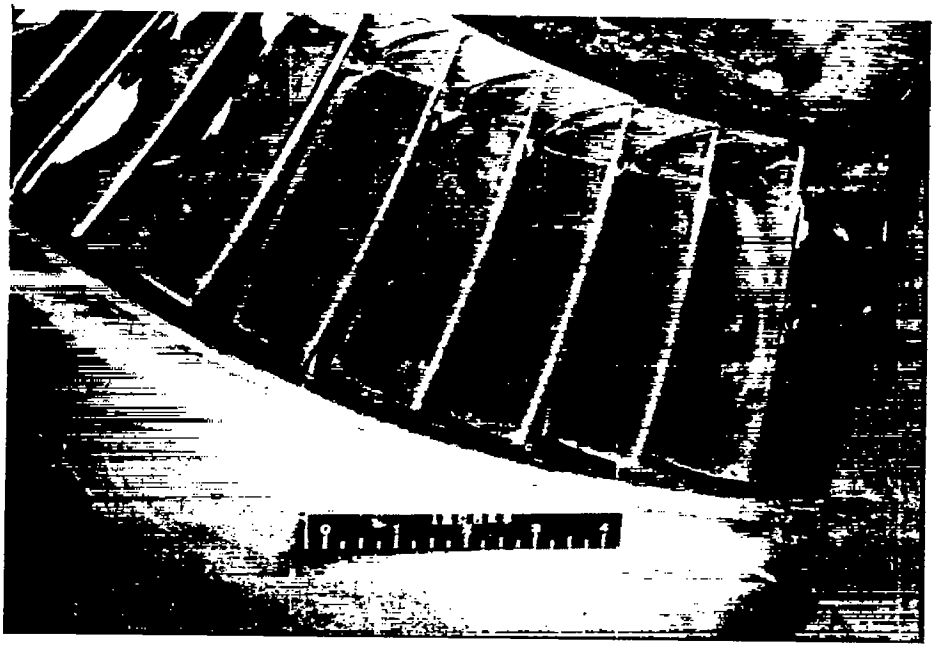

(a) Heaters on fan blades.

(b) Heaters on stator vanes.

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Figure 5. - Electric blade heaters in cooling-fan installation.

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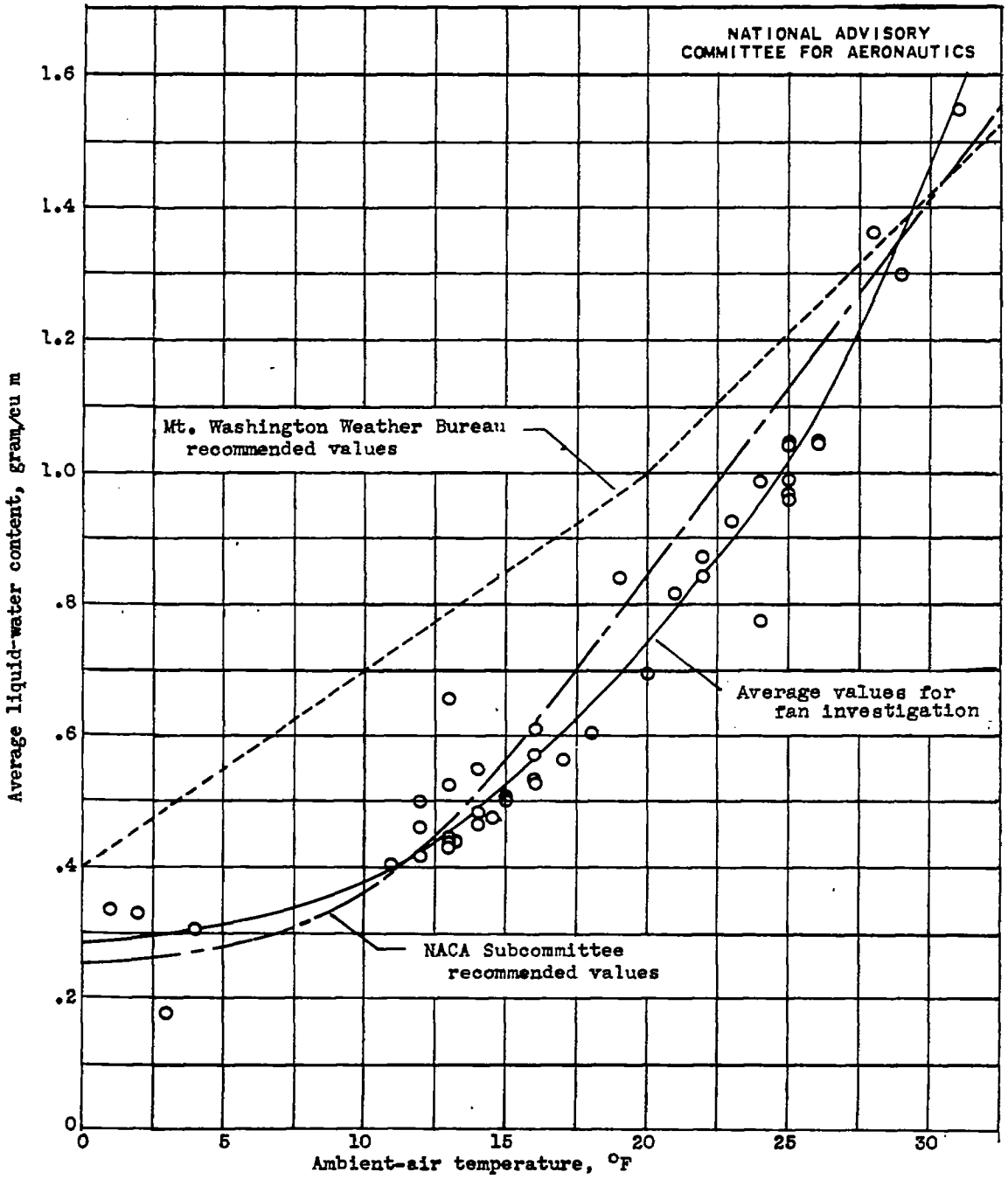
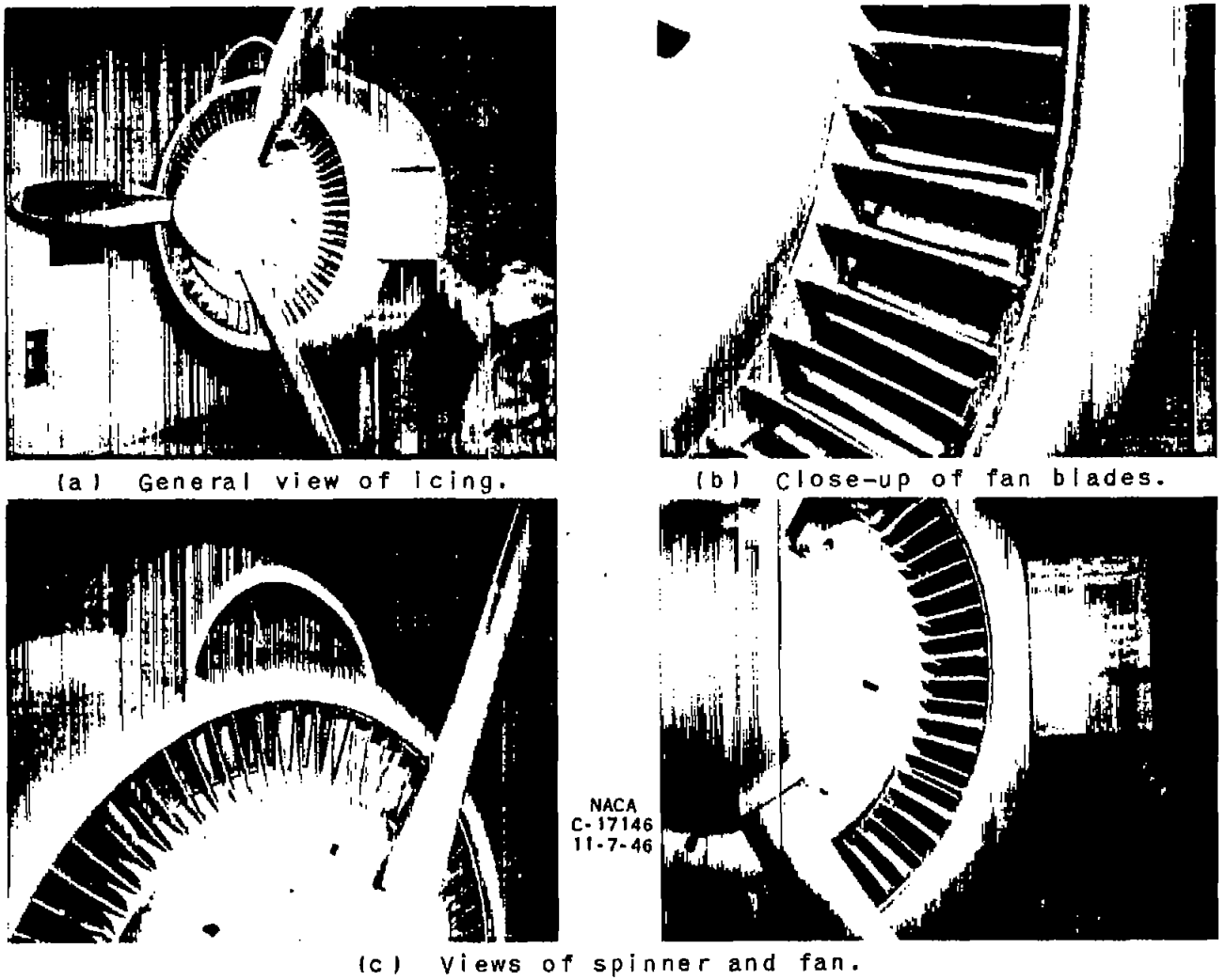


Figure 6. - Comparison of liquid-water content in icing research tunnel with recommended values.

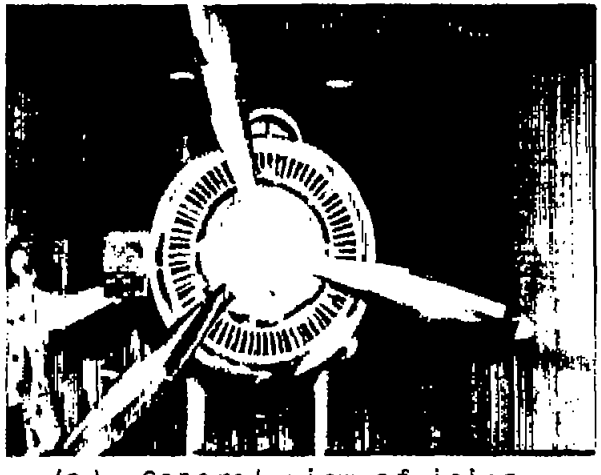


(a) General view of icing.

(b) Close-up of fan blades.

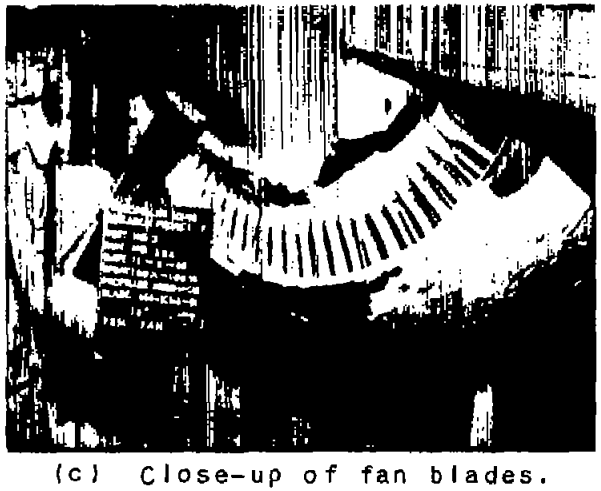
(c) Views of spinner and fan.

Figure 7. - Ice formations on cooling-fan installation after 5-minute run at air temperature of 2°F, liquid-water content of 0.3 gram per cubic meter, and fan speed of 872 rpm.



(a) General view of icing.

(b) View of ice formations on fan and spinner.



(c) Close-up of fan blades.

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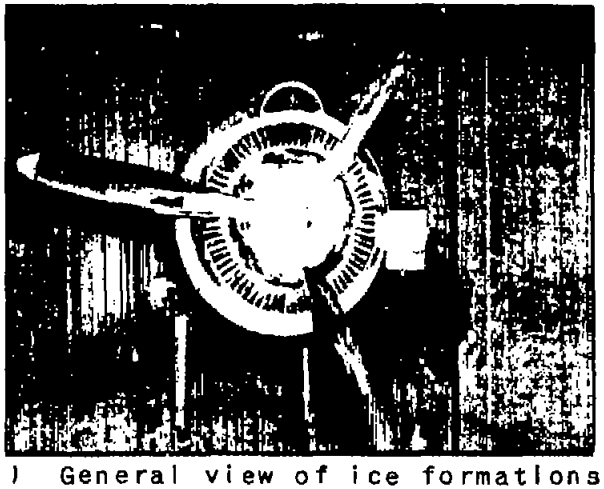
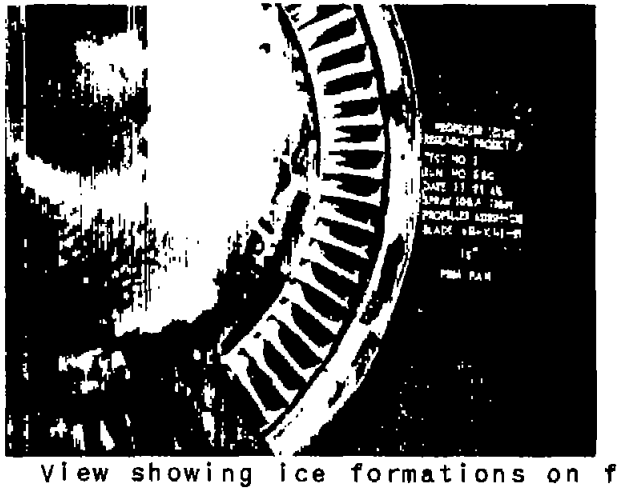
(d) View looking forward showing ice formations on stator vanes.

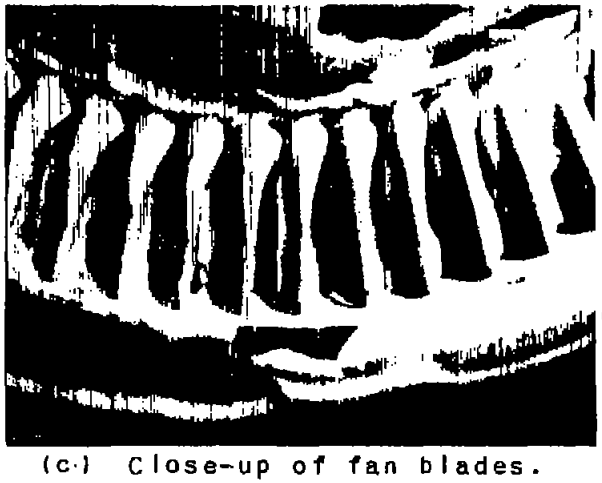
Figure 8. - Ice formations on cooling-fan installation after 5-minute run at air temperature of 16° F, liquid-water content of 0.5 gram per cubic meter, and fan speed of 897 rpm.



(a) General view of ice formations.



(b) View showing ice formations on fan blades.



(c) Close-up of fan blades.

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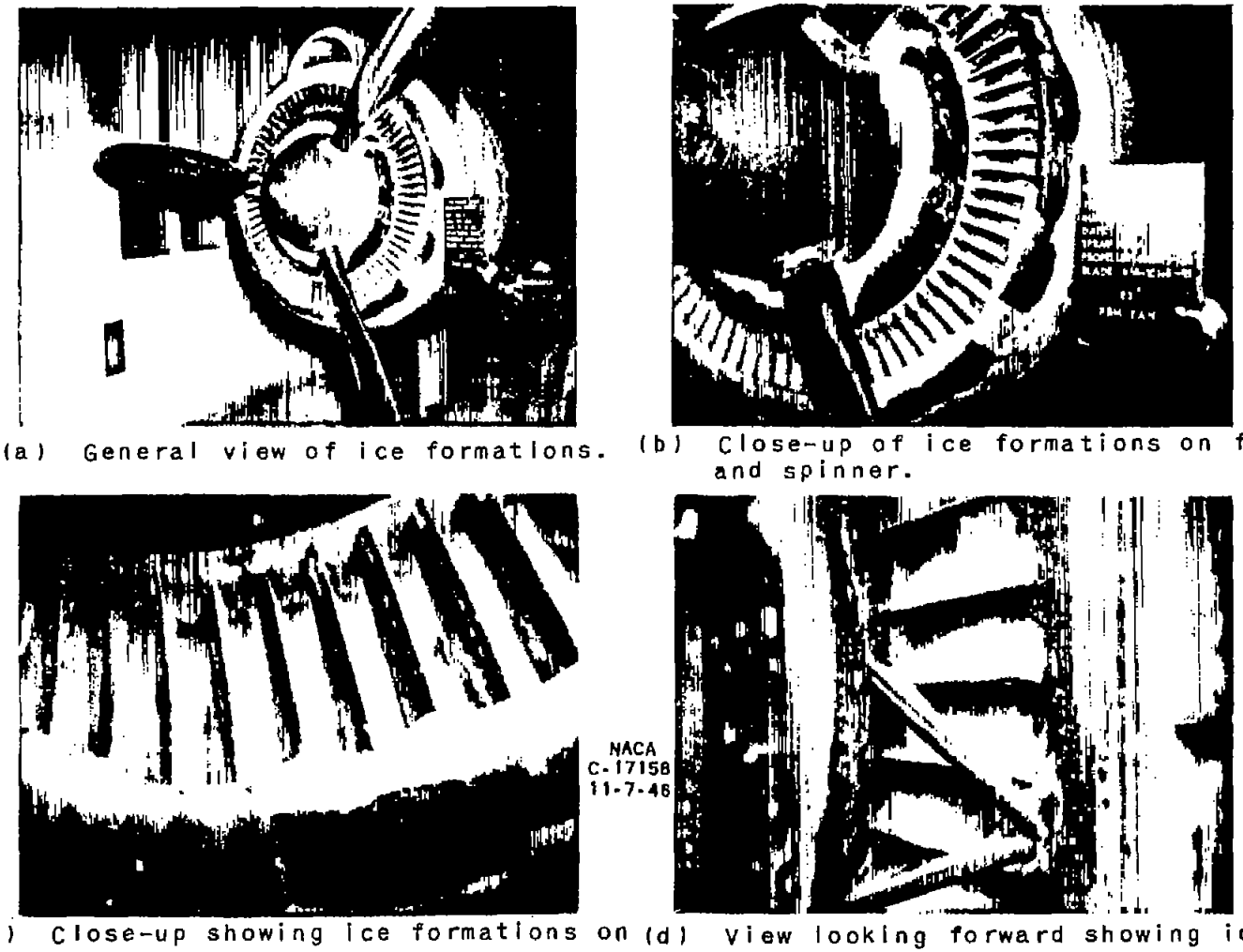
(d) View looking forward showing ice formations on stator vanes.

Figure 9. - Ice formations on cooling-fan installation after 10-minute run at air temperature of 14° F, liquid-water content of 0.5 gram per cubic meter, and fan speed of 1060 rpm.



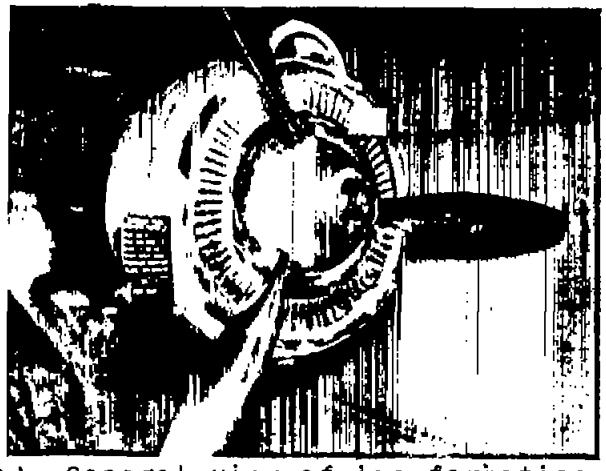
(a) General view of ice formations.

(b) Close-up of ice formations on fan and spinner.

(c) Close-up showing ice formations on fan blades and blocking of stator vanes.

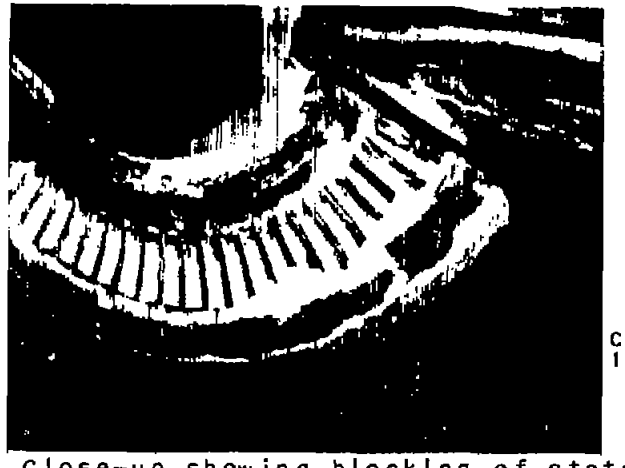
(d) View looking forward showing ice formations blocking stator vanes.

Figure 10. - Ice formations on cooling-fan installation after 5-minute run at air temperature of 23° F, liquid-water content of 0.9 gram per cubic meter, and fan speed of 872 rpm.



(a) General view of ice formations.

(b) Close-up of ice formations on fan blades.



(c) Close-up showing blocking of stator vanes.

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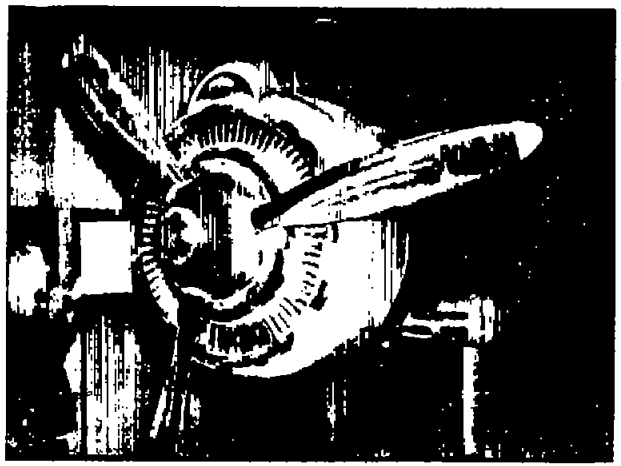
(d) View looking forward showing ice formations on stator vanes.

Figure 11. - Ice formations on cooling-fan installation after 7-minute run at air temperature of 23° F, liquid-water content of 0.9 gram per cubic meter, and fan speed of 1065 rpm.



(a) General view of ice formations.

(b) Close-up showing bridging of ice over fan blades.

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(c) Close-up showing blades that had thrown off ice.

Figure 12. - Ice formations on cooling-fan installation after 5-minute run at air temperature of 17° F, liquid-water content of 0.7 gram per cubic meter, and fan speed of 872 rpm.

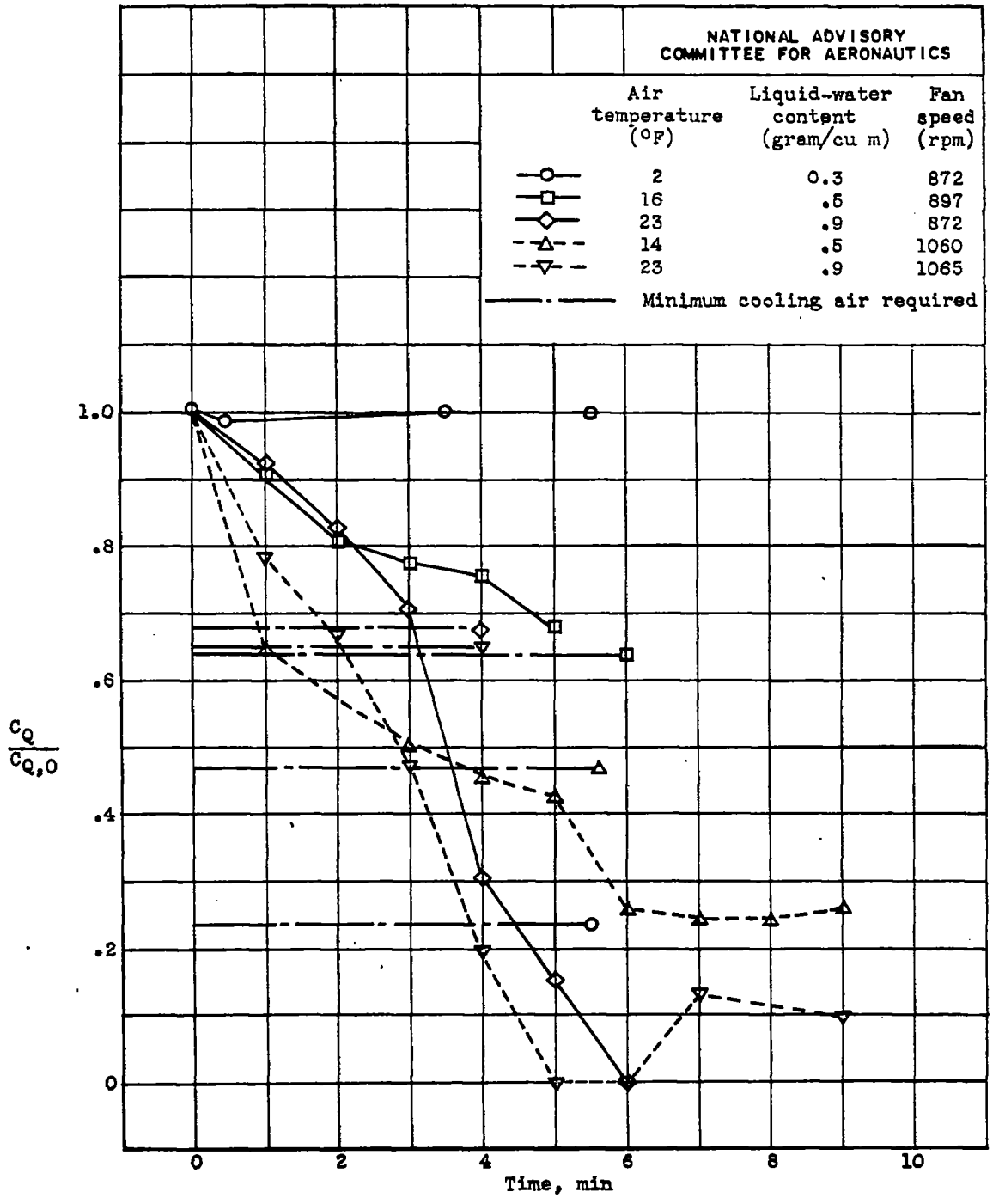

Figure 13. - Reduction in cooling-air-flow coefficient ratio for various icing and fan-speed conditions for investigation of cooling-fan installation.

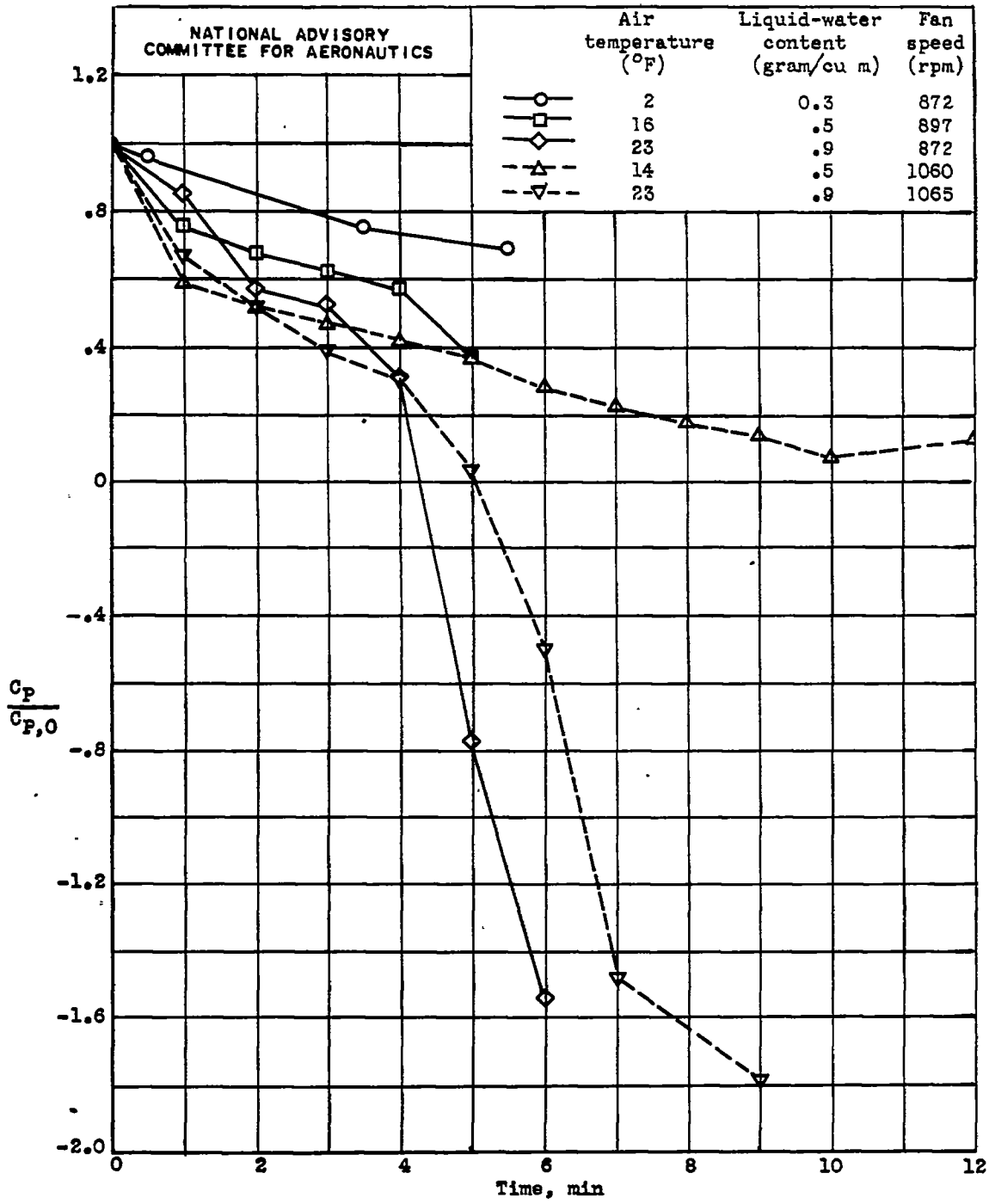

Figure 14. - Reduction in fan-pressure coefficient ratio for various icing and fan-speed conditions for investigation of cooling-fan installation.

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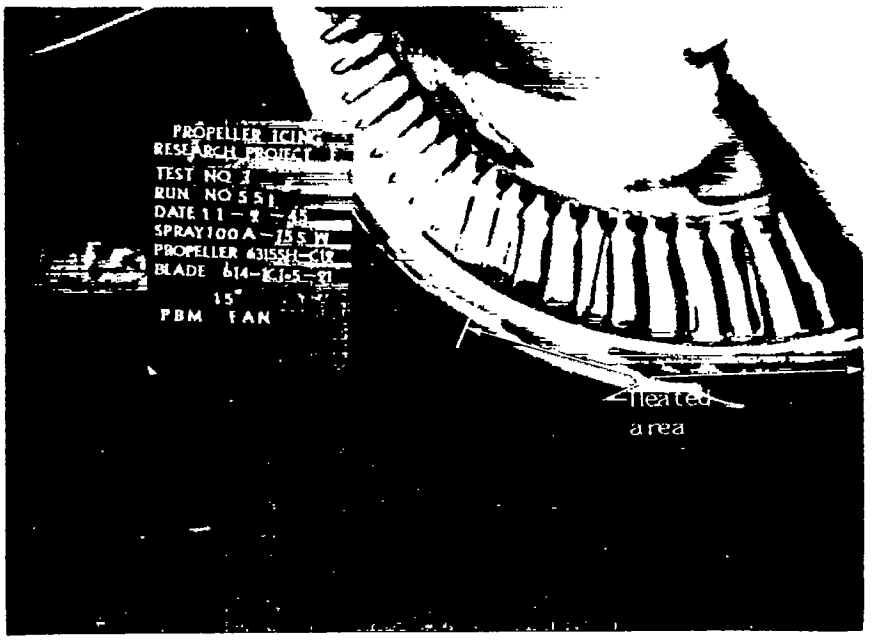
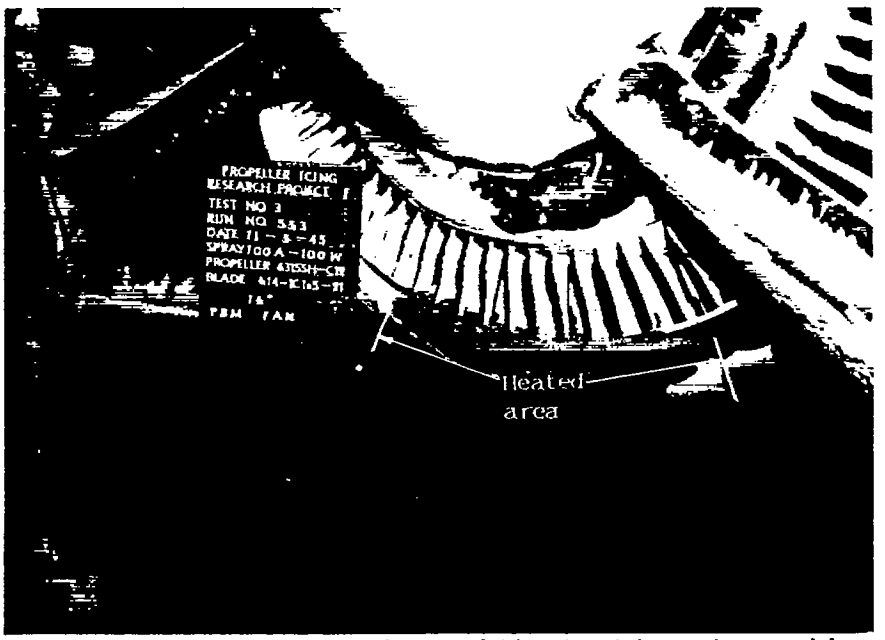


(a) Close-up showing de-icing with single steam line. Air temperature, 13° F; liquid-water content, 0.4 gram per cubic meter; fan speed, 874 rpm.



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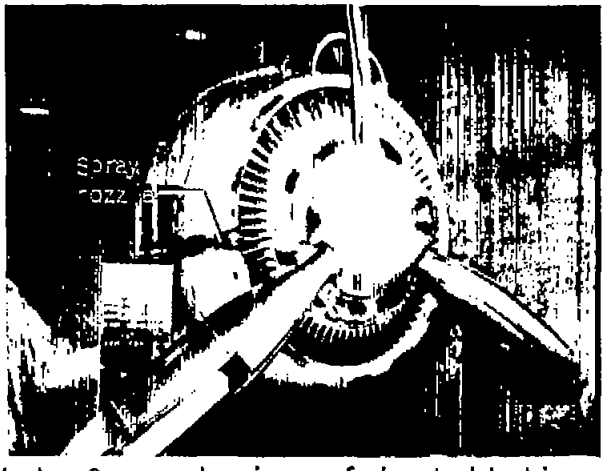
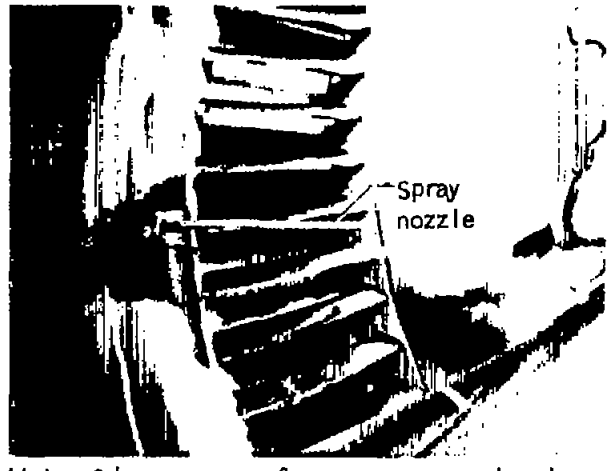
(b) Close-up showing de-icing with double steam line. Air temperature, 16° F; liquid-water content, 0.5 gram per cubic meter; fan speed, 917 rpm.

Figure 15. - Views showing effect of steam-heat de-icing of cowling and inlet duct in cooling-fan installation after 5 minutes of icing.



(a) General view of installation.



(b) Close-up of spray nozzle bar.

(c) Close-up of thrust face of fan blades.

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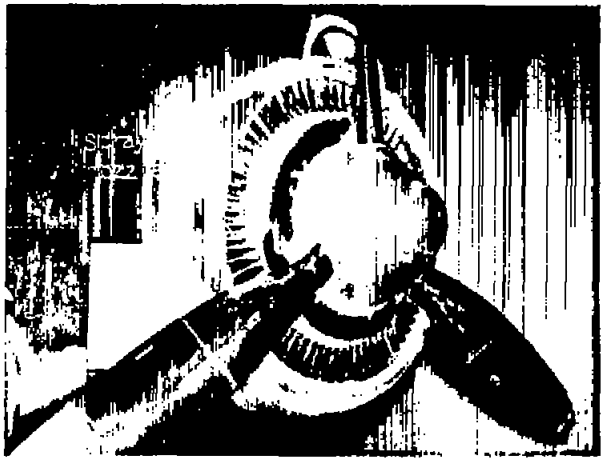
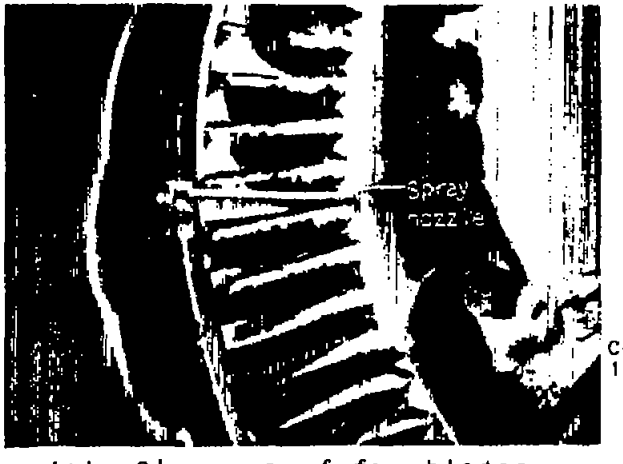
(d) View looking forward through stator vanes.

Figure 16. - Views showing effect of alcohol de-icing of cooling-fan installation at air temperature of 13° F, liquid-water content of 0.4 gram per cubic meter, fan speed of 895 rpm, and alcohol flow of 0.5 pound per minute.



(a) General view of installation.

(b) View showing ice formations on leading edge of stator vanes.



(c) Close-up of fan blades.

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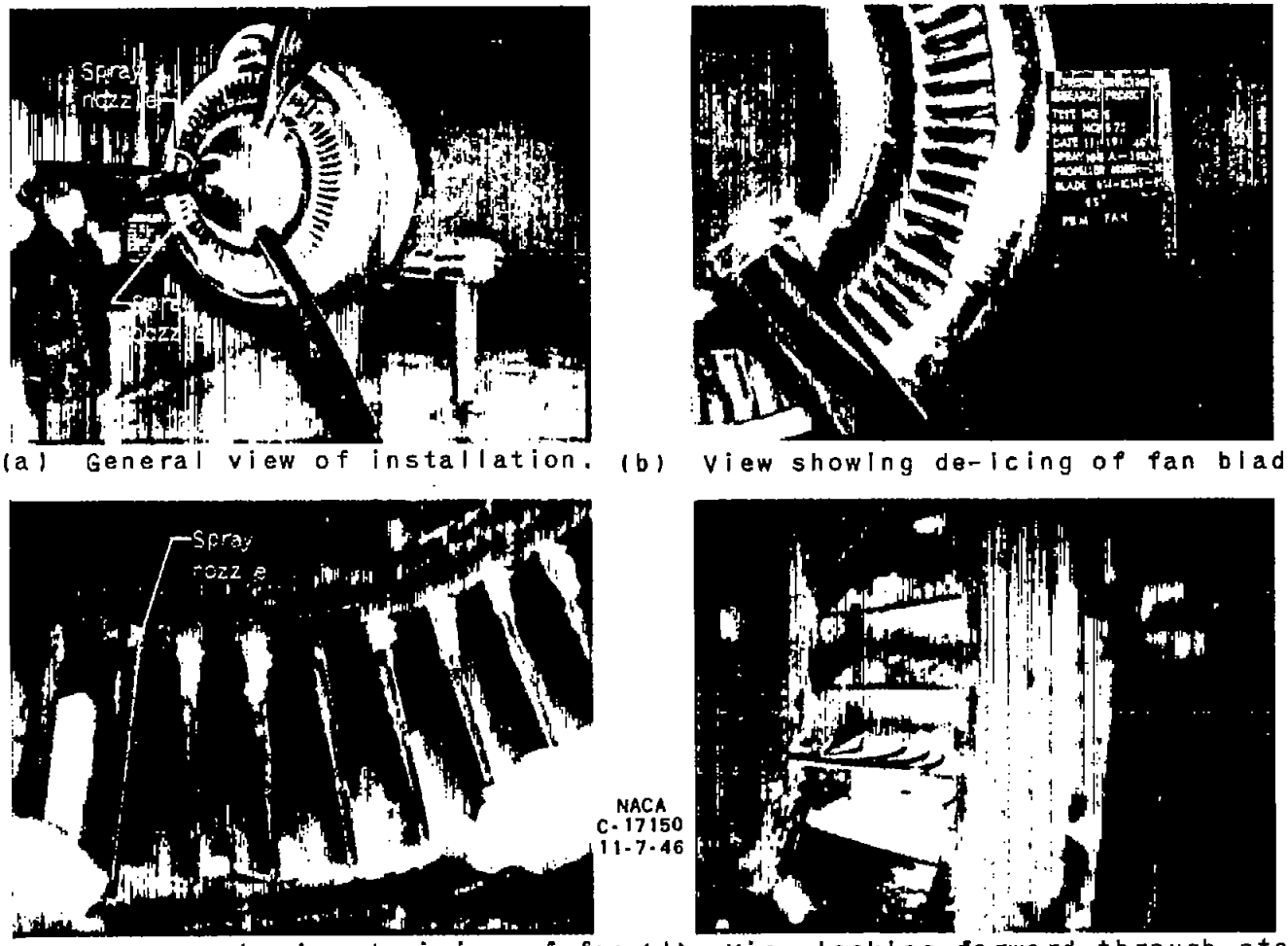
(d) View looking forward through stator vanes.

Figure 17. - Views showing effect of alcohol de-icing of cooling-fan installation at air temperature of 25° F, liquid water content of 1.0 gram per cubic meter, fan speed of 875 rpm, and alcohol flow of 0.5 pound per minute.



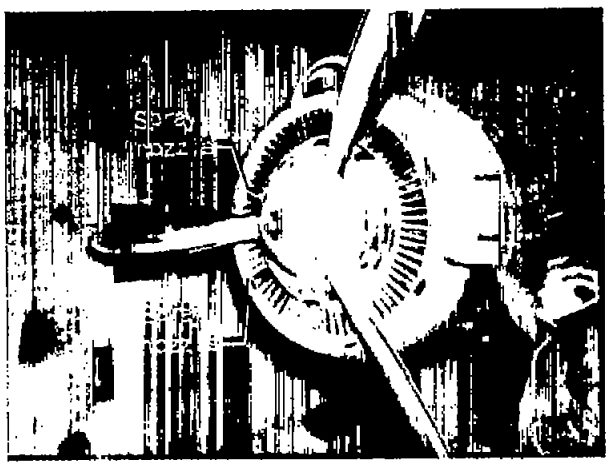
(a) General view of installation.

(b) View showing de-icing of fan blades.

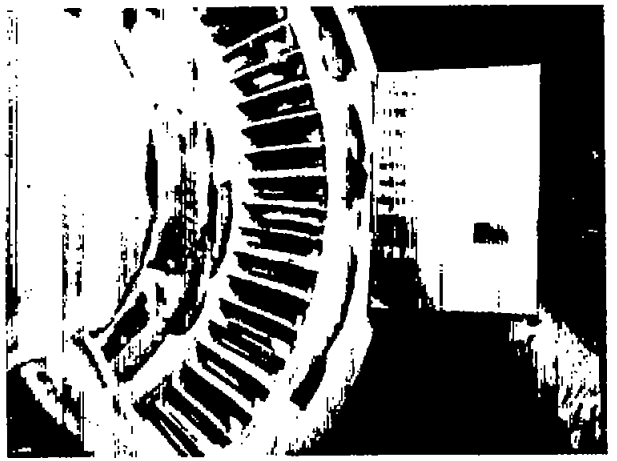
(c) Close-up showing de-icing of fan blades.

(d) View looking forward through stator vanes.

Figure 18. - Views showing effect of alcohol de-icing of cooling-fan installation at air temperature of 24° F, liquid-water content of 1.0 gram per cubic meter, fan speed of 950 rpm, and alcohol flow of 1.2 pounds per minute.



(a) General view of installation.



(b) View showing de-icing of fan blades.

(c) Close-up showing de-icing of fan blades.

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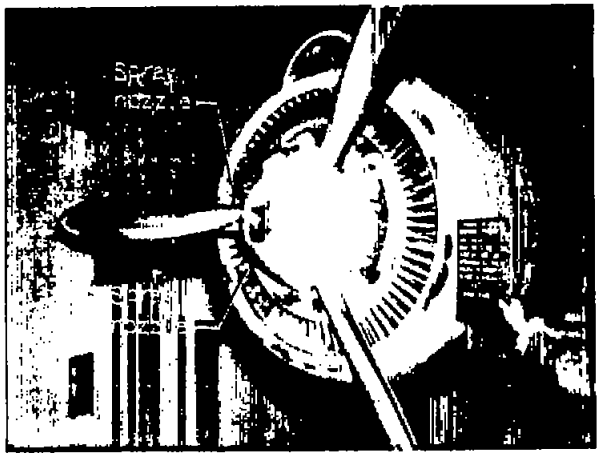
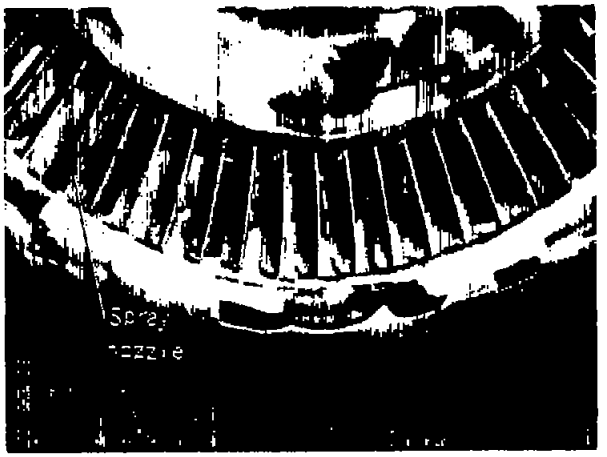
(d) View looking forward through stator vanes.

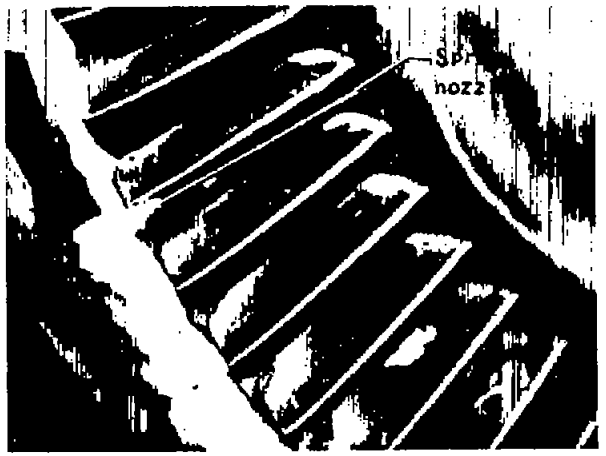
Figure 19. - Views showing effect of alcohol de-icing of cooling-fan installation at air temperature of 14° F, liquid-water content of 0.5 gram per cubic meter, fan speed of 952 rpm, and alcohol flow of 1.5 pounds per minute.



(a) General view of installation.



(b) View showing de-icing of fan blades and throwback on stator vanes.



(c) Close-up of fan blades.

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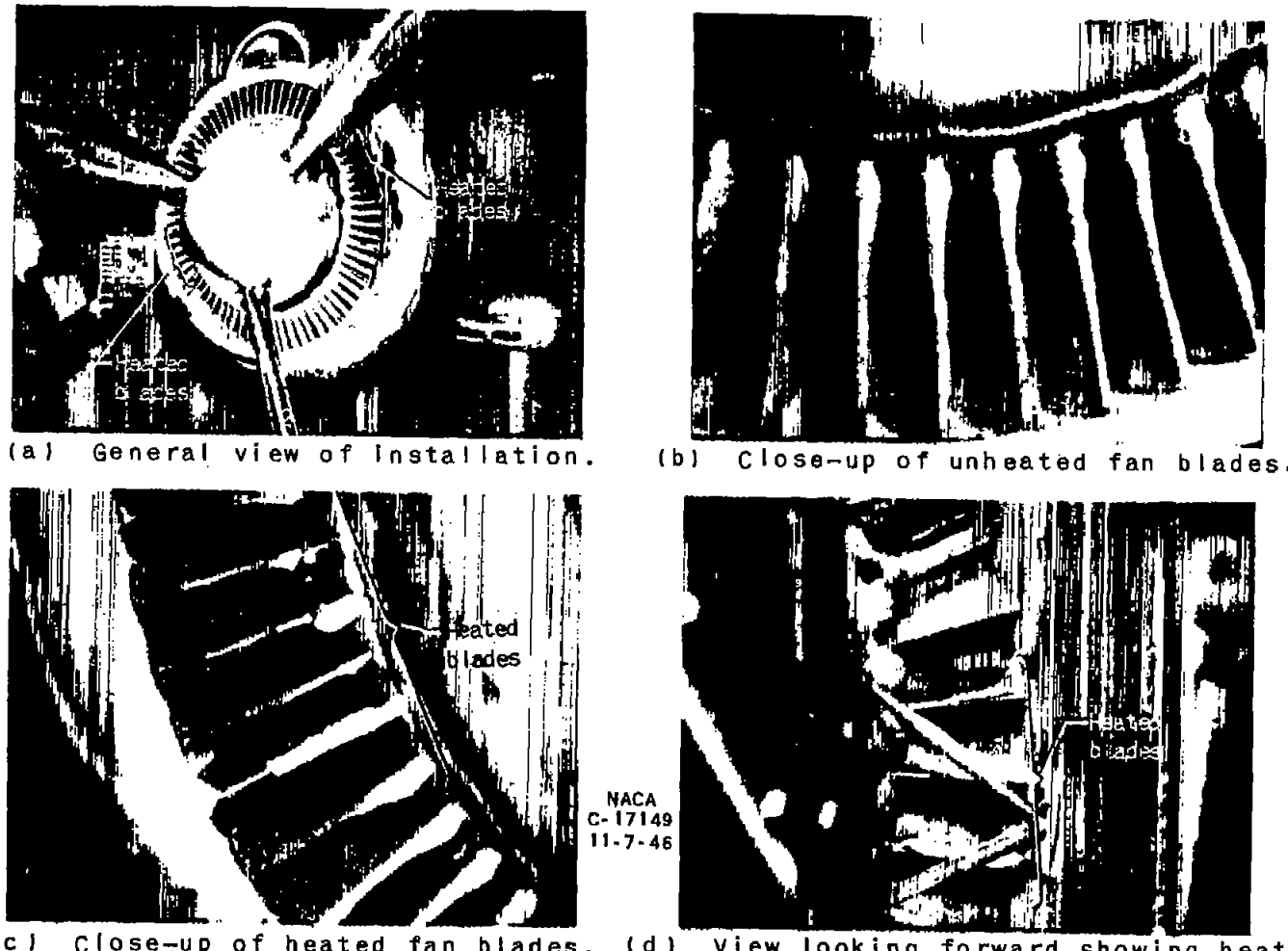
(d) View looking forward through stator vanes.

Figure 20. - Views showing effect of alcohol de-icing of cooling-fan installation at air temperature of 13° F, liquid-water content of 0.5 gram per cubic meter, fan speed of 950 rpm, and alcohol flow of 2.3 pounds per minute.



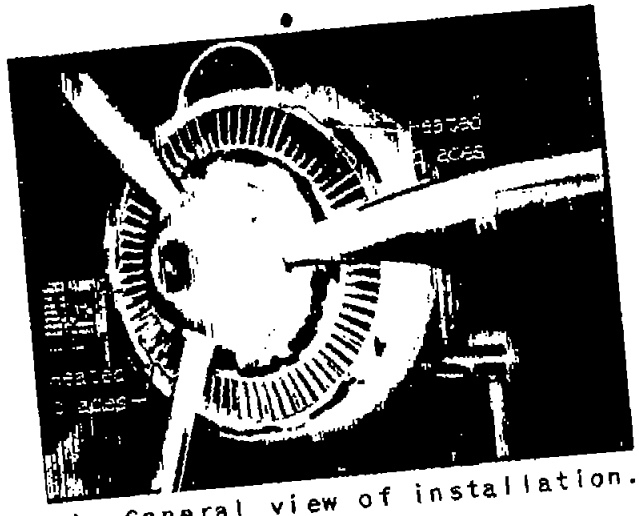
(a) General view of installation.

(b) Close-up of unheated fan blades.

(c) Close-up of heated fan blades.

(d) View looking forward showing heated and unheated stator vanes.

Figure 21. - Views showing de-icing of cooling-fan installation by electric blade heaters after 5-minute run at air temperature of 15° F, liquid-water content of 0.5 gram per cubic meter, fan speed of 954 rpm, and power density of 5 watts per square inch.



(a) General view of installation.

(b) View showing heated and unheated fan blades.

(c) Close-up of heated fan blades.

(d) View looking forward showing heated and unheated stator vanes.

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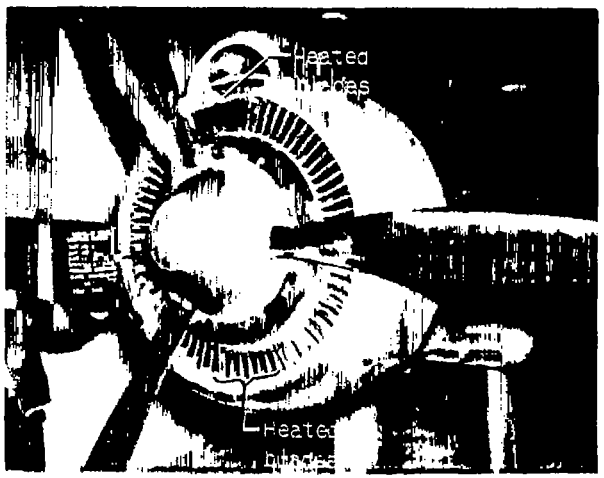
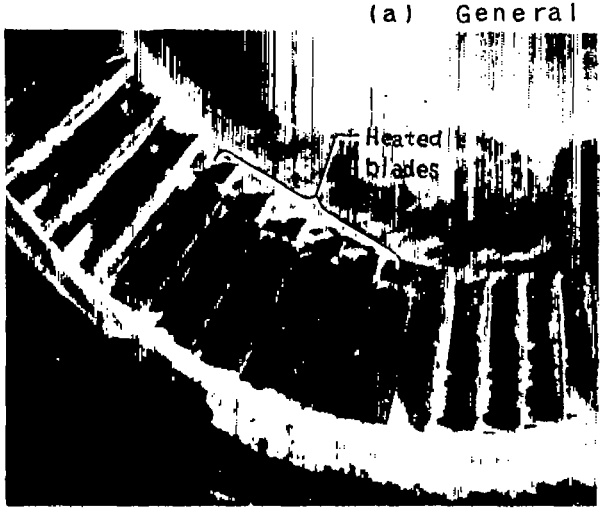
Figure 22. - Views showing de-icing of cooling-fan installation by electric blade heaters after 5-minute run at air temperature of 16° F, liquid-water content of 0.6 gram per cubic meter, fan speed of 950 rpm, and power density of 6 watts per square inch.



(a) General view of installation.



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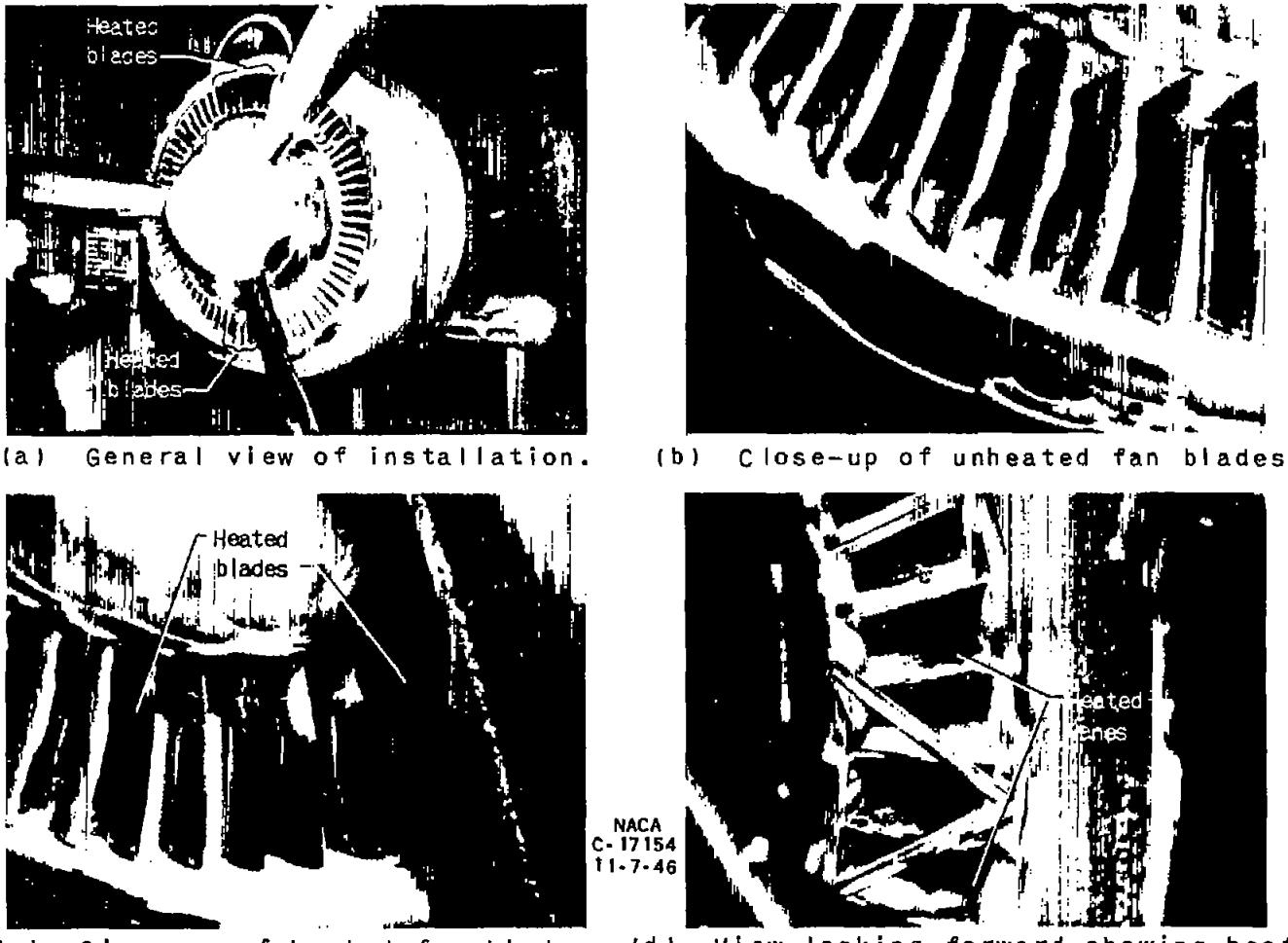
(b) Close-up of heated fan blades. (c) Close-up of unheated fan blades.

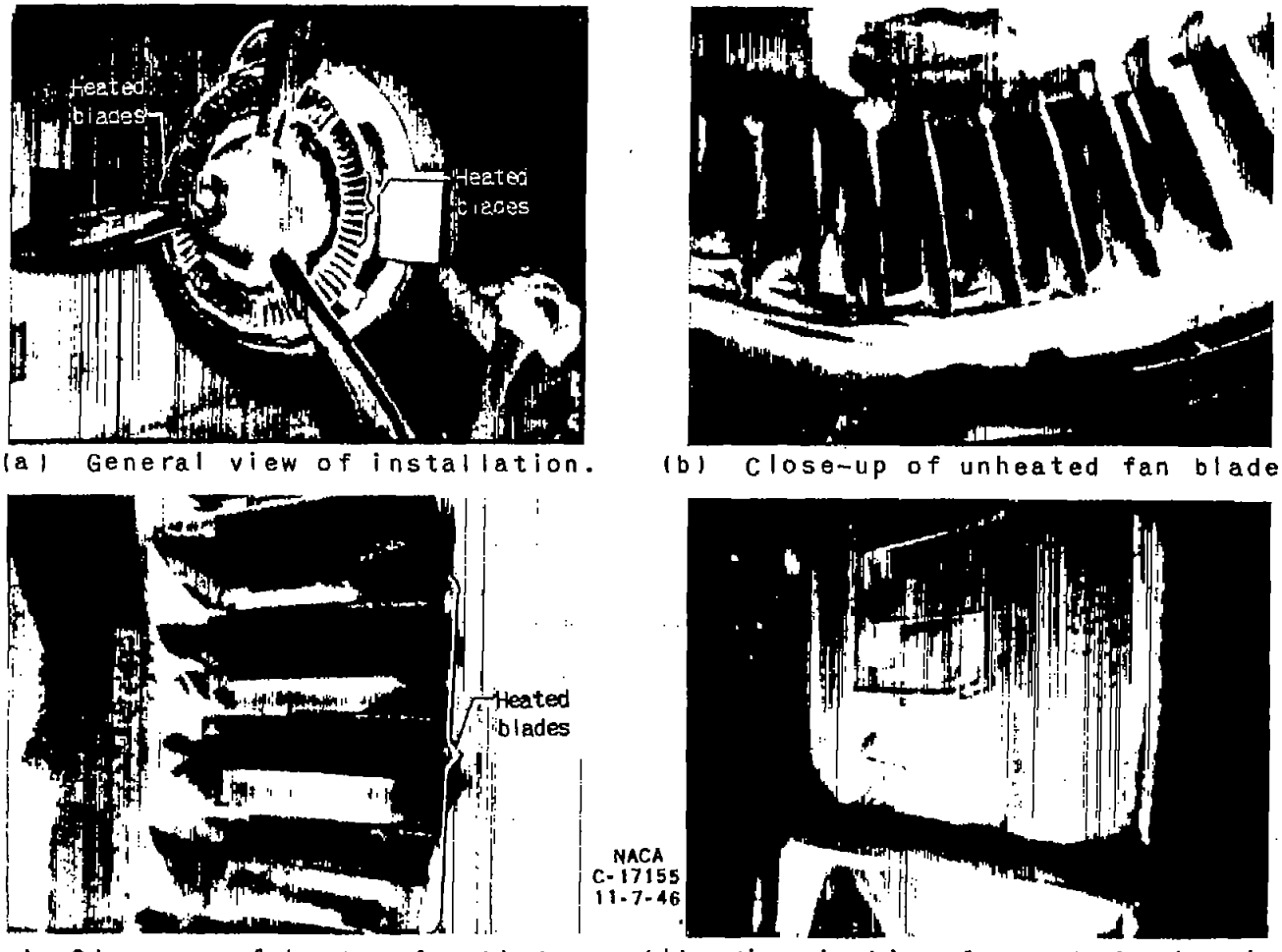
Figure 23. - Views showing de-icing of cooling-fan installation by electric blade heaters after 5-minute run at air temperature of 28° F, liquid-water content of 1.2 grams per cubic meter, fan speed of 950 rpm, and power density of 6 watts per square inch.



(a) General view of installation. (b) Close-up of unheated fan blades.

(c) Close-up of heated fan blades. (d) View looking forward showing heated stator vanes.

Figure 24. - Views showing de-icing of cooling-fan installation by electric blade heaters after 10-minute run at air temperature of 14° F, liquid-water content of 0.5 gram per cubic meter, fan speed of 950 rpm, and power density of 6 watts per square inch.



(a) General view of installation.

(b) Close-up of unheated fan blades.

(c) Close-up of heated fan blades.

(d) View looking forward showing ice formations on heated stator vanes.

Figure 25. - Views showing de-icing of cooling-fan installation by electric blade heaters after 10-minute run at air temperature of 22° F, liquid-water content of 1.0 gram per cubic meter, fan speed of 952 rpm, and power density of 6 watts per square inch.