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# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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# LABORATORY INVESTIGATION OF ICE FORMATION AND ELIMINATION IN THE INDUCTION SYSTEM OF A LARGE TWIN-ENGINE CARGO AIRCRAFT

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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# LABORATORY INVESTIGATION OF ICE FORMATION AND ELIMINATION IN THE INDUCTION SYSTEM OF A LARGE TWIN-ENGINE CARGO AIRCRAFT

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## SUMMARY

The icing characteristics, the de-icing rate with hot air, and the effect of impact ice on fuel metering and mixture distribution have been determined in a laboratory investigation of that part of the engine induction system consisting of a three-barrel injection-type carburetor and a supercharger housing with spinner-type fuel injection from an 18-cylinder radial engine used on a large twin-engine cargo airplane.

The induction system remained ice-free at carburetor-air temperatures above 36° F regardless of the moisture content of the air. Between carburetor-air temperatures of 32° and 36° F with humidity ratios in excess of saturation, serious throttling ice formed in the carburetor because of expansion cooling of the air; at carburetor-air temperatures below 32° F with humidity ratios in excess of saturation, serious impact-ice formations occurred. Spinner-type fuel injection at the entrance to the supercharger and heating of the supercharger-inlet elbow and the guide vanes by the warm oil in the rear engine housing are design features that proved effective in eliminating fuel-evaporation icing and minimized the formation of throttling ice below the carburetor.

Air-flow recovery time with fixed throttle was rapidly reduced as the inlet-air wet-bulb temperature was increased to 55° F; further temperature increase produced negligible improvement in recovery time. Larger ice formations and lower icing temperatures increased the time required to restore proper air flow at a given wet-bulb temperature.

Impact-ice formations on the entrance screen and the top of the carburetor reduced the over-all fuel-air ratio and increased the spread between the over-all ratio and the fuel-air ratio of the individual cylinders. The normal spread of fuel-air ratio

was increased from 0.020 to 0.028 when the left quarter of the entrance screen was blocked in a manner simulating the blocking resulting from ice formations released from upstream duct walls during hot-air de-icing.

## INTRODUCTION

During World War II, the operation of heavily loaded cargo aircraft above the critical engine altitude resulted in the loss of many aircraft due to induction-system icing. The power required to maintain safe altitudes in adverse weather conditions over mountains may demand full-ram cold-air intake and prohibit continuous use of alternate hot air with the attendant altitude loss. Intermittent hot-air de-icing of the carburetors has been resorted to but rough engine operation or engine stoppage may result from excessive variations of the fuel-air mixture caused by slow response or overcompensation of the automatic mixture control during high rates of temperature increase at altitude, from water entering the air-metering passages of the carburetor, or from partial blocking of the carburetor inlet by large pieces of ice melted off the duct walls. Emergency de-icing and ice prevention by means of alcohol sprays upstream of the carburetor proved to be erratic and constituted a fire hazard as well as a serious transportation problem because of the weight of the alcohol required for long flights.

An investigation of the icing and de-icing characteristics of an entire induction system from air inlet to engine has been made at the NACA Cleveland laboratory. One part of the investigation consisted of a study of the impact-icing characteristics of the air scoop and the ducting upstream of the carburetor. This research was performed in the icing research tunnel at the Cleveland laboratory and led to the design of an air-scoop entrance that minimized the formation of serious impact ice in the induction system (reference 1).

It had been previously established (references 2 to 4) that the icing characteristics of an airplane-engine induction system could be conservatively determined in terms of carburetor-inlet conditions by means of a laboratory setup that used only the carburetor and the engine-stage supercharger and supplied fuel and conditioned air at the proper pressure, temperature, and humidity ratio. A correlation of the icing characteristics obtained in such a laboratory setup (reference 2), in an airplane on the ground (reference 3) and in flight (reference 4), and in a multicylinder engine on a dynamometer test stand has been made in reference 4.

The investigation reported herein was therefore conducted on the setup described in reference 5 but with the appropriate carburetor and supercharger assembly. Air-supply limitations restricted the experiments to the 60-percent power rating of the engine. The results obtained at this power level are considered to be conservative for operation at normal rated power (reference 2).

The purpose of this investigation was to establish: (1) the basic icing characteristics of the system in terms of carburetor inlet-air temperature and humidity ratio, (2) the hot-air de-icing characteristics in terms of the wet-bulb temperature of the de-icing air and the time required to restore 95 percent of the maximum possible hot-air flow after various degrees of initial icing, and (3) the effects of carburetor-ice formations on fuel metering and mixture distribution to the cylinders.

## APPARATUS

A complete detailed description of the apparatus, which was modified to suit the carburetor-supercharger assembly investigated, is presented in reference 5. Photographs of the installation are shown in figure 1. The carburetor-supercharger assembly consisted of a 3-barrel injection type carburetor with spinner-type fuel injection and an 18-cylinder radial engine accessory and supercharger housing. A diagram of the carburetor and the supercharger-inlet elbow is shown in figure 2. The carburetor screen for this engine is 1/4-inch mesh with 0.030-inch-diameter wire fitting close to the top of the boost venturi on the top flange of the carburetor. Observation windows were provided in the supercharger-inlet elbow, as shown in figure 3, to permit inspection of ice formations during the runs.

Each of the nine supercharger outlets of the engine accommodates two cylinders through Y-type intake pipes. In the laboratory installation, single intake pipes were connected to nine extension tubes that joined in a collector ring with a single outlet. Manifold pressure was controlled by a damper in the pipe downstream of the collector ring.

The air ducting used for hot-air de-icing consisted of two parallel systems with heaters and humidification facilities in each system. One system supplied air under icing conditions and the other systems supplied hot air for de-icing. Each duct had a tight shut-off valve and a bleed line, which was also equipped with a tight shut-off valve. The operation of these valves was such that, when either the air used for icing or that used for de-icing was being passed through the carburetor, the other air supply was so bypassed through the bleed line that proper temperature and moisture conditions could be maintained in both systems.

The inlet to the supercharger impeller of this engine is submerged in the accessory drive housing and affords a degree of inherent ice protection because the hot oil in the passages for the various shafts of the accessory drive housing heat the walls of the air passage. Thermocouples were installed throughout the supercharger-inlet elbow and turning vanes, as shown in figure 3, to determine the temperature of the surface where ice was expected to form.

A flight-type two-capsule pressure recorder was used to record continuously carburetor-metering suction differential and orifice differential for the air flow from which fuel flow and air flow could be computed for the rapidly changing conditions encountered during de-icing. The record was made on photographic film and included timing marks at 1-second intervals and indexing marks to indicate the start of de-icing.

The combustibles analyzer used to determine the mixture distribution consisted of a multiport valve for taking samples successively from each outlet pipe, a metering block for diluting the mixture sample with air, an electrically heated platinum filament, and a balanced Wheatstone bridge. Combustion on and around the filament of the fuel in the sample, which was diluted to below the explosive limit, increases the filament temperature, changing its resistance. This change in resistance was measured by a balanced Wheatstone bridge and was proportional to the amount of combustibles present in the sample. The analyzer was calibrated by taking samples downstream of the collector ring where the fuel-air ratio was calculated from fuel-flow and air-flow readings. This method of calibration, together with the inherent accuracy of the instrument, allowed the fuel-air ratio to be determined to within 0.002. Fine mesh screens were installed in the upstream end of each branch pipe to insure thorough mixing of the fuel and the air before the sample was removed for analysis.

## PROCEDURE

The procedure followed for the icing investigation consisted in varying carburetor-air temperature and humidity ratio as determined by dew-point or wet-bulb measurement and rate of water injection for the purpose of determining the limiting conditions for the occurrence of icing. The icing characteristics were appraised by inspection of the carburetor and the supercharger-inlet elbow or by observation of the drop in air flow resulting from blockage of the induction system by ice. Serious icing was the icing that caused a 2-percent loss in air flow within 15 minutes. Experiments were made with and without fuel injection to determine whether carburetor ice, formed at air temperatures above 32° F with simulated-rain injection, was caused by the expansion-cooling effect in the carburetor or by the refrigeration effect of fuel evaporation.

Normal engine temperatures were simulated by maintaining an oil temperature of approximately 160° F during the investigation. The fuel and the water temperatures were maintained at approximately 40° F. Previous research (reference 2) demonstrated that the latent heat of vaporization of fuel and the latent heat of water have a more pronounced effect on induction system icing than the temperature of the fuel or the water at the point of injection. It was therefore not considered necessary to vary the fuel or the water temperature with change in air temperature.

The initial engine operating conditions selected for the entire investigation were: carburetor top-deck pressure, 22.2 inches of mercury absolute; air flow, 7000 pounds per hour; supercharger gear ratio, low; simulated-rain temperature, 40° F; fuel temperature, 40° F; and fuel-air ratio, 0.075. The fuel used was AN-F-22 (62-octane), which gives conservative results because it is more volatile than the service fuel AN-F-28 (100-octane) generally used in the engine (reference 2). Humidity ratios were varied between 0.0018 and 0.027 for carburetor-air temperatures from 44° to 17° F. The carburetor screen was removed after initial experiments when it was learned that the use of carburetor screens was no longer mandatory during impact-icing weather. Most of the icing and the mixture-distribution investigations and all the de-icing investigations were made without the carburetor screen.

Hot-air de-icing was investigated by first icing the carburetor at either of two impact-icing conditions (air saturated at 0° or 25° F and simulated-rain injection of 590 grams/min) until a predetermined air-flow loss had occurred and then de-icing the system with hot air at different wet-bulb temperatures. The effect of the magnitude of the ice formation on the de-icing time was studied by allowing the air flow to be reduced by 2000 and 4000 pounds per hour in two series of experiments at 25° F.

During the initial icing period, warm air was bled through the de-icing air duct at a rate of 3000 pounds per hour to prevent surging of the system pressure-control valve when the de-icing air was switched to the carburetor and to permit stabilizing the temperature and the humidity of the de-icing air in advance.

For the determination of fuel-air-mixture distribution, samples from the nine tubes leading to the collector ring and from the outlet of the collector ring were successively passed through the combustibles analyzer. Some difficulty was experienced in determining mixture distribution when ice was present in the induction system because of changes in ice formation before sampling was completed. At an air temperature of 25° F with simulated-rain injection, conditions that were nearly stable could be maintained by shutting off the water after the air flow had decreased approximately 500 pounds per hour. Local ice formations were simulated by covering sections of the carburetor screen with cardboard, which blocked the air flow in that region.

## RESULTS AND DISCUSSION

### Icing Investigation

The limits of no icing, serious throttling icing, and serious impact icing are plotted against carburetor-air dry-bulb temperature and humidity ratio in figure 4. These data show that for the operating conditions used in these experiments this induction system is ice-free at any humidity ratio less than saturation or at carburetor-air temperatures above 36° F with any humidity ratio. At carburetor-air temperatures between 32° and 36° F, no appreciable difference in appearance or effect of the ice formation occurs as a result of fuel injection, which indicates that ice in this range is caused solely by the expansion cooling of air by carburetor throttling. At carburetor-air temperatures below 32° F, throttling continues to have an effect upon the ultimate ice accretion in the system but is less significant than impact icing.

Impact ice forms rapidly on the carburetor screen and the air-metering parts of the carburetor at temperatures below 32° F and humidities above saturation. The entrance screen, which is flat and fits very closely to the boost venturi, became iced (fig. 5(a)) to the extent that air flow was reduced 50 percent in 6 minutes at a carburetor-air temperature of 28° F with a water-injection rate of 500 grams per minute (humidity ratio, 0.0136). When such icing occurs, the metering of the carburetor can be impaired without any ice forming on the air-metering parts because of reduced air flow through the boost venturi. Water passing through the screen before it is blocked with ice causes ice formation on the venturi, boost venturi, and impact tubes (fig. 5(b)) and results in excessively rich or lean mixtures dependent upon the principal location of the ice.

Water or ice in any of the small drilled air passages of the carburetor throttle body and regulator unit through which air should flow continuously can upset fuel metering by altering the calibrated restrictions or completely blocking the passages. Figure 2 is a schematic diagram of the carburetor throttle body and regulator unit showing the air-flow path in the metering system. Water entering the impact tubes must either drain through very small bleed holes into the main venturi or pass through the automatic mixture-control valve into chamber A. A fixed restriction connects chambers A and B. Two outlet passages lead to the boost venturi from chamber B. A vent in the lower passages is provided to return trapped water to the air stream when the throttle is closed.

The results of the icing investigation are presented in table I, which shows that the reduction of fuel-air ratio to excessively lean values may in some cases be the critical factor in the seriousness of impact-ice formations. A fuel-air ratio of approximately 0.074 is obtained with the mixture control in the automatic-rich position at an air flow of 7000 pounds per hour, as shown from the results of the flow-bench calibration of the carburetor in figure 6. The serious drop in fuel-air ratio after 15 minutes of impact icing shown by some of the points in figure 6 could be partly overcome by moving the mixture control to full rich; this control movement bypasses the automatic mixture-control unit and gives uncompensated metering-suction differential across the diaphragm. The full-rich bypass valve (fig. 2) would be effective unless ice had blocked the passage from the impact tubes to chamber A.

Spinner-type fuel injection from a slinger ring directly into the inducer blades of the impeller on this engine effectively prevents the reverse flow and eddying of the fuel spray around the throttles that is responsible for much of the fuel-evaporation ice formed when fuel is injected near the carburetor. Centrifugal force at the slinger ring also prevents blocking of the fuel discharge holes by ice accretions.

Icing of the turning vanes of the supercharger-inlet elbow is reduced by the proximity of warm oil passing through the rear accessory housing. Representative metal temperatures obtained in the supercharger-inlet elbow after 12 minutes under icing conditions with simulated-rain injection of 500 grams per minute were as follows:

| Carburetor-air temperature, °F | Thermocouple[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | Metal temperature, °F | | | | | | | |
| 35 | 43 | 75 | 76 | 36 | 69 | 58 | 38 | 37 |
| 38 | 44 | 75 | 75 | 38 | 70 | 61 | 40 | 39 |

[1] See figure 3 for thermocouple locations.

The temperatures at the rear wall of the supercharger-inlet elbow (thermocouples 2 and 3) are high enough to afford some ice protection but the impeller-shaft-boss (thermocouple 1) and turning-vane (thermocouples 4, 7, and 8) temperatures are only slightly above carburetor-air temperature. These temperatures could be slightly increased with increased oil temperature or circulation in this section of the engine.

Under very light impact-icing conditions at a temperature of 29° F when the carburetor-entrance screen was not used, little ice formed on the carburetor (fig. 7(a)), a heavy deposit formed on the throttle plates (fig. 7(b)), and a trace of ice was observed on the top inlet-guide vane at the supercharger-impeller entrance (fig. 7(c)). This ice did not seriously affect operation during a 3-hour run; the top guide vane makes poor thermal contact with the warm walls of the inlet elbow and is the location most susceptible to ice formation below the carburetor. (See fig. 7(c).)

Under heavier impact-icing conditions, the ice formation at the top of the carburetor occurs more rapidly and relatively smaller amounts of ice form on the throttle plates for a given loss in air flow.

## De-Icing Investigation

The icing conditions, the de-icing conditions, and the recovery data obtained during hot-air de-icing are presented in table II.

Criterion of de-icing effectiveness. - At the same carburetor-deck pressure for the icing and the de-icing conditions, the lower density of the de-icing air caused the maximum possible recovered warm-air flow to be less than the initial cold-air flow. The variation of mass air flow with carburetor-air temperature was experimentally determined for constant engine speed, throttle angle, and carburetor-deck pressure corresponding to a nominal setting of 7000 pounds per hour at the icing temperature. The experimentally determined values of mass air flow were then used to calculate the value of maximum possible warm-air flow corrected for any initial departure from the nominal conditions. The time required to recover 95 percent of this value was taken as the criterion of de-icing effectiveness because the asymptotic approach to full recovery makes full-recovery time difficult to determine precisely.

A previous investigation (reference 6) has demonstrated that de-icing time is a function of the wet-bulb temperature of the warm air. Calculated curves showing de-icing time after icing at 25° F for various relative humidities plotted against dry-bulb temperature are shown in figure 8.

Effect of icing temperature on de-icing time. - No exact relation exists between the amount of ice removed and the rate at which heat is supplied because the de-icing process does not consist in melting all the ice but involves melting the ice only until the bond between the ice and the metal is sufficiently weakened to allow the air stream to break the bond and carry the ice away.

The de-icing time is greater for ice formed at 0° F than for that formed at 25° F (fig. 9). The heat content of ice at 0° F is only 12 Btu per pound less than for ice at 25° F and the difference between the heat requirements for melting a pound of ice in the two cases is only 8 percent. But the difference between the observed de-icing times varies from a maximum of 47 percent at a wet-bulb temperature of 43° F to an almost negligible difference at wet-bulb temperatures above 60° F. The discrepancy may be partly attributable to the variable effects of thermal capacity and conductivity of the metal parts of the carburetor with the effect of thermal capacity predominating at low rates of de-icing and the effect of conductivity bringing about more rapid ice-bond melting at higher rates of heating.

Effect of degree of icing on de-icing time. - The results of hot-air de-icing after ice is permitted to form under the same conditions at 25° F until an air-flow loss of either 2000 or 4000 pounds per hour is experienced are shown in figure 10. Icing under these conditions should give formations of the same type and in the same location, varying only in magnitude. This formation is confirmed by the fact that the de-icing curves for the two cases are similar but displaced with respect to de-icing time and no doubt are part of a complete family of such curves. This comparison shows that de-icing time is a function of the amount of ice to be removed.

In this case, as previously, the de-icing air is not required to melt all the ice but merely to loosen it from the metal surfaces. The time required to remove a larger formation of ice is greater because the ice covers a greater area and the greater thickness of ice provides more thermal insulation of the metal surfaces and more completely obstructs the flow of de-icing air.

De-icing is accomplished within 0.4 minute or less whenever the enthalpy of the air is greater than 30 Btu per pound or the wet-bulb temperature of the de-icing air is greater than 58° F. The air-flow recovery time at fixed throttle rapidly reduces with increase in inlet-air wet-bulb temperature to 55° F; further temperature increase produces negligible improvement in recovery time.

Correlation between air-flow recovery and fuel-air ratio. - At the start of de-icing, rather high fuel-air ratios occur with icing temperatures of 0° F but with the application of hot air the fuel-air ratio drops and remains quite low at the time of air-flow recovery. At 25° F, the fuel-air ratio at the start of de-icing and after air-flow recovery are both affected by the severity of the icing; fuel-air ratio remains abnormally low for some time after recovery from an air-flow loss of 4000 pounds per hour but regains nearly normal values immediately after recovering from a loss of 2000 pounds per hour. As indicated in table II, and as shown in figure 11, the fuel-air ratio at the start of de-icing and after satisfactory air-flow recovery is in many cases unsuitable for proper engine operation and would cause rough running and loss of power if not complete stoppage. In such cases adequate exhaust heat to insure de-icing at the rates obtained in these experiments may be unavailable. The low fuel-air ratios experienced during de-icing and at the time of recovery are probably caused by water freezing in the impact tubes or in the passages between the impact tubes and the diaphragm chamber in the carburetor; because the passages are submerged in the carburetor body, almost the entire carburetor must be warmed in order to remove such an ice restriction. During very serious icing conditions and especially during use of hot air for de-icing, the fuel-air ratio would remain within combustible limits for a longer period by a change to full-rich mixture-control setting.

## Mixture-Distribution Investigation

Mixture-distribution patterns at a carburetor-air temperature of 80° F and an engine speed of 2000 rpm with wide-open throttle show good reproducibility (fig. 12), the maximum deviation from the mean for each cylinder being approximately 4 percent. The results of this investigation are in fair agreement with reference 7 with respect to the spread in fuel-air ratios between the richest and the leanest cylinders. The geometry of the patterns obtained at approximately the same conditions of engine speed, throttle angle, over-all fuel-air ratio, and carburetor-air temperature do not agree with the patterns of reference 7. The data obtained from the laboratory installation under conditions of steady flow are of value in determining the effect of ice accretions on mixture distribution but are probably not indicative of the distribution for a complete engine.

Effect of icing on mixture distribution. - The change in mixture distribution obtained at full-open and part-throttle (28°) settings when the induction system is allowed to ice under impact-icing conditions is shown in figure 13. In both cases, the respective initial and final air flows and carburetor-air temperatures are approximately the same. The average spread in fuel-air ratios between the richest and the leanest cylinders at full throttle is greater after icing of the carburetor than before but is less after icing at a throttle angle of 28°. The most significant effect of icing the carburetor is the decrease in over-all fuel-air ratio in both cases.

Effect of location of simulated-ice formation on mixture distribution. - The effect on mixture distribution of blocking the carburetor screen with pieces of cardboard to simulate the blocking caused by ice formations dislodged from upstream duct walls during hot air de-icing is shown in figure 14 for a carburetor-air temperature of 77° F. A typical distribution pattern obtained with full screen opening is included to provide a basis for comparison. In general, the distribution patterns are similar. The difference between the richest and the leanest cylinders is approximately the same for the blocked and unblocked screen except that blocking the left quarter of the screen apparently affects the distribution the most, causing a fuel-air ratio spread of approximately 0.028 between the richest and the leanest cylinders. The spread was approximately 0.020 with full screen opening.

Because of the absence of erratic metering in dry-air conditions at low altitude, the effect of water or ice in the air-metering passages of the carburetor is considered to be the cause of the serious lowering of fuel-air ratio experienced under icing conditions (fig. 13), as well as the cause of failure to restore fuel-air ratio upon completion of air-flow recovery during hot-air de-icing.

## SUMMARY OF RESULTS

The results of the investigation of the icing characteristics, the de-icing rate with hot air, and the effect of impact ice on fuel metering and mixture distribution conducted on the laboratory installation of a carburetor and supercharger assembly of an 18-cylinder radial engine with the nine supercharger outlets joined in a collector ring are as follows:

1. At carburetor-air temperatures above 36° F, the induction system remained ice-free regardless of the moisture content of the air.

2. At carburetor-air temperatures between 32° and 36° F with humidity ratios in excess of saturation, serious throttling ice formed in the carburetor because of expansion cooling of the air.

3. Serious impact ice formed in the induction system at carburetor-air temperatures below 32° F with humidity ratios in excess of saturation.

4. Spinner-type fuel injection at the supercharger-impeller entrance eliminated all tendencies toward fuel-evaporation icing.

5. Warming of the supercharger-inlet elbow and guide vanes by lubricating oil in the rear engine housing minimized the formation of throttling and impact ice on the walls and supercharger entrance vanes below the carburetor.

6. Air-flow recovery time at fixed throttle was rapidly reduced with increase in inlet-air wet-bulb temperature to 55° F and air-flow recovery was accomplished in 0.4 minute or less with de-icing-air wet-bulb temperatures greater than 58° F.

7. Larger ice formations and lower icing temperatures both increased the de-icing recovery time at a given wet-bulb temperature.

8. The trapping and the freezing of water in the carburetor-air metering passages at below freezing carburetor-air temperatures resulted in erratic fuel metering and delayed recovery of proper fuel-air ratio after hot-air de-icing.

9. Ice accretions in the carburetor resulted in lowered over-all fuel-air ratio and an increased deviation in fuel-air ratio to the individual cylinders from the over-all fuel-air ratio.

10. Blocking of the carburetor screen simulating the blocking caused by ice formations released from upstream duct walls during hot-air de-icing had no adverse effect on mixture distribution except when the left quarter of the screen was covered, causing an increase in fuel-air ratio spread from 0.020 to 0.028.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 9, 1947.

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## TABLE I - RESULTS OF ICING INVESTIGATION

| Average dry-bulb temperature (°F) | Humidity ratio (lb water/lb dry air) | Air-flow loss due to icing in 15 min (lb/hr) | Fuel-air ratio | | Remarks |
|---|---|---|---|---|---|
| | | | At start | At end of 15 min | |
| 44 | 0.0070 | ------------- | 0.075 | 0.075 | (b),(e) |
| 43 | .0258 | ------------- | .075 | .075 | (b),(e) |
| 43 | .0168 | ------------- | .076 | .075 | (b),(e) |
| 42 | .0117 | ------------- | .075 | .074 | (b),(e) |
| 40 | .0263 | ------------- | (a) | (a) | (b),(e) |
| 40 | .0118 | ------------- | (a) | (a) | (b),(e) |
| 38 | .0147 | ------------- | .074 | .073 | (b),(e) |
| 36 | .0055 | ------------- | .074 | .074 | (b),(e) |
| 36 | .0241 | ------------- | .074 | .073 | (b),(e) |
| 36 | .0102 | ------------- | .074 | .073 | (b),(e) |
| 36 | .0149 | ------------- | .074 | .074 | (b),(e) |
| 36 | .0044 | ------------- | .075 | .076 | (b) |
| 35 | .0143 | 400 | .077 | .078 | (c),(e) |
| 34 | .0223 | 450 | .075 | .065 | (c) |
| 34 | .0059 | 800 | .074 | .071 | (c) |
| 33 | .0053 | 250 | .075 | .065 | (c) |
| 32 | .0026 | ------------- | .074 | .073 | (b) |
| 31 | .0035 | ------------- | .075 | .073 | (b) |
| 31 | .0224 | 3000 | .074 | .039 | (d) |
| 31 | .0087 | 3300 | .077 | .044 | (d) |
| 30 | .0046 | 1000 | .073 | .073 | (d) |
| 30 | .0046 | 1300 | .073 | .077 | (d) |
| 28 | .0032 | ------------- | .075 | .073 | (b),(e) |
| 28 | .0042 | 1800 | .073 | .077 | (d) |
| 28 | .0136 | 3500 | .075 | .054 | (d) |
| 25 | .0037 | 800 | .077 | .077 | (d) |
| 24 | .0022 | ------------- | .075 | .077 | (b) |
| 24 | .0019 | ------------- | .074 | .080 | (b) |
| 24 | .0018 | ------------- | .075 | .074 | (b) |
| 23 | .0033 | 750 | .075 | .075 | (d) |
| 23 | .0033 | 1200 | .075 | .075 | (d) |
| 20 | .0025 | ------------- | .075 | .074 | (b) |
| 17 | .0020 | ------------- | .074 | .075 | (b) |

[a] Fuel-flow data not obtained.

[b] No icing.

[c] Serious throttling icing.

[d] Serious impact icing.

[e] Carburetor screen used.

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## TABLE II - RESULTS OF HOT-AIR DE-ICING

| Icing conditions | | | | De-icing conditions | | | | Recovery data | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial air flow (lb/hr) | Initial air temperature (°F) | Initial fuel-air ratio (auto. rich) | Air-flow loss (lb/hr) | De-icing air at carburetor top deck | | | | 95-percent maximum possible recovery | | Fuel-air ratio (auto. rich) | |
| | | | | Wet-bulb temperature (°F) | Dry-bulb temperature (°F) | Relative humidity (percent) | Enthalpy from 0° F (Btu/lb) | Air flow (lb/hr) (a) | Recovery time (min) | At start of de-icing | At time of recovery |
| 7200 | 25 | 0.082 | 4000 | 43 | 64 | 16 | 18.85 | 6360 | 2.70 | 0.090 | 0.065 |
| 7240 | | .082 | | 52 | 52 | 100 | 24.52 | 6570 | .80 | .087 | .054 |
| 7200 | | .069 | | 53 | 93 | 4 | 26.31 | 6000 | .80 | .054 | .049 |
| 7010 | | .083 | | 55 | 60 | 75 | 26.70 | 6190 | .75 | .097 | .064 |
| 7120 | | .088 | | 56 | 110 | 0 | 27.51 | 5880 | .27 | .061 | .057 |
| 7250 | | .092 | | 63 | 100 | 13 | 33.21 | 6100 | .27 | (b) | .045 |
| 7250 | | .070 | | 68 | 92 | 32 | 37.96 | 6010 | .32 | .050 | .046 |
| 6960 | | .082 | | 68 | 110 | 12 | 37.96 | 5810 | .22 | .057 | .044 |
| 6770 | | .080 | | 68 | 110 | 12 | 37.96 | 5660 | .25 | .050 | .051 |
| 7160 | | .070 | | 70 | 107 | 17.5 | 40.19 | 5845 | .33 | .066 | .043 |
| 6990 | | .093 | | 70 | 108 | 17 | 40.19 | 5670 | .12 | .065 | .051 |
| 7160 | | .073 | | 73 | 88 | 51 | 43.46 | 5945 | .25 | .047 | .042 |
| 7110 | | .070 | | 80 | 104 | 38 | 52.64 | 5870 | .22 | .058 | .042 |
| 7050 | | .082 | | 85 | 110 | 38 | 59.79 | 5780 | .25 | .042 | .048 |
| 7010 | | .072 | | 90 | 100 | 69 | 68.29 | 5685 | .15 | .044 | .040 |
| 7170 | | .089 | | 90 | 104 | 59 | 68.29 | 5880 | .28 | (b) | .046 |
| 6960 | | .084 | | 98 | 100 | 93 | 85.22 | 5680 | .25 | .254 | .044 |
| 7040 | 0 | 0.086 | 4000 | 43 | 52 | 52 | 18.85 | 6550 | 5.00 | 0.084 | 0.050 |
| 7490 | | .080 | | 52 | 78 | 11 | 24.52 | 6830 | 1.50 | .070 | .057 |
| 7340 | | .080 | | 56 | 88 | 13 | 27.51 | 6430 | .57 | .083 | .054 |
| 7040 | | .090 | | 58 | 106 | 3 | 29.40 | 6150 | .43 | .162 | .048 |
| 7430 | | .077 | | 70 | 102 | 13.5 | 40.19 | 6650 | .25 | .102 | .040 |
| 7260 | | .076 | | 72 | 75 | 87 | 42.22 | 6570 | .37 | .117 | .045 |
| 7060 | | .086 | | 80 | 110 | 30 | 52.64 | 6240 | .23 | .114 | .054 |
| 7230 | | .078 | | 90 | 105 | 57.5 | 68.29 | 6400 | .27 | .054 | .055 |
| 7240 | | .084 | | 100 | 115 | 60 | 89.00 | 6450 | .12 | .094 | .049 |
| 7200 | 25 | 0.082 | 2000 | 43 | 64 | 16 | 18.85 | 6360 | 2.12 | 0.070 | 0.065 |
| 7160 | | .081 | | 52 | 85 | 9 | 24.52 | 6040 | .33 | .064 | .060 |
| 7070 | | .081 | | 53 | 63 | 55 | 26.31 | 6230 | .20 | .069 | .061 |
| 7060 | | .087 | | 60 | 108 | 4 | 30.62 | 5670 | .13 | .065 | .063 |
| 7060 | | .080 | | 70 | 90 | 40 | 40.19 | 5880 | .12 | .071 | .062 |
| 7170 | | .082 | | 70 | 90 | 40 | 40.19 | 6030 | .13 | .069 | .061 |
| 7020 | | .081 | | 70 | 90 | 40 | 40.19 | 5860 | .12 | .071 | .060 |
| 7370 | | .080 | | 84 | 115 | 30 | 58.90 | 5980 | .10 | .068 | .076 |
| 7050 | | .078 | | 100 | 113 | 64 | 89.00 | 5650 | .07 | .060 | .075 |

[a] Calculated values corrected for initial departure from nominal air flow conditions at start of icing.

[b] Carburetor metering-suction differential values below range of recorder.

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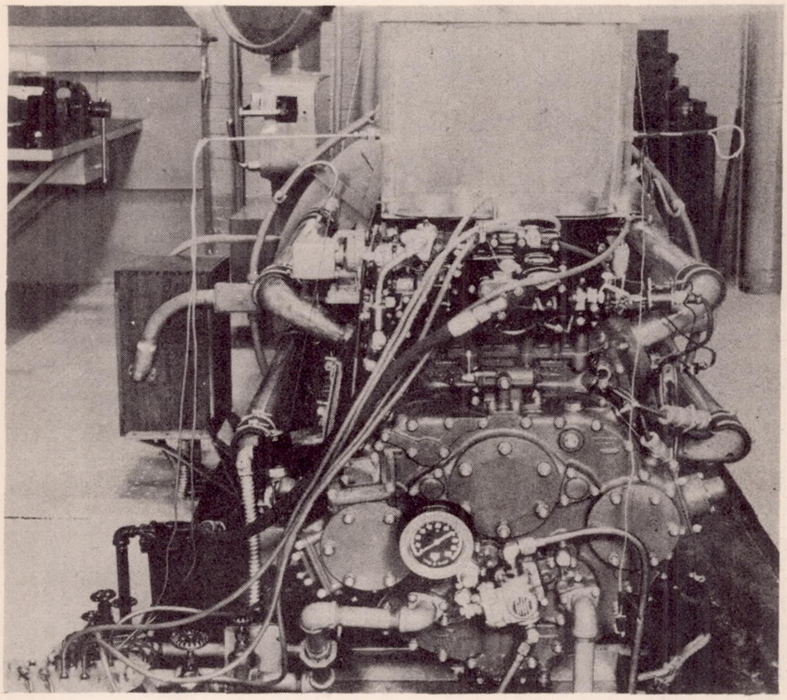
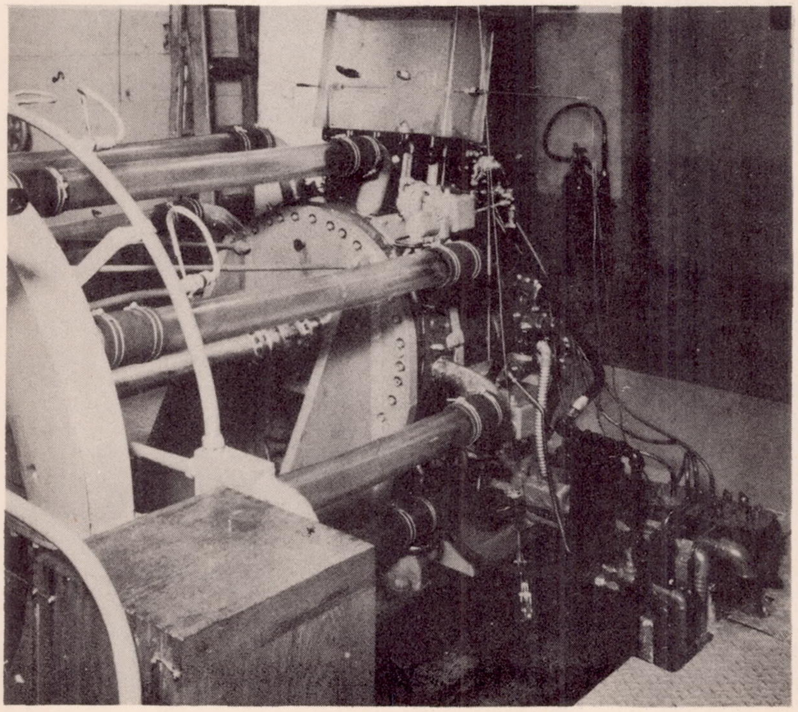


(a) Rear view.



(b) Three-quarter front view.

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Figure 1. - Induction-system de-icing installation of rear engine section with carburetor and transparent plastic observation duct.

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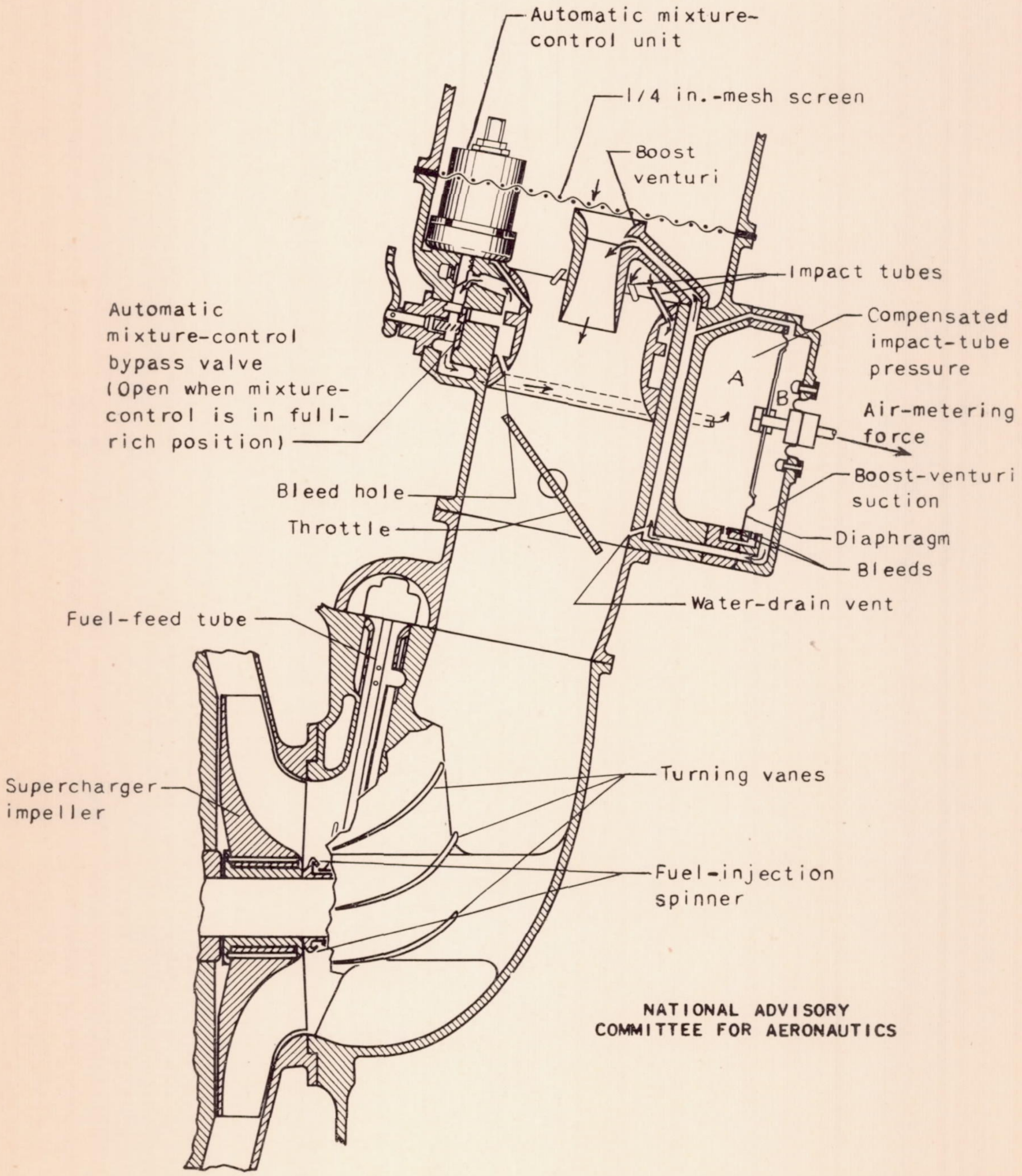

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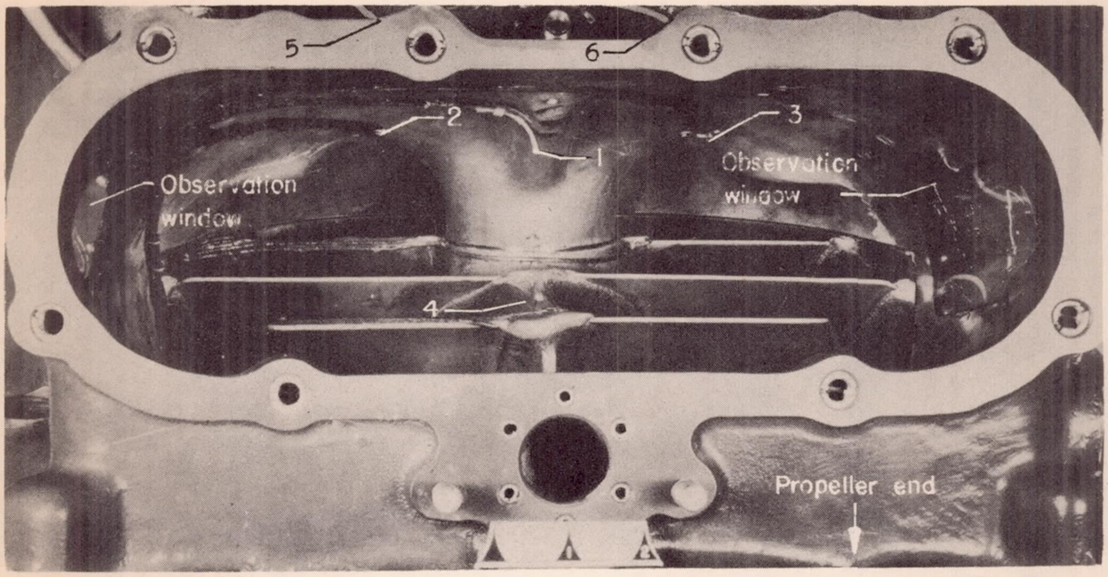
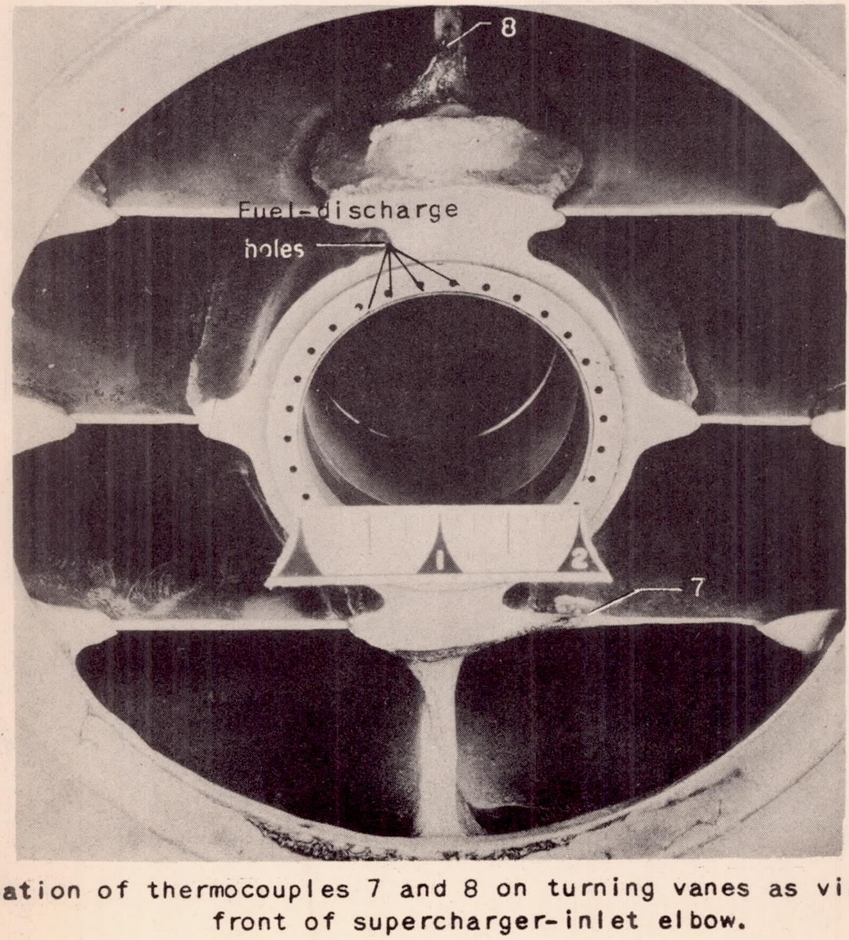
Figure 2.- Schematic diagram of carburetor and supercharger-inlet elbow.



(a) Location of thermocouples 1 to 6 and observation windows as viewed from top of supercharger-inlet elbow.



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(b) Location of thermocouples 7 and 8 on turning vanes as viewed from front of supercharger-inlet elbow.

Figure 3. - Thermocouple and observation-window installation on supercharger-inlet elbow.

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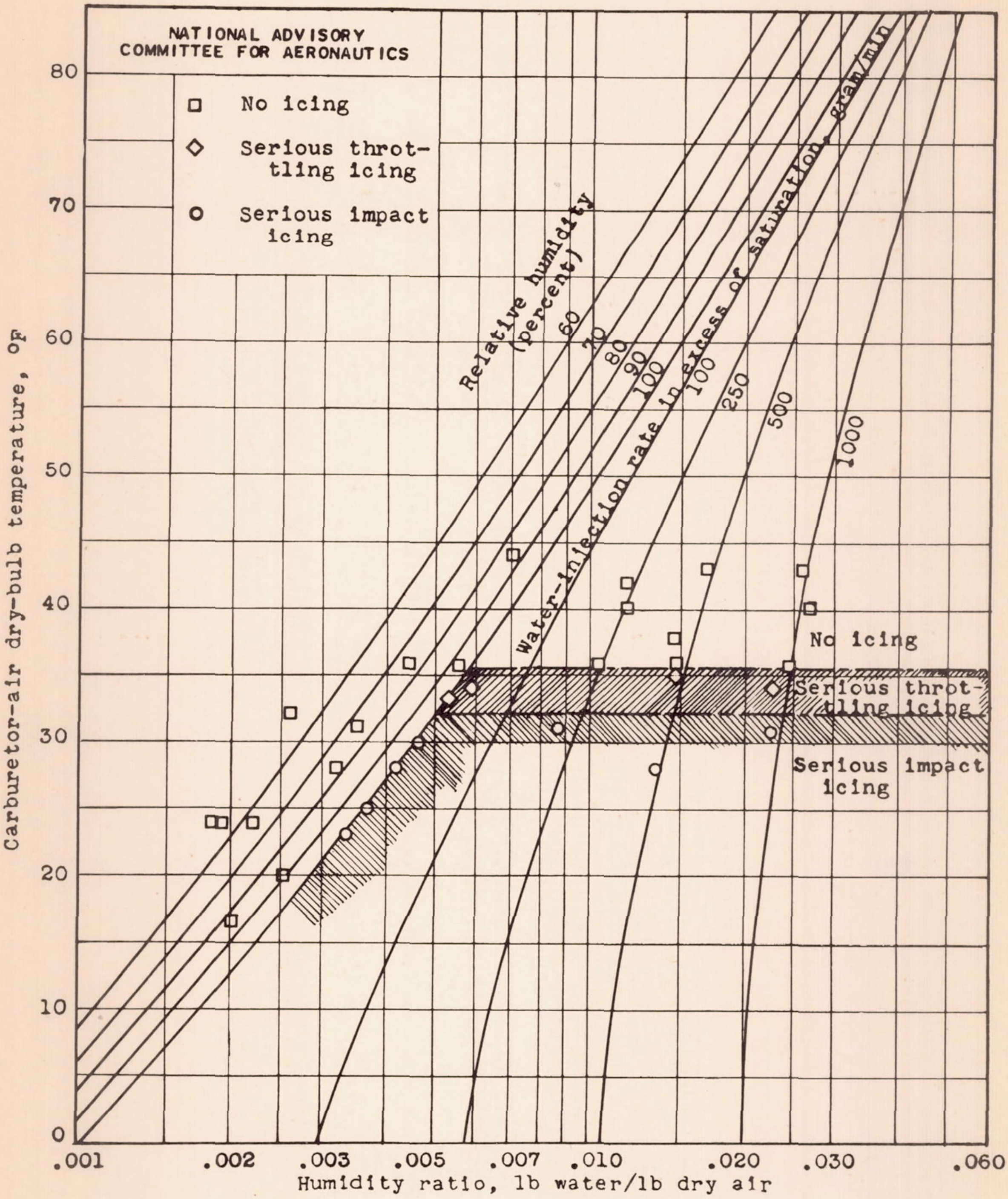

Figure 4. - Icing characteristics of engine induction system.

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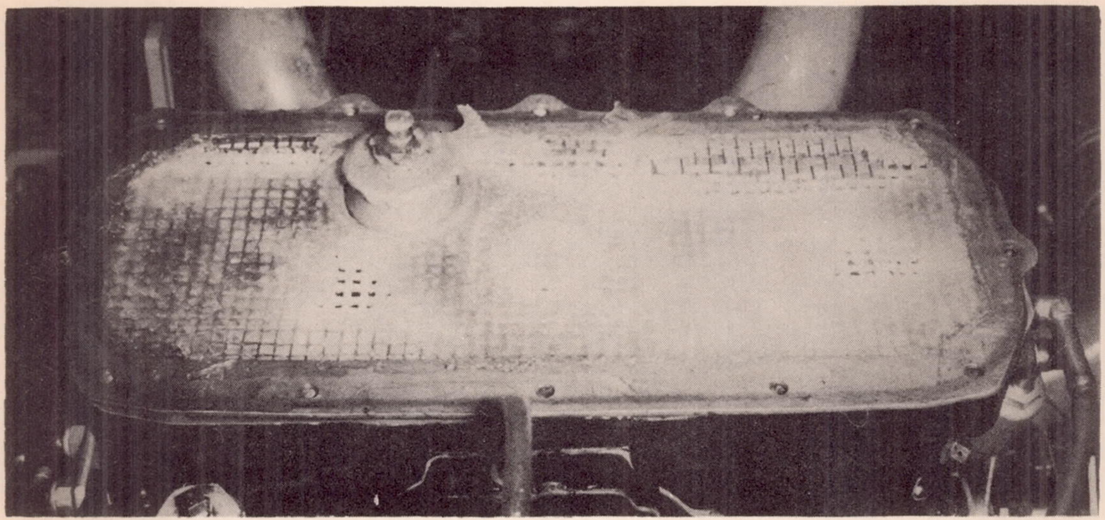

(a) Screen icing.

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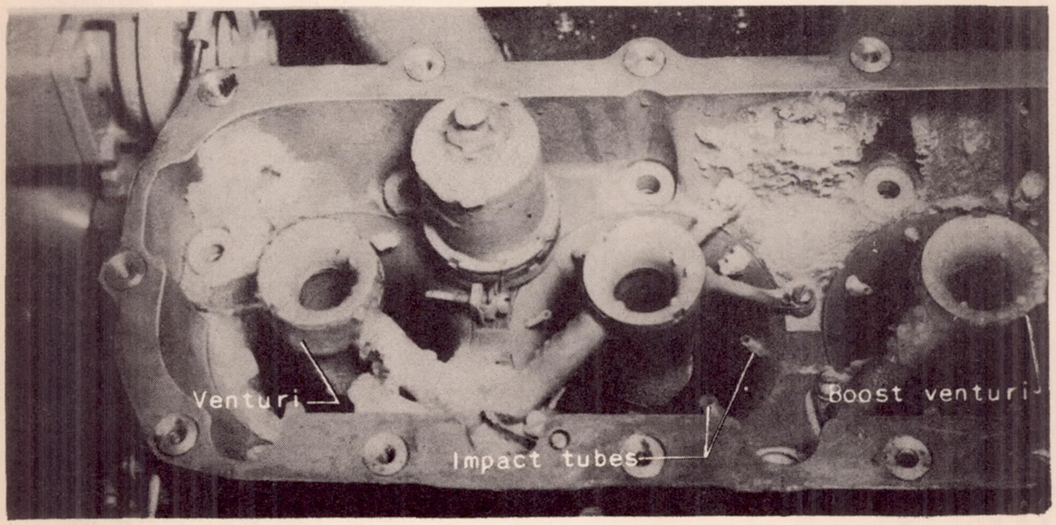


(b) Venturi, boost-venturi, and impact-tube icing.

Figure 5. - Impact-ice formations on carburetor screen and carburetor top deck.

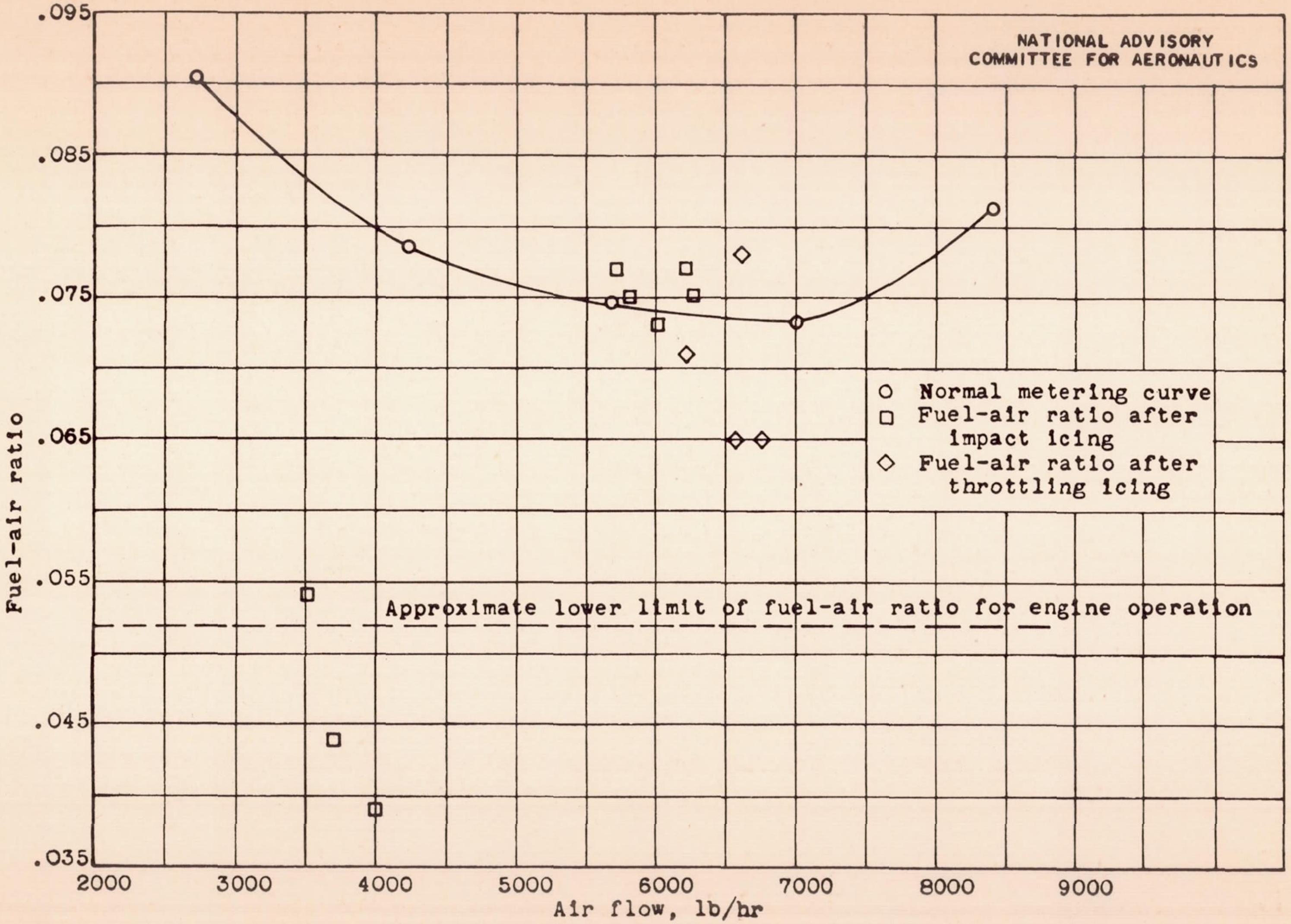
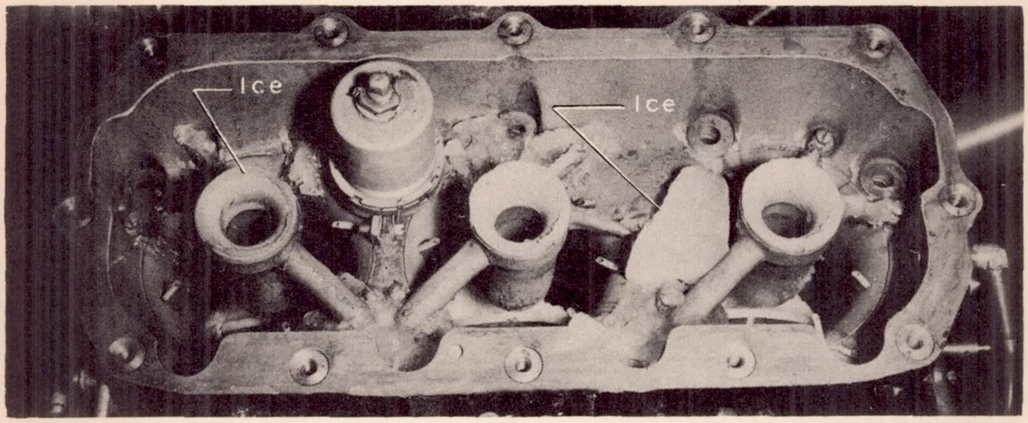
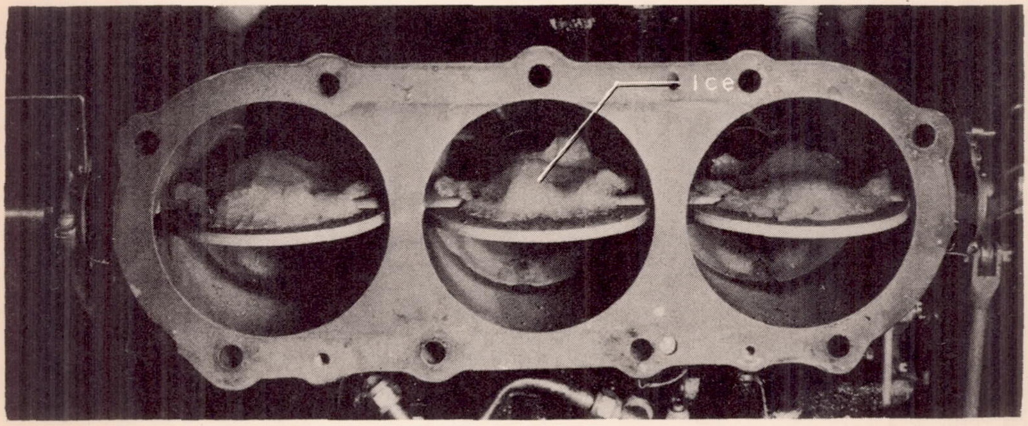


Figure 6. - Fuel-air ratios obtained after 15 minutes of serious icing compared with flow-bench-calibration results showing normal metering.



(a) Carburetor top deck.



(b) Throttle plates.

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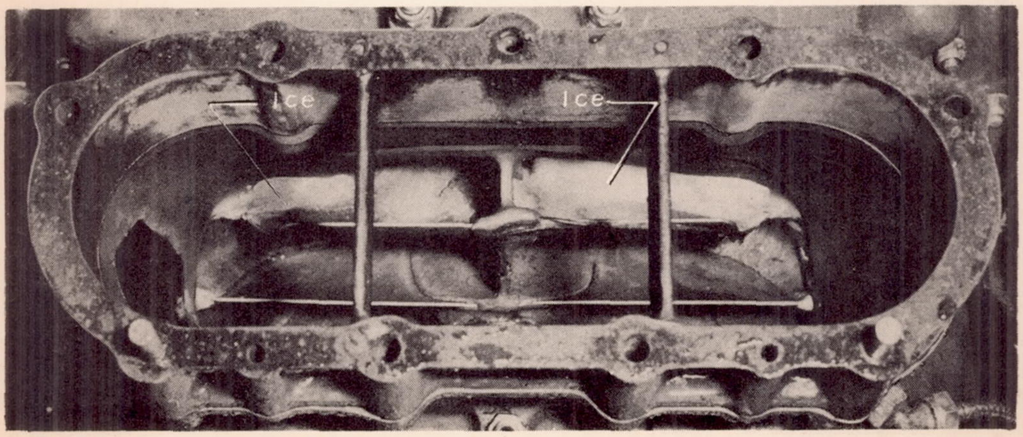

(c) Supercharger-impeller entrance vanes.

Figure 7. - Impact-ice formation on carburetor and supercharger turning vanes after 3 hours of icing.

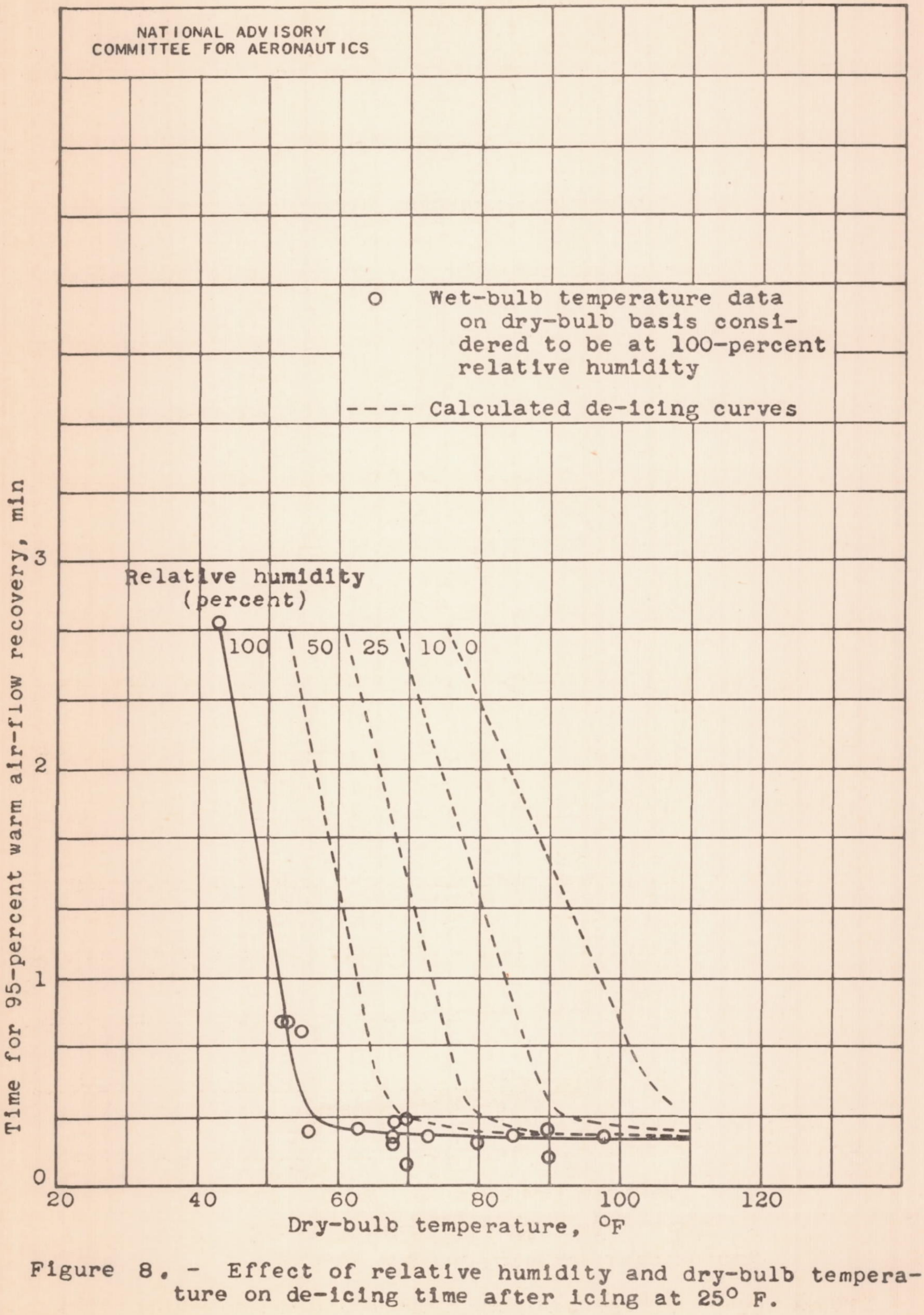

Figure 8. - Effect of relative humidity and dry-bulb temperature on de-icing time after icing at 25° F.

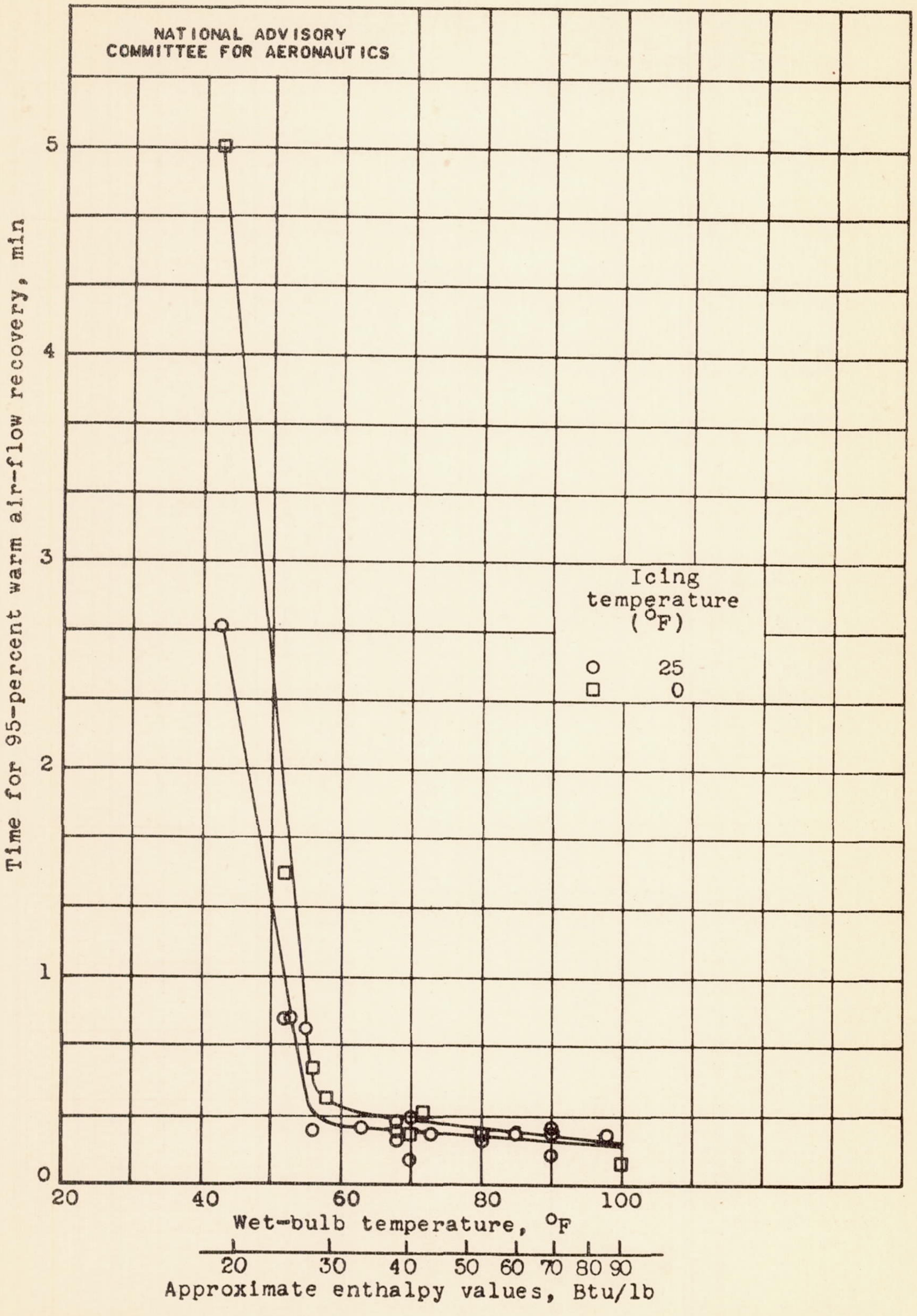

Figure 9. - Effect of icing temperature on de-icing time.

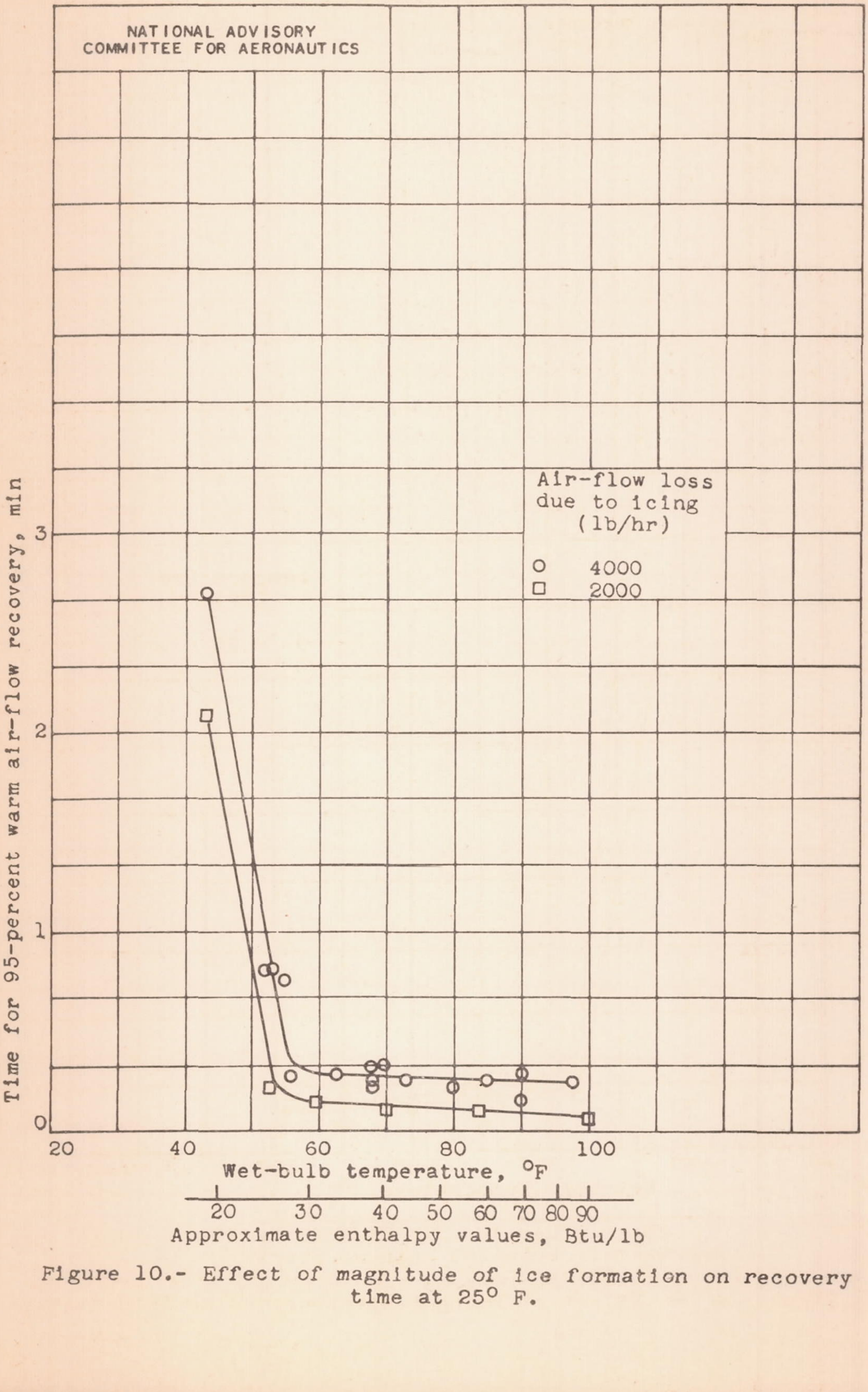

Figure 10.- Effect of magnitude of ice formation on recovery time at 25° F.

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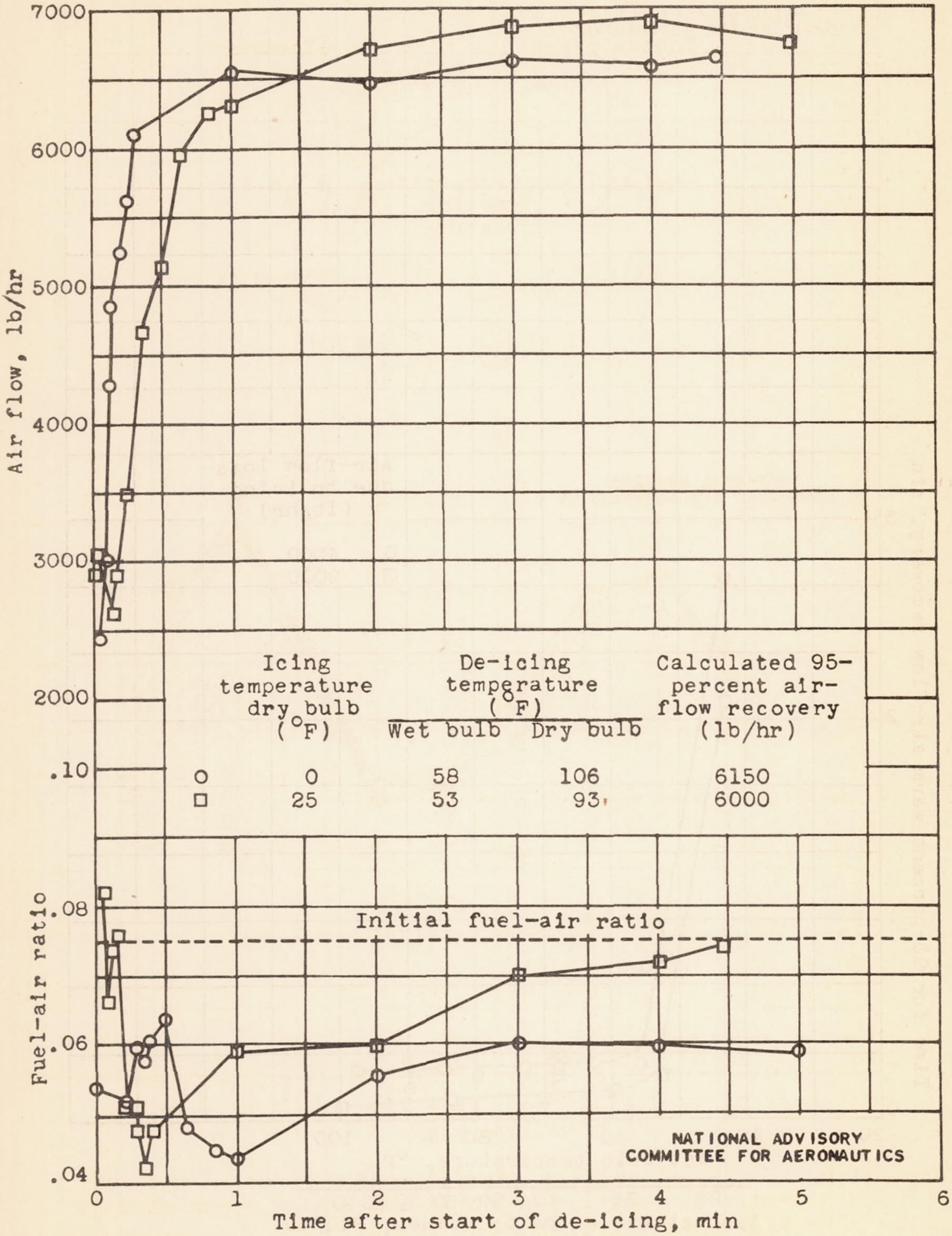

Figure 11. - Typical time-history curves of hot-air de-icing.

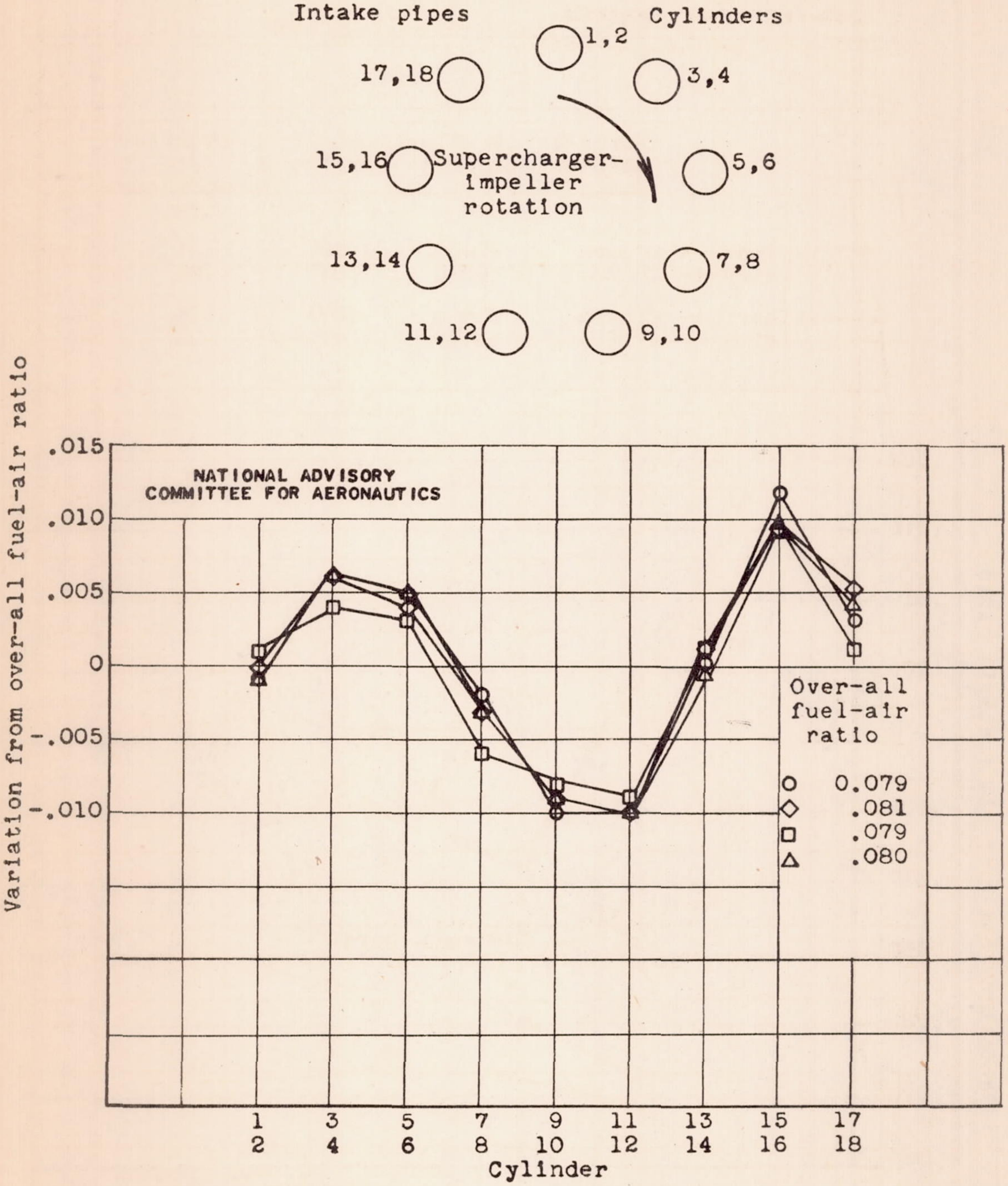

Figure 12. - Reproducibility of mixture-distribution data at carburetor-air temperature of 80° F and engine speed of 2000 rpm with wide-open throttle.

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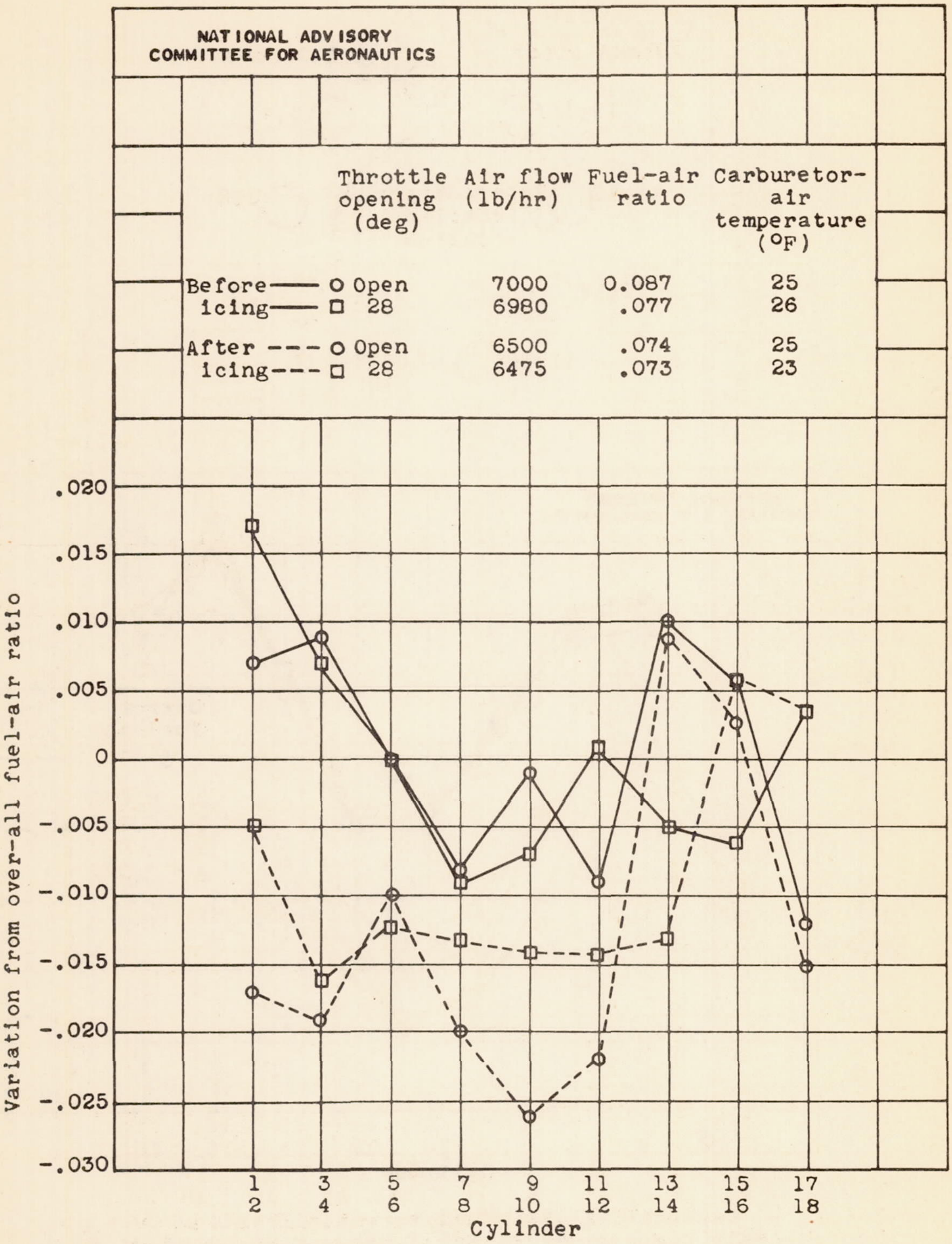

Figure 13. - Effect of carburetor icing on mixture distribution at two different throttle angles.

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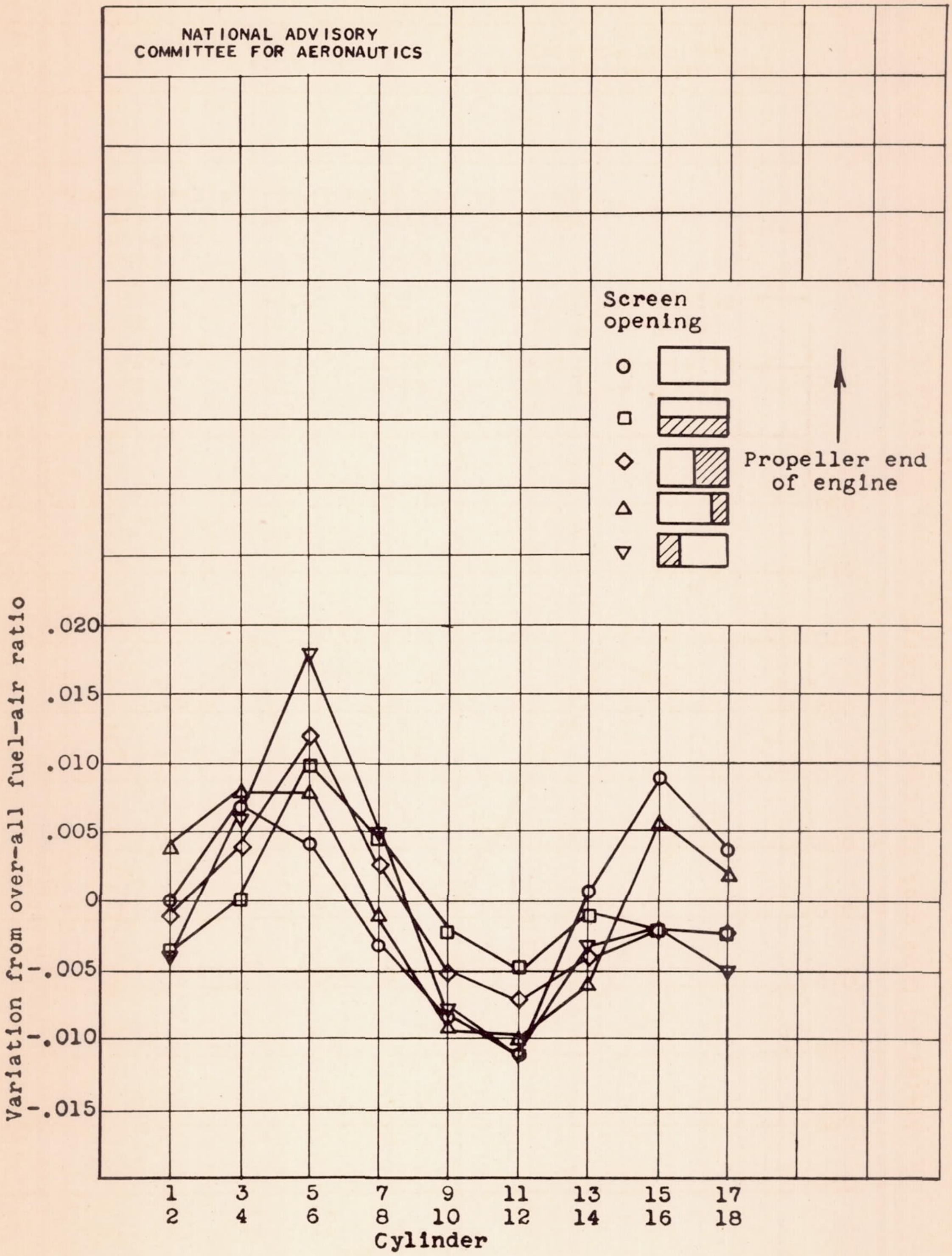

Figure 14. - Effect of simulated-ice-formation location on mixture distribution at a carburetor-air temperature of 77° F.