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ICING TESTS OF AIRCRAFT-ENGINE INDUCTION SYSTEMS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

ICING TESTS OF AIRCRAFT-ENGINE INDUCTION SYSTEMS

By Leo B. Kimball

SUMMARY

A comprehensive program of icing tests has been conducted on an aircraft-engine induction system consisting of a Wright R-1820, G-200 blower section, Holley 1375-F carburetor and adapter, and specially built air scoop. It was the object of this research program to determine the effect of a number of possible factors on icing of engine-induction systems. These factors included carburetor-air temperature, air-moisture content, water-droplet size, throttle opening, mixture ratio, rate of air flow, altitude, and others.

Both fuel evaporation icing and throttle icing were considered in this investigation. No tests were made on impact icing, however. It was found that two of the factors, carburetor-air temperature and amount of free water present in the intake air, had the major effect on icing in the induction system tested.

The rate of ice formation increased rapidly with increase in rate of air flow at constant moisture content, and it is therefore concluded that the rate of icing is a function of the mass flow of free water through the induction system. Throttle icing was critical at temperatures near the freezing point of water but diminished to a negligible degree at a carburetor-air temperature of 40° F or above.

When there was no free moisture present and the relative humidity of intake air was 100 percent or less, ice formed in the induction system at such a slight rate that neither the rate of air flow nor the mixture ratio was seriously affected. With free moisture present, ice formed in the induction system to a sufficient degree to affect both the rate of air flow and the mixture ratio at carburetor-air temperatures up to 60° F. Ice did not form under any conditions when the carburetor-air temperature was 80° F or above.

From the results of this research program it is concluded that induction-system air scoops should be designed to prevent as much water as possible from entering the carburetor. A brief study has been conducted on this problem. The interior passages of induction systems should be free from protuberances on which ice can adhere.

The investigation described in this report was conducted at the National Bureau of Standards in a special laboratory provided with air blowers and refrigeration equipment.

INTRODUCTION

The program of tests described in this report was designed to determine the effect of a number of factors on induction-system icing, with the view of obtaining data which would serve as a guide for safe winter operation of airplanes and which might also lead to the design of improved induction systems from the icing standpoint.

Tests also have been made on methods of eliminating ice formations in induction systems by means of the injection of alcohol into the intake air and by preheating the air. This research is continuing and it is planned to issue further reports with results of the de-icing tests.

The present report is limited to a description of the icing tests and a brief study of the possibility of preventing, by design modifications, the ingestion of rain into induction systems. There is also included a brief appendix describing tests made on several induction-system ice-warning indicators.

The NACA induction-system icing program at the National Bureau of Standards was initiated in January 1941. The project is financed jointly by the Army, the Navy, and the National Advisory Committee for Aeronautics. Support has also been received from the Civil Aeronautics Administration.

Acknowledgment is due to several manufacturers of aircraft and equipment who have supplied engineering personnel and apparatus, and also to several commercial air lines who have furnished equipment and flight-test data on induction-system icing.

APPARATUS AND METHOD OF OPERATION

The icing tests were carried out in an altitude laboratory at the National Bureau of Standards. This laboratory is equipped with refrigeration machinery located in a separate building, consisting of two 25-ton compressors, condensers, receivers, and steam-heating units. It was possible to vary the temperature and humidity of the carburetor intake air within wide limits. Two electrically driven Nash exhausters, located at the end of the exhaust air duct, draw the combustion mixture through the induction system.

The tests described in this report were made in an induction system consisting of a specially built air scoop and a Holley 1375-F carburetor and adapter mounted on a Wright R-1820, G-200 engine. The laboratory induction-system installation was designed to simulate the conditions of flight as closely as possible. The testing apparatus is shown schematically in figure 1. A second schematic sketch, figure 2, has been prepared to show important details of the induction-system installation. A photograph showing much of the equipment in the altitude chamber is given in figure 3.

A glass window was built into the rear wall of the carburetor adapter and a small electric light placed inside the adapter. By means of these devices it was possible to observe the ice as it formed in the induction system.* The visual observations of icing proved to be of considerable assistance in analyzing much of the data obtained.

Referring to figure 1, air was drawn into the cold room across the refrigeration coils and through the intake duct, which contains a straightening grid and water-spray nozzles, and thence through the air scoop into the induction system. The air flow was measured by means of either of two interchangeable flat-plate orifices located in the intake duct as shown in figure 1. The larger orifice was used on all wide-open-throttle runs, while the smaller orifice was used for the part-throttle runs.

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*Later in the program a glass window was installed in the air scoop, so that ice forming around the fuel nozzle bar could be seen.

The orifices were made according to A.S.M.E. standards, and were considered accurate within 1 percent. The orifice differential pressure was indicated by a water manometer and also by a differential pressure recorder. By means of the latter instrument it was possible to record quite accurately the complex changes of the air flow during the icing process. Figure 4, a typical chart from this pressure recorder, illustrates the rapid drop in air flow from the cruising rate of 4000 pounds per hour under severe icing conditions. The various fluctuations in the air-flow curve were caused by ice formations breaking off and re-forming. The initial rate of air flow was controlled by bleeding additional air into the outlet duct, thus adjusting the pressure drop across the induction system to a value corresponding to the desired rate of air flow under ice-free conditions.

The temperature of the intake air was automatically controlled by a Brown instrument to an indicated accuracy of $\pm 1/4^{\circ}$ F. The air temperature was indicated by two calibrated glass thermometers and recorded by a four-pen recorder. As a further check on the accuracy of air-temperature measurements, a thermocouple was placed between the two glass thermometers in the air scoop and connected to one of the 12-point recording potentiometers which are shown in figure 5.

Gasoline was supplied into the carburetor by a special fuel pump driven by a 1/2-horsepower electric motor. It was possible to pump fuel into the carburetor at rates up to 1600 pounds per hour. The gasoline flow was regulated by a combination of two methods. One of these consisted of bypassing a portion of the fuel back to the supply tanks by means of a manually operated valve. The fuel flow was further regulated by adjusting a pressure valve at the carburetor. For measurement of the rate of gasoline flow, one of three calibrated rotameters of various capacities was used. These instruments are shown in figure 5 at the left of the recording potentiometers. The rate of fuel flow was also indicated and recorded on a differential recording flowmeter. The temperature of the fuel was measured in the pipe leading to the carburetor and was recorded on a chart.

The throttle opening was regulated either at the carburetor or by a control handle at the observation station. The latter control is shown in the lower right-hand corner of figure 5.

The humidity of the intake air was regulated up to the saturation point by injection of steam into the intake air duct a short distance downstream from the cold room. A nozzle bar, located downstream from the straightening grid, was employed to add free water above saturation to the air in order to simulate rain ingestion. Three types of nozzle bars were used for producing water droplets of various sizes. The small nozzles produced a droplet estimated at about 30-50 microns in diameter; the medium-size nozzles produced water droplets about 1 millimeter in size; the large nozzle produced droplets of about 3-millimeter diameter. The grid in the air duct on the upstream side of the water nozzles was installed to straighten the flow of air around the nozzles and to reduce stratification. The absolute moisture content of the intake air was measured by first heating an air sample, which was bypassed through the measuring unit, until all the water in suspension was vaporized and then measuring the relative humidity of the air at the elevated temperature by means of wet and dry bulb thermometers.

Water ingestion into the intake air was measured by either of two rotameters, depending on the rate of ingestion. For most tests it was found that the temperature of the ingested water could be maintained reasonably close to that of the intake air by passing the water through a coil of tubing wound around the outlet duct leading from the engine blower section, as shown in the left side of figure 3. For some tests involving high values of rain density it was found necessary to employ an ice bath for this purpose.

Provisions were made to heat the engine blower section by means of steam in order to simulate flight conditions. It was also decided to direct against the carburetor adapter an air stream to simulate velocity and temperature (100° F) that would exist within an engine cowling during flight. This condition was attained by means of an electric fan mounted behind the bank of steam coils, as shown in the left side of figure 3.

The temperatures of the metal passages at various points in the induction system were measured by means of thermocouples. The locations of a number of these thermocouples are indicated in figure 2 and also in figure 7, which shows the interior of the engine blower section. The metal temperatures were recorded by 12-point recording potentiometers.

The temperature of the mixture was measured by means of a thermocouple mounted in the rear wall of the carburetor adapter and extending into the mixture stream.

The effect of altitude was simulated by the operation of the slide valve in the air-intake duct. Altitude was measured by means of a static tube located in the intake duct on the downstream side of the slide valve. During each altitude test run the gasoline pressure was adjusted in order to maintain the same differential between the fuel diaphragm chamber and the air entrance to the carburetor that would occur at sea level.

With the thought that vibration of an airplane engine in operation might affect the tendency of ice particles in an induction system to be shaken loose, a fairly large air vibrator was attached to the engine blower section. Several icing tests were made to ascertain the effect of such vibration on the icing tendency. No measurable effect of this vibration on the rate of ice formation could be detected from the results of these tests. It was therefore decided not to include the effect of vibration in the testing program either as an icing factor or as a constant test condition.

The fuel used in this research program was taken from a special supply of 50,000 gallons of 73-octane, nonleaded fuel in order to remove any possible error which might result from the use of different fuels. The volatility of the gasoline was so selected to match as nearly as practicable those of the aircraft fuels now in use. A sample distillation of the gasoline employed is as follows:

Distillation	Deg F
First drop	114.8
5 percent distilled	140.0
10 percent distilled	145.4
15 percent distilled	149.0
20 percent distilled	154.4
30 percent distilled	163.4
40 percent distilled	174.2
50 percent distilled	183.3
60 percent distilled	192.2
70 percent distilled	201.2
80 percent distilled	212.0
90 percent distilled	228.0
95 percent distilled	242.0
End point	263.0

Distillation (Cont.)	Deg F
Recovery, percent	98.1
Residue, percent	.9
Loss, percent	1.0
Barometric pressure, millimeters	755
Vapor pressure, pounds per square inch	6.8

TESTS AND PROCEDURE

In beginning each test run the air flow was first adjusted to the desired rate at the proper throttle angle and carburetor pressure drop. When the air temperature had stabilized, fuel was introduced into the air stream at the carburetor. The rate of fuel flow was set by means of the mixture control to give the required fuel-air ratio. Moisture was then added to the intake air in order to reach the desired relative humidity or rate of rain ingestion.

The recording instruments were started during each run with the injection of gasoline, and timing was accomplished with a stop watch. Observed readings were taken at short-time intervals, according to the rate of fluctuation of the air and gasoline flows. When the air flow had either dropped to some predetermined value or had remained unchanged during a reasonable period of time the run was concluded. The carburetor was then immediately removed for examination of the ice formation. Photographs were taken of the ice formed in the induction system during a number of runs.

As each test run progressed, the presence of ice in the induction system could be detected by the irregularities in the curves of air flow and fuel flow on the recording charts caused by small pieces of ice continually breaking off and re-forming.

In an effort to explore thoroughly the effect of each factor on icing, a great number of test runs over a wide range of conditions were made. Of these tests, 100 are recorded in table II. The tendency toward icing produced in most of these runs is shown in the various charts.

The carburetor-air temperature was varied from 32.5° F to 90° F. The moisture content of the air was varied from 75-percent relative humidity up to saturation plus 100-grams-per-cubic-meter rain density. The rates of air flow explored ranged from 2000 to 10,000 pounds per hour, the throttle opening from 15° to 73°, and the mixture ratio from 0.060 to 0.120. Tests were made at pressure altitudes from sea level up to 20,000 feet. The operating limits of the mixture ratio for the Wright R-1820 engine were assumed to be from 0.050 to 0.130. No consideration was given in the program to the effect of icing on the mixture distribution since the tests were not made on a complete engine.

DISCUSSION OF RESULTS

Ice which forms in an engine-induction system can be classified under three general types:

1. Atmospheric impact ice - forms on and ahead of the throttle at temperatures below the freezing point of water due to the ingestion of snow, sleet, or supercooled water particles which freeze on impact.

2. Throttling ice - forms around the throttle as a result of the change in kinetic energy of the air caused by passing through this high-velocity section of the carburetor.

3. Refrigeration ice - forms at and below the fuel nozzles as a result of cooling the intake air and ingested water by the evaporation of the fuel.

This third type of ice, also known as fuel ice, is encountered more frequently in flight than either of the other types since it forms at outside air temperatures considerably above 32° F. For this reason almost the entire program of tests was devoted to a study of refrigeration icing. Thus far no tests have been made on impact icing at the National Bureau of Standards. Impact-icing tests have been made by another agency, however. (See reference 1.)

It appears from comparing the results obtained in this investigation with icing tests made in other laboratories that the ranges of conditions effecting icing vary somewhat in induction systems made by different manufacturers. In view of this condition, it is believed that the data contained in this report should be of value in the operation of the induction system tested but should be applied with some reserve in connection with other types. In general, however, the manner in which ice formed in the induction system tested and the relative effect of various factors on the icing tendency should be similar in the induction system of any modern aircraft engine.

Two factors, carburetor-air temperature and amount of free water in the intake air, were found to have a predominant effect on icing.* All other factors considered had a very minor effect. It is possible, however, that some of the icing factors described in this report as minor might have a more appreciable effect on the icing tendency during borderline icing conditions. The two sets of major and minor factors which influence the occurrence of ice can be grouped as follows:

Major Icing Factors

(1) Carburetor-air temperature

(2) Moisture content of air

Minor Icing Factors

(1) Rate of air flow

(2) Throttle opening

(3) Droplet size

(4) Fuel-air ratio

(5) Altitude

(6) Metal temperatures of engine blower section

(7) Fuel temperature

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*Fig. 8, a view of the carburetor adapter after run 9, made at 40° F carburetor-air temp. and rain density of 10 grams/m^3, shows the large amount of ice formed within a period of 20 min.

The results showed that with free water present in the air when the carburetor-air temperature is near the freezing point, refrigeration ice forms very rapidly in the induction system. Figures 15 and 16 indicate that the zone of dangerous icing extends above 50° F and that the rate of icing is progressively lessened as higher carburetor-air temperatures are reached. At 32.5° F carburetor-air temperature and rain density of 10 grams per cubic meter, the air flow was reduced from 4000 to 3000 pounds per hour within 2 minutes. At 50° F under similar conditions, the air flow was reduced from 4000 to 3000 pounds per hour in 30 minutes. At temperatures above 50° F, the rate of air flow through the induction system was not noticeably affected even though the rain density of the intake air was maintained at 10 grams per cubic meter. Fluctuations in the mixture ratio due to the presence of ice were observed at temperatures up to 70° F, however. An examination of the carburetor adapter at the conclusion of a test run made under similar conditions at carburetor-air temperature of 80° F revealed that no ice remained in the induction system. It is possible, of course, that small amounts of ice formed in the adapter at this temperature and were later broken off and carried through the system.

With increase in moisture content of the intake air above the saturation point, refrigeration ice formed very rapidly in the induction system. Somewhat in contrast to the results of previous investigations, it was found that at a moisture content of 100 percent relative humidity or less, the rate of ice accretion was very small and the rate of air flow remained almost constant for periods as long as 30 minutes. It was observed that ice formed and periodically was broken away from the walls of the carburetor adapter during many of these tests. This action was attributed to the fact that the ice insulated the walls from the colder mixture stream and because the adapter walls were heated from the outside to a certain extent by a flow of warm air from the fan previously described. With increase of moisture content above saturation, ice formed progressively faster. At 30-grams-per-cubic-meter rain density, it was seen that the rate of air flow was reduced from 4000 to 3000 pounds per hour in 3.5 minutes. When the rain density was increased to the extreme of 100 grams per cubic meter, however, the rate of air flow did not fluctuate from the original cruising power, indicating that the ice forming in the induction system was being washed off the walls of the passages by the great volume of water. Results of tests made to determine the effect of moisture content of the air on the icing tendency are given in figures 17 to 20.

A series of tests was made at a throttle opening of 20°, in which the rate of air flow was varied between 2000 and 4000 pounds per hour. The results (figs. 24 and 25) indicated very little difference in icing tendency and a low rate of ice accretion. In another series of tests made at full-throttle opening (figs. 22 and 23) the air flow was varied from 6000 to 10,000 pounds per hour. Refrigeration ice formed very rapidly in the induction system during these latter tests. When the data of both groups of tests were compared together and with other results (figs. 26 to 31) it was evident, however, that as the rate of air flow was increased with constant rain density, the rate of ice accretion increased quite rapidly. It can be concluded that the rate of ice formation is a function of the total amount of water entering the induction system in a given period of time.

The results of tests made over a wide range of throttle opening revealed that the amount of throttle opening had no appreciable effect on the rate of ice formation. The data of these tests are given in figures 26 to 31.

In order to determine the possible effect of varying the mixture ratio on the rate of ice formation, tests were made at cruising power and also at full throttle. The results of these tests (figs. 32 and 33) showed, however, that the mixture ratio had little or no effect on the rate of icing.

As might be expected, a general examination of all the test data showed that as ice formed in the induction system during each test, the fuel-air ratio was changed. It was noted that below 40° F carburetor-air temperature, the mixture ratio became quite rich and that at 40° F or more the mixture ratio usually became lean. These effects were caused to a great extent by ice formations on the fuel nozzle bar. In the case of the higher range of temperatures, ice formed on the nozzle bar on the lower side of the fuel-injection holes, thereby reducing the suction at that point and causing the mixture to become lean. At lower temperatures, however, ice formed higher in the induction system and often on the nozzle bar above the fuel holes, thereby increasing the suction of the air through the carburetor venturi, enriching the mixture.

During most of the tests the water introduced into the intake air was the medium-droplet size of about 1-millimeter diameter. A few tests were made with smaller water droplets (about 30 to 50 microns in diam.) in order to determine the possible effect of water-droplet size on the icing tendency. The small amount of data obtained, however, was not considered sufficient on which to base a conclusion on the effect of water-droplet size.

In a number of the tests it was found that water particles of colloidal proportions were contained in the air to the extent of 1 or 2 grams per cubic meter at a humidity of less than 100 percent. In these instances no wetting action was observed on the metal surfaces of the air scoop, indicating that the water particles were less than 0.1 micron in diameter.

Very little difference in the rate of ice formation was found in a comparison of tests made at various pressure altitudes. These data are given in figures 34 to 36. It is interesting to note in passing that the air-flow curves of runs 62 and 159, made at different temperatures and altitudes, were almost identical.

A series of icing tests was made under propeller load curve conditions. In the first group of runs, in which the rain density was held at 5 grams per cubic meter, the time during which the air flow remained equal to the initial rate increased somewhat with decreasing initial air flow and throttle opening. In each run of the second group, in which the rain density was maintained equal to that of run T-1, the air-flow rate remained approximately at the initial rate for substantially equal time periods, apparently as a result of the constant rate of water ingestion. In all of the tests, however, (figs. 37 and 38) the air flow dropped at about equal rate. The results of these tests indicate that variation of propeller load curve conditions has little effect on severity of icing. However, the results do supply further evidence of the critical effect of water ingestion.

Tests at constant rain density of 10 grams per cubic meter with no fuel flowing into the carburetor were made in order to determine the severity of throttle icing in the induction system. The carburetor-air temperature was varied from 33° to 41° F in these tests. Results are shown in figure 39. At 33° and 35° F, throttle ice formed so rapidly that the rate of air flow was reduced from

4000 to 2000 pounds per hour in slightly more than 4 minutes. The range of carburetor-air temperatures in which rapid throttle icing occurred was found to be quite narrow, however. At 39° F, or above, the air flow was very slightly affected by the formation of throttle ice.

Typical temperatures of various parts of the metal passages measured by means of thermocouples are given in table I. Early in the program some tests were made in which the engine blower section was heated by means of a steam jet over a range of temperatures from 40° F up to 290° F. It was found, however, that in this range the temperature of the carburetor-adapter walls varied only from 8° to 10° F, or a change of 2° F.

It was noticed during some tests in which heated air was not applied to the carburetor adapter, that frost quickly formed on the outside metal walls. As each of these tests proceeded and ice formed within the adapter, the frost gradually melted. This effect can be seen in figures 9 and 10. Melting of the frost was caused by the formation of ice within the adapter which insulated the metal walls from the colder mixture.

Examination of the carburetor adapter after many of the test runs showed that the ice within the adapter was melted away from the metal walls and was sufficiently loose so that it could be easily removed.* It was evident that the loosened ice would have passed on through the induction system except that it was prevented from doing so by the irregular shape of the adapter and blower section and by the various protuberances within the induction system. In view of this phenomenon a special bulletin (reference 3) was prepared. This bulletin contained a recommendation that induction systems should be designed so that all protuberances are eliminated.

No tests were made to determine the effect of heating the carburetor adapter on the rate of ice formation. It was apparent from the effects described above, however, that the application of heat to the walls of those portions of an induction system in which ice usually forms would decrease the icing tendency.

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*This effect is illustrated in fig. 11, a photograph of carburetor adapter taken after test run 16.

The temperature of the mixture ranged from 40° F at carburetor-air temperature of 80° F down to 2° F at 32.5° F carburetor-air temperature. Most of the mixture temperature values were below 32° F. It can be seen from figure 40 that the lowest mixture temperature occurred with the most rapid rate of icing. The mixture temperatures fluctuated considerably during the tests and it was therefore not possible to maintain consistently accurate values. These fluctuations in the mixture temperatures were caused by ice forming around the thermocouple bulb and thus insulating it from the mixture stream. A special bulletin (reference 4) has been published to describe this effect. In figure 21 it will be noted that as ice formed in the adapter, the temperatures of the metal walls and the combustion mixture both approached 32° F, the mixture being at a slightly lower value.

In general, it was noted in observations made through the glass window of the carburetor adapter that in almost all of the tests made at a high air-moisture content, a considerable quantity of ice formed within the adapter before any appreciable reduction in the air flow could be measured. The air flow then dropped very rapidly, indicating that if this condition was experienced in flight the engine power would be considerably reduced due to ice in the induction system before the pilot had sufficient warning to take preventive measures.

A number of additional tests were made to establish the outer limits of the atmospheric conditions under which ice formed in the induction system tested. The results of these tests of borderline conditions are given in figure 41. The range of conditions under which the air flow was affected by ice is represented by the double-shaded portion of the chart. Under all conditions outside of the outer curve no ice was encountered. The intermediate area between the outer curve and the inner double-shaded portion indicates the range of conditions in which ice was formed in the induction system but did not affect the air flow or fuel flow.

The conditions under which ice formed in the induction system were determined by making visual observations through the glass windows of the fuel nozzle bar and the interior of the adapter. Fluctuations of less than 2 percent in the air flow and fuel flow were considered as not being detrimental to engine operation. Fluctuations greater than 2 percent are indicated in figure 41 by crosses in the lower area.

As a result of the basic conclusion that rate of ice accretion is a direct function of the total amount of water ingested with the intake air, a brief theoretical study has been made to investigate possible methods of preventing rain from entering induction systems. It is evident that this can be accomplished if, in the design of intake passages, advantage is taken of the inertia of water particles.

An analytical study of the paths of water particles of different sizes in an air stream disturbed by the presence of a circular cylinder is contained in reference 5. It was found that at a velocity of 200 miles per hour the area against which droplets impinged decreased with decrease in droplet size. The report indicates that water particles, 10 microns in diameter, or smaller, will follow the path of an air stream regardless of any change in direction, that the paths of particles 10 to 1000 microns in diameter will vary in proportion to their size, while droplets of 1 to 5 millimeters in size have sufficient inertia that they can be separated from an air stream of curved path. In reference 2 it is shown that droplets of 1-millimeter diameter can be expected with a rain density of 0.27 gram per cubic meter, droplets of 2-millimeter diameter would occur with rain density of 2 grams per cubic meter, and that 3-millimeter droplets would be found in a rain density of 5.4 grams per cubic meter. This indicates that in the range of average rainfall, water droplets have sufficient mass so that they can be separated from an air stream because of their inertia.

It has been found in other investigations that water particles, by virtue of their inertia, can be separated from the intake air in an air scoop containing a plenum chamber and rain trap. Separation of water droplets can also be accomplished by greatly changing the path of the intake air. Figures 12, 13, and 14 illustrate various possible design applications of this theory. The first of these is a rotatable air scoop which can be reversed in position during rainfall. The other two sketches illustrate how the inertia separation principle, together with provisions for preheating the intake air, might be applied to intake systems incorporated within engine cowlings. In the system shown in figure 13, the cold-air valve C is closed during precipitation and air is admitted through the alternate intake D. In the design represented by figure 14, the flapper valve C at the lip of the cowl inlet is turned to the vertical position during precipitation so that the air is forced around a 90° turn in entering the intake system. This design has the advantage that a portion of the dynamic ram of the intake air is retained during the operation of the alternate inlet.

RECOMMENDATIONS

In view of the critical effect of total rate of rain ingestion on induction-system icing, it is evident that the intake passages of an aircraft engine should be designed so that water is prevented as much as possible from entering the carburetor with the intake air.

In the design of induction systems all possible protuberances should be eliminated. Interior surfaces, if possible, should also have a slight draft in the downstream direction and should be designed so that ice cannot be retained by the shape of the induction passages. It is evident that in an induction system having such features, ice would form only to a slight extent, would then be melted away from the walls due to its own insulating effect, and would then pass on through the system.

Based on observations made during this research program, it appears that by the application of heat to the carburetor adapter, icing could be still further minimized. Tests to investigate this effect more thoroughly are recommended.

From the tests made during this research program it is evident that throttle icing should be considered in the design of carburetors.

Fuel nozzle bars, throttles, and other exposed elements of carburetors should be designed so that a minimum amount of ice will form on them.

In view of the observation made during many of the icing tests that the air flow was not affected until a quite large amount of ice had formed in the carburetor adapter, it appears that the development of a dependable instrument to indicate the presence of ice in induction systems is desirable.

CONCLUSIONS

The following conclusions should be considered in their entirety only in connection with the induction system tested.

1. Two factors, carburetor-air temperature and moisture content of the intake air, were found to be the major causes of induction-system icing. All other factors considered had a minor or negligible effect on the rate of ice formation for the range of conditions investigated when each of these factors was varied independently with the others held constant.

2. With free moisture present in the intake air, ice formed rapidly in the induction system at carburetor-air temperatures up to 50° F. The mixture ratio was affected by the formation of ice at temperatures up to 70° F.

3. Ice did not form in the induction system tested under any conditions at a carburetor-air temperature of 80° F or above.

4. The rate of ice accretion at an air-moisture content of 100-percent relative humidity or less, with no free moisture present in the air, was so slight that neither the rate of air flow nor the mixture ratio was affected.

5. With constant rain density, the rate of icing was increased in proportion to increase in rate of air flow. From these tests it is concluded that the rate of icing is a function of the total mass flow of rain per hour through the induction system.

6. From the data obtained in this investigation, it is recommended that air scoops of engine-induction systems be designed to prevent as much water as possible from entering the carburetor.

7. The interior passages of induction systems should be free from protuberances on which ice can adhere and should also, if possible, have a slight draft in the downstream direction.

8. The development of a dependable ice-warning indicator for induction systems is desirable.

National Bureau of Standards,
Washington, D. C.

APPENDIX I

TESTS OF ICE-WARNING INDICATORS

From the icing tests described in this report, it has been concluded that the development of a dependable ice-warning indicator for induction systems is desirable. It has been pointed out that during almost all of the tests in which ice formed in the induction system, the rate of air flow, usually taken as an index of the presence of ice, remained almost constant until a large amount of ice had formed in the carburetor adapter. This phenomenon was noted by means of visual observations through the glass window in the rear wall of the adapter. In view of this condition, and also as a result of requests from the military services and commercial air-line operators, a number of tests have been made in the Wright G-200 induction-system installation at the National Bureau of Standards in an effort to develop a satisfactory ice-warning indicator for general use.

One of the chief difficulties in indicating the presence of ice in an induction system results from the tendency of ice to form at different locations, according to the atmospheric conditions encountered. In the NACA induction-system icing investigation and in tests made by other agencies, it has been found that impact ice forms in the air scoop and in the duct leading to the carburetor; throttle ice, by definition, forms in the vicinity of the carburetor throttle; while refrigeration of fuel-evaporation ice forms on the downstream side of the gasoline-spray nozzles, usually in the carburetor adapter. It was also noticed during the icing tests that at different values of the carburetor-air temperature, ice formed in different locations for each of the three types of ice. It is evident that an effective ice-warning indicator should be capable of detecting ice in the induction system regardless of the point where ice forms.

The ice-warning indicators which were tested are listed as follows:

(1) Anemometer type ice-warning indicator

(2) Cunningham ice-warning indicator

(3) Muter ice-warning indicator

(4) American Airlines ice-warning indicator

(5) National Bureau of Standards ice-warning indicator

All of these instruments with the exception of the anemometer type are described in reference 6.

The anemometer unit was installed in the carburetor adapter and mounted on the shaft of a small generator. The flow of air through the induction system caused the rotor to revolve and the resulting electric-current generator was indicated on an ammeter. As ice formed on the rotor, its speed decreased until it finally stopped because of being frozen solidly in the adapter. This device indicated the presence of ice but was considered unsatisfactory because it was subject to frequent repair resulting from damage to the rotor unit by ice and because the rotor in itself greatly increased the formation of ice in the induction system. It became evident in the tests of this device and in the program of icing tests that all possible obstructions should be eliminated from the interior of an induction system in order to reduce ice accretion.

A number of tests were made on several versions of the Cunningham instrument. When first tested, this device, which indicates the change in a pressure differential in an induction system due to ice accretion, responded only to localized ice formations and for this reason was operative only through a limited range. As the instrument was developed further it was found possible to adjust the sensitivity. It appears that in any further development of this device the range of indication must be further extended so that it will be more effective in varying conditions. In this way the location of the units in the induction system will not be so critical. One advantage of the Cunningham indicator is its light weight, several ounces per unit, indicating that several of these instruments might be installed within an induction system to indicate the presence of ice at any of several points where it might occur.

The Muter photoelectric cell-type indicator, which was mounted in the carburetor adapter, was found to be satisfactory in warning of the presence of ice. By recessing both the photoelectric cell and the light source in opposite walls of the adapter, the sensitivity of indication could be regulated. It was found that ice particles formed in these two recesses of the walls regardless of the other points where refrigeration ice was deposited. As ice formed, the reading of the milliammeter gradually increased to a full-scale deflection, indicating that the adapter was being filled with ice. This full-scale reading was usually reached several minutes before any change could be noticed in the rate of air flow.

The American Airlines instrument is a photoelectric cell-type indicator similar to the Muter ice-warning indicator, with the principal difference being that the photoelectric cell has a greater output and the current is read directly on a microammeter. This indicator was considered satisfactory on the basis of the limited tests made. One possible difficulty in the use of this instrument is that the sensitive microammeter might not be capable of withstanding the engine vibration to which it would be subjected.

The ice-warning indicator developed by members of the staff of the National Bureau of Standards, a modified photoelectric type, was found to provide satisfactory indication of the presence of ice during the few tests made on this instrument. The design of this ice-warning indicator has been turned over to an equipment manufacturer for possible commercial development.

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*The Civil Aeronautics Board is distributing this memorandum.

TABLE I

Blower Section
Wright Cyclone
1820-G 200
Holley 1375 F
Carburetor

TEMPERATURES MEASURED DURING ICING TESTS

Run	Air flow (lb/hr)	Carburetor air temperature (deg F)	Initial mixture ratio (F/a)	Mixture temperature (deg F)	Engine compartment temperature (deg F)	Top rear adaptor (deg F)	Bottom rear adaptor (deg F)	No. 2 blower section (deg F)	No. 7 blower section (deg F)	No. 8 blower section (deg F)
13	3820	40	.0746	3	100	8	17	36	37	39
16	3800	40	.0750	4	98	9	19	35	40	41
17	4000	40	.074	15	98	28	37	41	40	39
18a	3950	40	.0719	15	93	22	33	13	20	23
35	2990	40	.070	7	98	15	30	25	15	17
36	1990	40	.070	2	95	8	32	18	17	16
43	2960	40	.069	15	105	24	33	35	17	20
64	4030	32	.069	-2	95	15	31	32	39	14
65	3648	33	.077	2	95	—	14	32	25	30
A-1	4110	35	.069	0	101	21	21	32	21	20

(See fig. 2 for location of thermocouples)

W-97

TABLE II

TABULATION OF RESULTS

Run number	Altitude (ft)	Length of run (min)	Carburetor air temp. (°F)	Water conc. (1)	Droplet size (2) 1-2-3	Carburetor air flow (lb/hr) setting	Carburetor air flow (lb/hr) minimum	Throttle angle (deg)	F/A setting	F/A ratio maximum	F/A ratio minimum	Fuel temperature (°F)	Initial throttle drop (in. Hg)	Time at constant air flow (min)	Time during decrease of air flow (min)	Blower case metal temp. (°F) maximum	Blower case metal temp. (°F) minimum	Effect on engine operation (3) air flow	Effect on engine operation (3) F/A	Remarks
7	------	9.5	32.5	10	2	4000	1900	19	.062	.106	.054	70	---------	0	9.5	46	32	2	4	Very rapid icing
8	900	10	35	10	2	4000	2140	19	.070	.091	.065	67	10.4	0	9.5	-----	-----	2	2	Rapid icing
9	806	20	40	10	2	4000	2000	19	.070	.071	.038	70	10.2	8	12	-----	-----	2	3	Rapid icing
10	806	27	45	10	2	4000	2150	19	.070	.070	.030	70	10.25	9	18	-----	-----	2	3	Rapid icing
11	598	39	50	10	2	4000	2240	15	.070	.073	.037	70	10.1	9	30	57	55	1	1	Gradually increasing ice formation
12	673	40	55	10	2	4000	4000	15	.070	.070	.067	73	10.2	40	0	53	45	0	0	No appreciable icing
12a		28	59	10	2	3600	3500	21.5	.070	.072	.062	71	7.8	16.5	9.5	41	32	1	1	Very slight icing
12b	-26	30	65	10	2	4000	4000	21	.070	.069	.069	70	11.5	30	0	46	37	0	0	Trace of ice visible
12c		27	67	10	2	4000	3800	21.5	.070	.072	.070	76	7.91	27	0	42	33	0	0	Very slight icing
12d		25	74	10	2	3600	3720	21.5	.078	.078	.081	76	7.8	25	0	47	38	0	0	Very slight icing
12e	1091	35	80	10	1	4000	4000	21	.070	.069	.069	75	10.70	35	0	55	50	0	0	No visible icing
13	730	30	40	75%	2	4000	3930	21.5	.070	.073	.072	50	7.85	30	0	43	36	0	0	Very slight stabilized icing
14	730	30	39	100%	2	4000	3880	21.5	.070	.077	.074	71	7.85	30	0	24	14	0	0	No apparent icing
15	768	55	39	5	2	4000	2150	21.5	.070	.080	.055	72	8.00	24	31	34	28	1	1	Gradually increasing ice formation
16	777	17.5	39	10	2	4000	1950	21.5	.070	.074	.048	72	8.5	2	15.5	42	35	2	2	Increasing ice formation
17	532	10	40	20	2	4000	2420	20	.070	.075	.045	71	8.1	3	7	43	40	2	3	Rapid icing
18	598	5	40	30	2	4000	1650	20	.070	.070	.050	71	8.1	0	5	40	38	2	3	Rapid icing
18a		5	40	32	2	3900	2280	22	.070	.115	.072	67	11.4	4	1	40	16	2	2	Rapid icing
18b		6	40	42	2	"	1500	22	.070	.072	.054	68	11.5	4	2	42	18	2	2	Rapid icing
18c		4	40	57	2	"	2100	22	.070	.072	.043	67	11.6	3	1	37	22	2	3	Very rapid icing
18d		8	40	70	2	"	1800	22	.070	.072	.049	61	11.7	5	3	42	28	2	3	Rapid icing
18e		9	40	80	2	"	1600	22	.070	.072	.051	62	11.6	6	3	35	24	2	3	Rapid icing
18f		10	40	90	2	"	1800	22	.070	.072	.042	63	11.8	7	3	37	19	2	3	Rapid icing
18g		15	40	100 g/m³	2	"	3850	22	.070	.072	.070	64	11.2	15	0	42	42	0	0	No apparent icing
20		30	35	100%	2	4000	3650	20	.070	.081	.079	71	7.9	30	0	34	24	0	0	No apparent icing
21		20	35	5	2	4000	3750	20	.070	.097	.079	70	7.9	5	15	35	20	1	2	Increasing icing
22		7.5	35	10	2	4000	3150	20	.070	.081	.089	72	7.8	0	7.5	35	20	2	2	Rapidly increasing icing
23		2	35	20	2	4000	2800	20	.070	.081	.110	72	7.8	0	2	33	19	2	2	Very rapid icing
25	3660	14	35	5	2	10000	3650	73	.106	.121	.080	66	4.9	0	14	42	22	2	1	Rapid icing. F/A rose and fell off
25a	3617	18	40	5	2	10000	1400	73	.120	.152	.075	59	2.10	0	18	32	15	2	1	Rapid icing. F/A rose and fell off
26	2098	16	35	5	2	8000	2200	73	.106	.112	.067	64	1.8	0	16	42	24	2	1	Rapid icing. F/A rose and fell off
26a	2644	30	40	5	2	8000	3800	73	.107	.107	.098	60	1.35	0	30	40	26	2	1	Rapid icing. F/A fluctuated
27	1990	14	35	5	2	6000	2350	73	.106	.106	.072	63	.95	0	14	38	27	2	1	Rapid icing
27a	2098	27	40	5	2	6000	2400	73	.139	.144	.084	81	12.2	6	21	40	34	2	1	Rapid icing
31	986	30	40	5	2	6000	5300	20	.070	.077	.054	73	12.05	30	0	35	22	0	1	Slight stabilized icing
32	749	90	40	5	2	4000	2770	21.5	.070	.071	.049	-	11.10	11	79	49	28	1	3	Gradually increasing icing
33	467	90	40	5	2	3000	2710	20	.070	.070	.062	75	3.80	38	52	48	29	1	1	Slightly increasing icing
35	560	97	40	5	2	3000	2060	15	.070	.070	.043	70	13.45	65	32	45	23	1	3	Gradually increasing icing
36	392	66	40	5	2	2000	1960	15	.070	.071	.064	75	3.10	66	0	38	20	0	1	Slight icing
38	1398	15	35	5	2	6000	3300	73	.100	.101	.077	57	.71	0	15	44	15	2	1	Rapid icing
38a	1863	8	35	5	2	7000	2450	73	.100	.101	.046	63	1.0	0	8	44	26	2	3	Very rapid icing
38b	1446	18	40	5	2	6000	2400	73	.100	.099	.071	57	.72	0	18	40	27	2	1	Very rapid icing
38c	2108	10	40	5	2	7000	3000	73	.100	.101	.063	57	1.00	0	10	42	27	2	1	Very rapid icing
39	1883	18	35	5	2	6000	3400	65	.100	.100	.059	54	1.80	0	18	43	24	2	1	Very rapid icing
39a	2079	10	35	5	2	7000	1370	65	.100	.102	.072	48	1.81	0	10	43	20	2	1	Rapid icing
39b	1446	18	40	5	2	6000	2700	65	.100	.102	.070	60	.98	0	18	45	26	2	1	Rapid icing
39c	2108	10	40	5	2	7000	2750	65	.100	.101	.060	56	1.35	0	10	50	20	2	1	Rapid icing

TABLE II.- TABULATION OF RESULTS (Continued)

Run number	Altitude (ft)	Length of run (min)	Carburetor air temp. (°F)	Water conc. (1)	Droplet size (2) 1-2-3	Carburetor air flow (lb/hr) setting	Carburetor air flow (lb/hr) minimum	Throttle angle (deg)	F/A setting	F/A ratio maximum	F/A ratio minimum	Fuel temperature (°F)	Initial throttle drop (in. Hg)	Time at constant air flow (min)	Time during decrease of air flow (min)	Blower case metal temp. (°F) maximum	Blower case metal temp. (°F) minimum	Effect on engine operation (3) air flow	Effect on engine operation (3) F/A	Remarks
40	1639	18	35	5	2	6000	3300	50	.100	.099	.078	56	2.1	0	18	44	18	2	1	Rapid icing
40a	2010	10	35	5	2	7000	2900	50	.100	.098	.045	50	3.25	0	10	42	24	2	1	Rapid icing
40b	1494	18	40	5	2	6000	2700	50	.100	.100	.063	56	1.95	0	18	45	24	2	1	Rapid icing
40c	2207	14	40	5	2	7000	3500	50	.100	.099	.031	52	3.00	0	14	51	31	2	3	Mixture fluctuated before falling off. Rapid icing
41	1475	20	35	5	2	6000	3650	35	.100	.101	.056	53	5.36	0	20	44	20	2	1	Rapid icing
41a	1814	9	35	5	2	7000	1900	39	.100	.117	.063	53	11.2	0	9	42	12	2	1	F/A rose before falling off. Rapid icing
41b	1446	26	40	5	2	6000	4450	35	.100	.101	.072	61	5.8	0	26	50	32	2	1	Rapid icing
41c	8108	12	40	5	2	7000	3250	38	.100	.159	.102	52	11.5	0	12	50	20	2	4	F/A dropped before rising beyond operating range
42	645	66	40	5	2	3000	2950	50	.070	.072	.070	--	0.5	66	0	52	23	0	0	No appreciable icing
43	233	90	40	5	2	3000	2600	35	.070	.071	.063	68	1.15	12	78	40	20	1	1	Gradually increasing icing
44	373	75	40	5	2	3000	1970	25	.070	.070	.057	69	2.0	6	69	39	29	1	1	Gradually increasing icing
45	467	90	40	5	2	3000	2710	20	.070	.070	.062	75	3.8	38	52	48	29	1	1	Slight increasing icing
46	560	97	40	5	2	3000	2060	15	.070	.070	.048	70	13.45	65	32	45	23	1	3	Gradually increasing icing
42a	986	33	40	5	2	4000	2680	50	.070	.072	.059	69	.80	0	33	38	32	1	1	Slowly increasing ice formation
43a	1072	48	40	5	2	4000	2230	35	.070	.075	.051	72	1.75	0	48	32	26	1	1	Slowly increasing ice formation
44a	1081	80	40	5	2	4000	3080	25	.070	.073	.047	66	4.25	0	80	36	22	1	1	Slowly increasing ice formation
45a	-----	75	40	5	2	4000	2000	22	.070	.071	.050	66	9.35	0	75	32	22	1	1	Slowly increasing ice formation
51	692	25	40	5	2	4000	1570	21	.060	.071	.042	59	13.8	0	25	33	22	1	3	Fluctuating air flow. Increasing ice formation
52	834	12	40	5	2	4000	2450	21	.080	.140	.085	62	11.2	0	12	29	26	1	4	Fluctuating air flow. Increasing ice formation
53	910	24	40	5	2	4000	3450	21	.090	.097	.087	64	11.6	0	24	33	22	2	1	Increasing icing
54	1024	12	35	5	2	6000	2600	73	.090	.093	.085	65	1.0	0	12	38	28	2	1	Rapid icing
55		14	35	5	2	6000	2350	73	.106	.106	.072	63	.95	0	14	38	27	2	1	Rapid icing
56	1072	12	35	5	2	6000	2700	73	.115	.113	.079	64	1.0	0	12	42	25	2	1	Rapid icing
60	570	52	35	5	2	4000	2400	73	.070	.069	.052	63	.50	10	42	35	22	1	1	Increasing icing
60a	607	60	40	5	2	4000	2500	73	.070	.070	.052	54	.50	10	50	39	23	1	1	Gradually increasing icing
61	9079	26	35	5	2	4000	2250	73	.070	.074	.055	60	1.95	12	14	44	15	1	1	10,000 ft altitude. Gradually increasing icing
62	19578	43	35	5	2	4000	1650	73	.070	.121	.063	65	.20	4	39	48	18	1	4	20,000 ft altitude. Fluctuating mixture. Increasing icing
62a	18569	60	40	5	2	4000	3600	73	.070	.078	.063	66	2.10	15	45	54	16	1	2	20,000 ft altitude. Fluctuating mixture. Slight icing
130	9844	50	40	100%	2	4000	4000	20	.080	.081	.077	74	7.5	50	0	35	27	0	0	No apparent icing
131	636	26	40	5	2	4000	1830	20	.080	.080	.066	-----	6.25	4	22	37	32	1	1	Mixture fluctuates. Increasing icing
132	692	8	40	10	2	4000	1650	20	.080	.086	.065	-----	6.94	0	8	38	30	2	1	Mixture fluctuated. Rapid icing
132a	636	6	40	15	2	4000	2450	20	.080	.081	.060	-----	7.63	2	4	56	30	2	1	Rapid icing
136	730	30	39	100%	----	3880	3880	21.5	.077	.080	.077	71	7.85	30	0	24	14	0	0	No apparent icing
137	872	32	40	5	1	4000	1900	21	.070	.072	.039	75	10.3	11	21	32	27	2	3	Rapid icing
138	967	16	40	10	1	4000	1930	21	.070	.073	----	74	10.35	5½	10½	33	28	2	3	Very rapid icing
158	919	60	40	5	2	4000	2520	35	.070	.071	.063	64	1.80	3	57	50	29	1	1	Gradually increasing icing
159	9360	42	40	5	2	4000	1700	35	.070	.074	.054	58	3.45	0	42	67	32	1	1	10,000 ft altitude. Increasing icing. Fluctuating F/A
160	730	10	33	10	2	4000	1980	21.5	----	----	----	--	10.7	0.5	5.5	--	--	2	-	Throttle frozen. Ice in venturi tubes
161	730	6	35	10	2	4000	1950	21.5	----	----	----	--	10.7	0	4.5	--	--	2	-	Rapid icing. Throttle frozen
162	730	13	37	10	2	4000	2270	21.5	----	----	----	--	10.6	0	13	--	--	2	-	Rapid icing
163	730	10	36	10	2	4000	1920	21.5	----	----	----	--	10.9	0	9	--	--	2	-	Throttle frozen
164	777	18	38	10	2	4000	3520	21.5	----	----	----	--	10.8	0	14	--	--	1	-	Throttle frozen
165	542	15	38	10	2	3000	2530	16	----	----	----	--	13.8	0.5	10	--	--	1	-	Stable icing
166	777	15	39	10	2	4000	3800	21.5	----	----	----	--	10.7	0	5	--	--	1	-	Throttle frozen
167	995	30	40	10	2	4000	3770	21.5	----	----	----	--	10.4	0	17	--	--	1	-	Slight icing in venturi tubes
168	853	30	41	10	2	4000	4000	21.5	----	----	----	--	10.7	30	0	38	34	0	-	No ice
T-1	-----	15	40	5	2	6000	2420	37.5	.070	.070	.053	66	4.9	0	15	61	50	2	1	Rapid icing
T-1a	-----	15	40	5	2	6000	2420	37.5	.070	.070	.053	66	4.9	0	15	61	50	2	1	Rapid icing
T-2	-----	22	40	5	2	5000	2100	29	.070	.070	.051	68	7.25	4	18	62	27	2	1	Rapid icing
T-2a	-----	17	40	5	2	5000	1750	27.5	.070	.075	.057	68	7.30	4	13	66	32	2	1	Rapid icing
T-3	-----	22	40	5	2	4000	2300	21.5	.070	.072	.051	68	9.15	0	22	36	30	2	1	Rapid icing
T-4	-----	60	40	5	2	3000	2500	16.5	.070	.071	.065	66	10.5	8	52	42	28	1	1	Slight icing
T-4a	-----	16	40	10	2	3000	1550	17	.070	.070	.047	65	10.45	0	16	67	35	2	3	Rapid icing

TABLE II.- TABULATION OF RESULTS (Concluded)

Run number (4)	Altitude (ft)	Length of run (min)	Carburetor air temp. (°F)	Water conc. (1)	Droplet size (2) 1-2-3	Carburetor air flow (lb/hr) setting	Carburetor air flow (lb/hr) minimum	Throttle angle (deg)	F/A setting	F/A ratio maximum	F/A ratio minimum	Fuel temperature (°F)	Initial throttle drop (in. Hg)	Time at constant air flow (min)	Time during decrease of air flow (min)	Blower case metal temp. (°F)	Effect on engine operation (3) air flow	Effect on engine operation (3) F/A	Remarks
169	S.L.	6	31	70%	2	4050	4050	21.5	.060	.060	.060	43	--------	6	0	-----------	0	0	Faint frost
170	S.L.	6	35	72%	2	4050	4050	21.5	.061	.060	.060	43	--------	6	0	-----------	0	0	Faint frost
171	S.L.	6	45	47%	2	4050	4050	21.5	.060	.060	.060	43	--------	6	0	-----------	0	0	Very faint trace around bolts
172	S.L.	6	50	47%	2	4000	4000	21.5	.066	.066	.066	53	--------	6	0	-----------	0	0	Very faint trace around bolts
173	S.L.	6	55	50%	2	4050	4050	21.5	.065	.065	.060	54	--------	6	0	-----------	0	0	Faint trace around bolts
174	S.L.	6	60	37%	2	4050	4050	21.5	.066	.066	.066	59	--------	6	0	-----------	0	0	Faint trace of ice on bolts and in adapter
175	S.L.	6	65	40%	2	4050	4050	21.5	.068	.068	.068	61	--------	6	0	-----------	0	0	No ice
176	S.L.	6	65	68%	2	4200	4200	21.5	.067	.067	.067	-----	--------	6	0	-----------	0	0	Ice in adapter on bolts
177	S.L.	6	70	50%	2	4250	4250	21.5	.068	.068	.068	-----	--------	6	0	-----------	0	0	Ice on obstructions
178	S.L.	6	45	40%	2	4000	4000	21.5	.069	.070	.069	42	--------	6	0	-----------	0	0	No ice
179	S.L.	6	65	30%	2	4050	4050	21.5	.068	.068	.068	58	--------	6	0	-----------	0	0	No ice
180	S.L.	6	65	52%	2	4050	4050	21.5	.067	.067	.067	61	--------	6	0	-----------	0	0	Frost in adapter
181	S.L.	6	65	38%	2	4050	4050	21.5	.068	.068	.068	61	--------	6	0	-----------	0	0	Very faint trace
182	S.L.	6	65	30%	2	4050	4050	21.5	.068	.068	.068	60	--------	6	0	-----------	0	0	No ice
183	S.L.	6	65	10g	2	4000	4000	21.5	.073	.076	.072	-----	--------	9	0	-----------	0	2	Ice on nozzle bar. Mixture rich
184	S.L.	9	65	5g	2	4000	4000	21.5	.072	.072	.071	61	--------	9	0	-----------	0	0	Ice on nozzle
185	S.L.	9	65	15g	2	4000	4000	21.5	.073	.073	.072	65	--------	9	0	-----------	0	0	No ice
186	S.L.	9	50	17g	2	4000	3550	21.5	.073	.074	.062	50	--------	3	6	-----------	1	1	Drop in flow both gas and air
187	S.L.	12	50	25g	2	3950	3850	21.5	.056	.076	.058	50	--------	6	6	-----------	1	2	Fluctuations
188	S.L.	9	50	35g	2	3950	3000	21.5	.076	.076	.056	-----	--------	3	6	-----------	1	1	Change in air flow and fuel flow
189	S.L.	12	50	40g	2	4080	4050	21.5	.068	.068	.067	50	--------	9	3	-----------	0	0	Slight effect on engine
190	S.L.	9	50	45g	2	4030	4030	21.5	.071	.071	.070	51	--------	9	0	-----------	0	0	Nozzle bar icing
191	S.L.	9	50	50g	2	4030	4000	21.5	.071	.071	.068	50	--------	6	3	-----------	0	1	Slight icing on nozzle
192	S.L.	9	50	55g	2	4030	4030	21.5	.071	.073	.070	50	--------	9	0	-----------	0	2	Unstable icing
193	S.L.	9	50	60g	2	4030	4030	21.5	.072	.073	.072	49	--------	9	0	-----------	0	2	Unstable icing
194	S.L.	9	50	65g	2	4000	4000	21.5	.075	.076	.075	50	--------	9	0	-----------	0	0	Nozzle bar icing
195	S.L.	9	50	70g	2	4000	3950	21.5	.075	.076	.075	50	--------	6	3	-----------	0	2	Nozzle icing
196	S.L.	10	60	60g	2	4000	4000	21.5	.072	.074	.072	60	--------	10	0	-----------	0	2	Slight nozzle icing
197	S.L.	9	60	65g	2	4030	4030	21.5	.073	.073	.073	60	--------	9	0	-----------	0	0	Slight nozzle icing
198	S.L.	9	60	70g	2	4030	4030	21.5	.073	.073	.073	60	--------	9	0	-----------	0	0	No ice

[1]Water concentration in percent relative humidity or in grams per cubic meter of dry air in excess of 100 percent relative humidity.
[2]Droplet size 1, small; 2, medium; 3, large.
[3]Effect on engine operation
Air flow 0, no effect; 1, gradual drop; 2, rapid drop.
F/A ratio 0, no effect; 1, slight drop; 2, slight increase; 3, drop beyond operating range; 4, increase beyond operating range.
[4]Test runs 169 to 198 cover the investigation of limiting icing conditions of the R-1820, G-200 induction system.

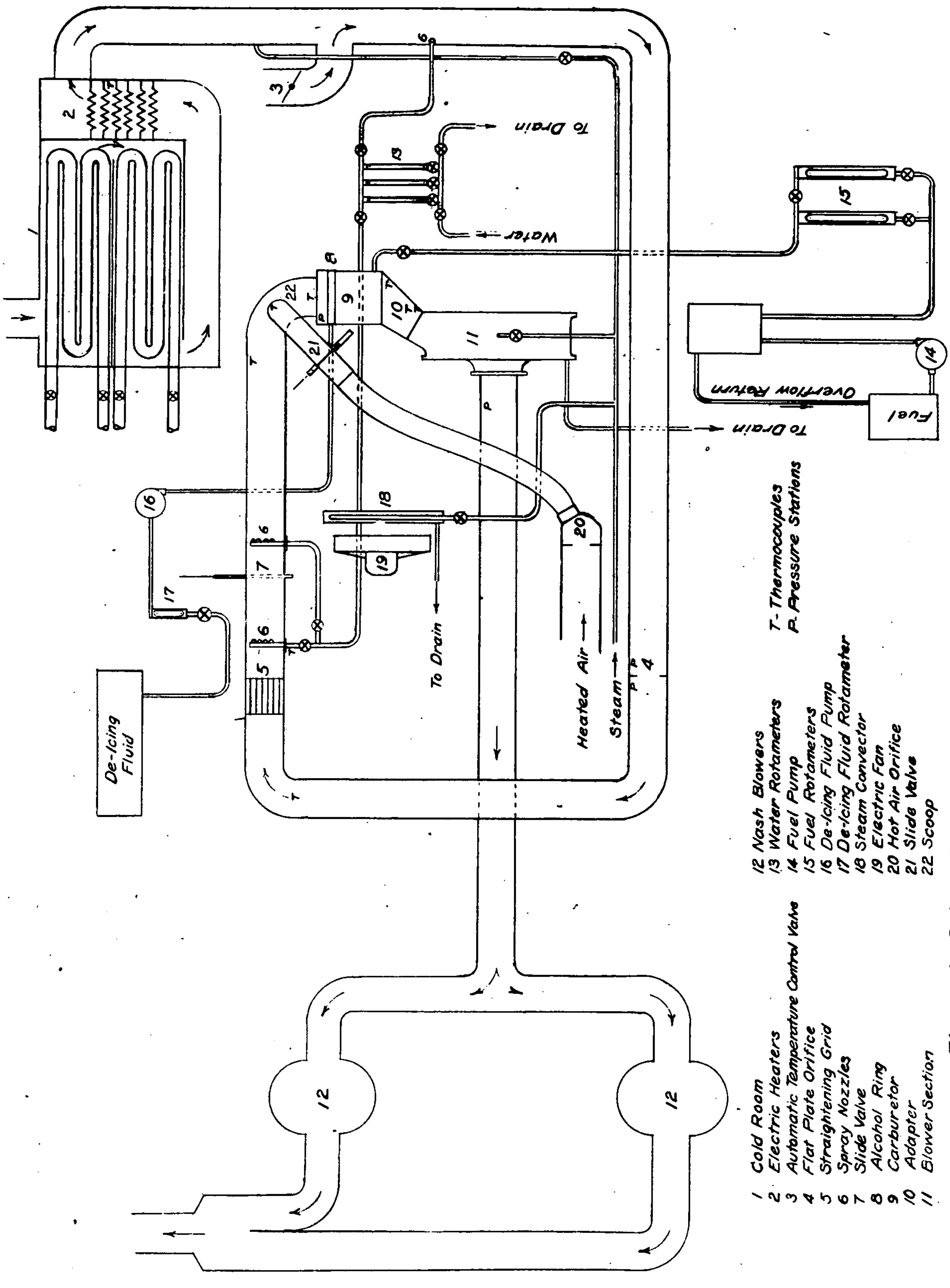

Figure 1.- Schematic Diagram Of Induction-System Testing Apparatus

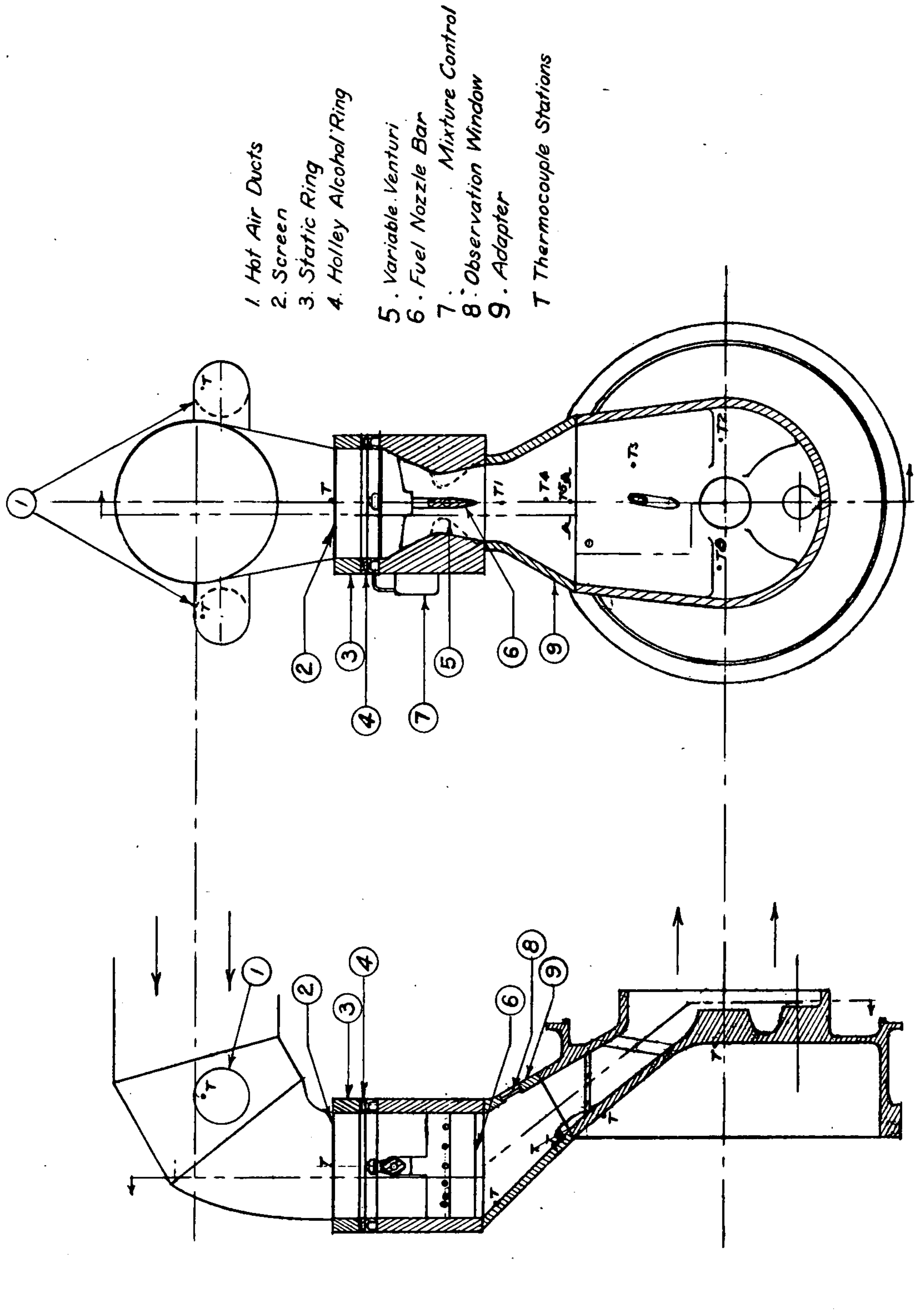

Figure 2, Schematic Diagram of Induction System

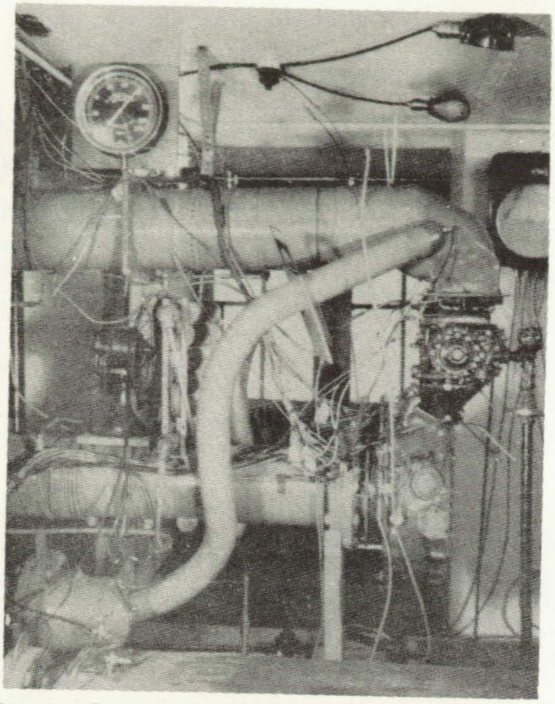

Figure 3.- General view of induction system icing testing apparatus, (showing cold and hot air intake ducts, carburetor, engine blower section, and outlet duct.)

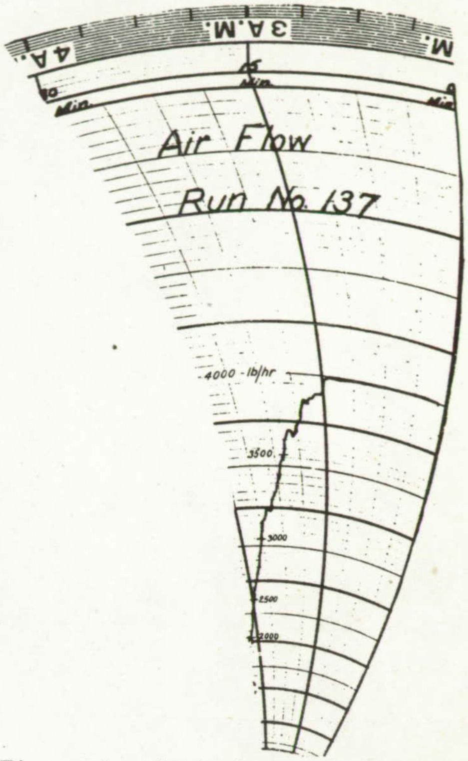

Figure 4.- Typical recorded air flow chart.

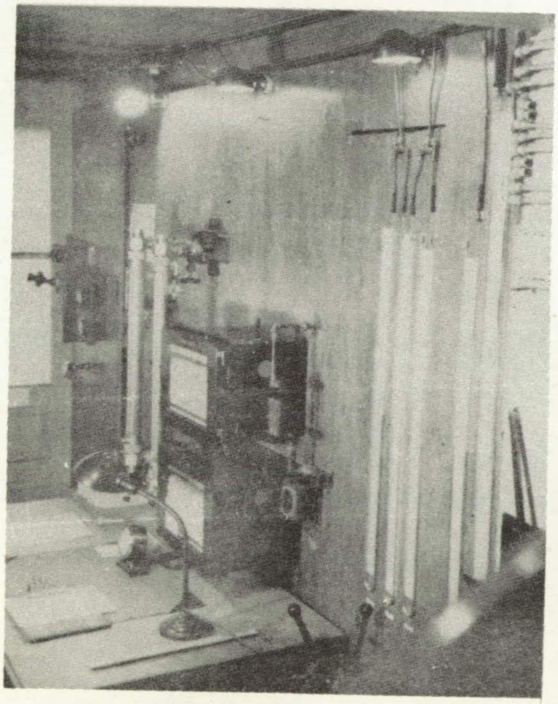

Figure 5.- Recording potentiometers, manometers, mixture and throttle manual controls, and gasoline rotameters.

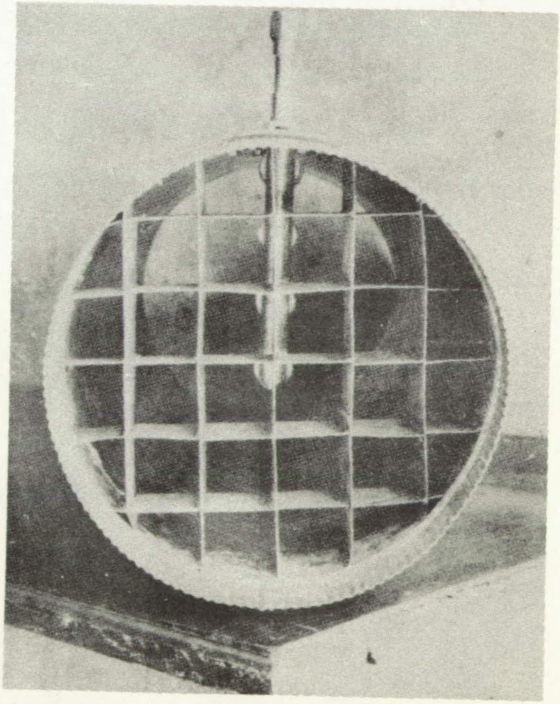

Figure 6.- Straightening grid in inlet air duct.

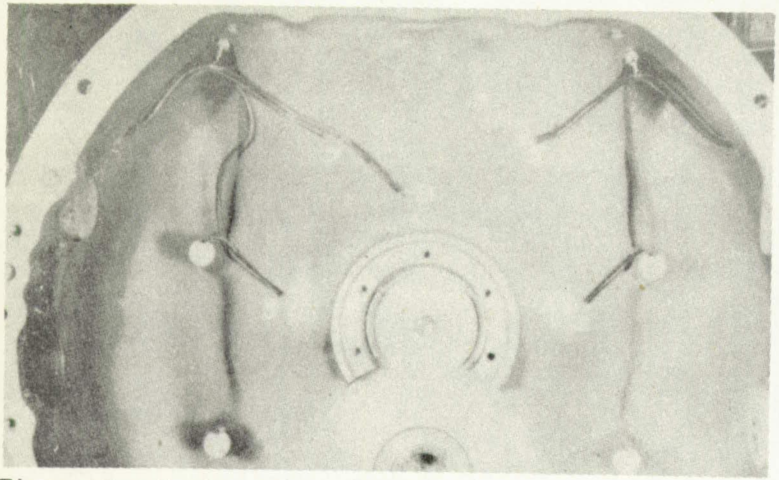

Figure 7.- Engine blower section, showing thermocouples installed.

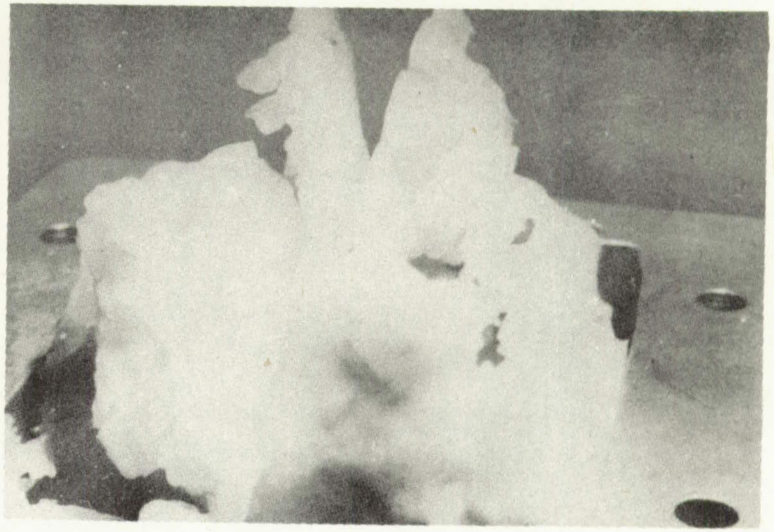

Figure 8.- Ice formation in adapter after run number 9. (See figure 15.)

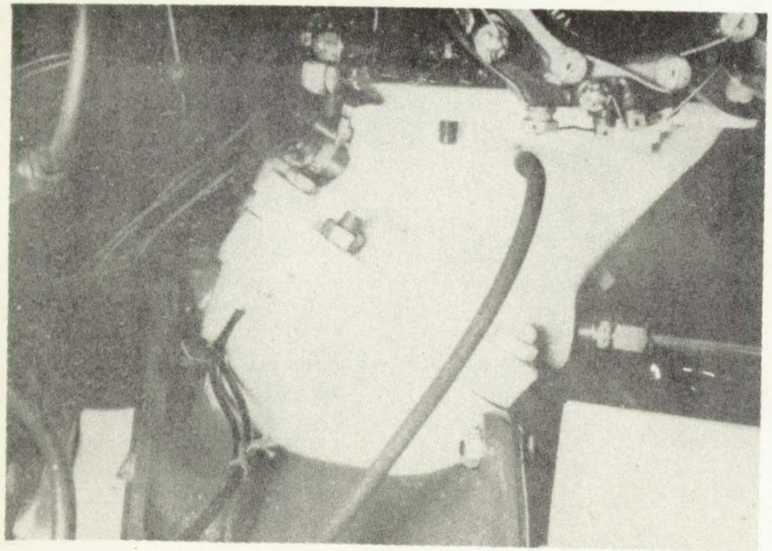

Figure 9.- Frosting of carburetor adapter during test run

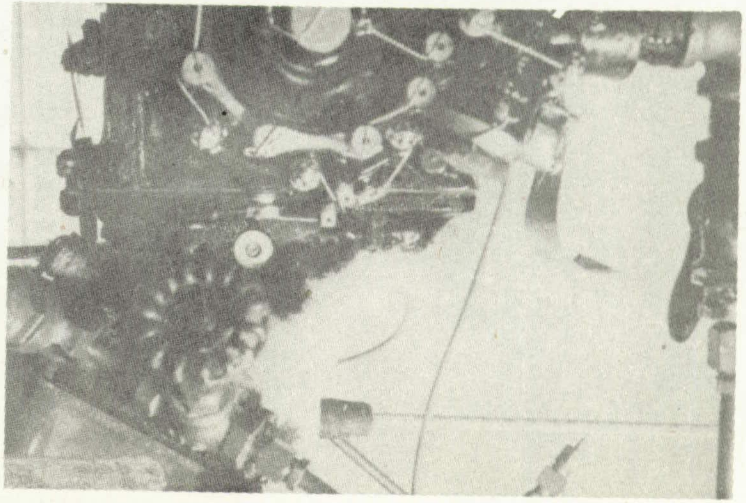

Figure 10.- Recession of frost on carburetor adapter resulting from ice forming within adapter.

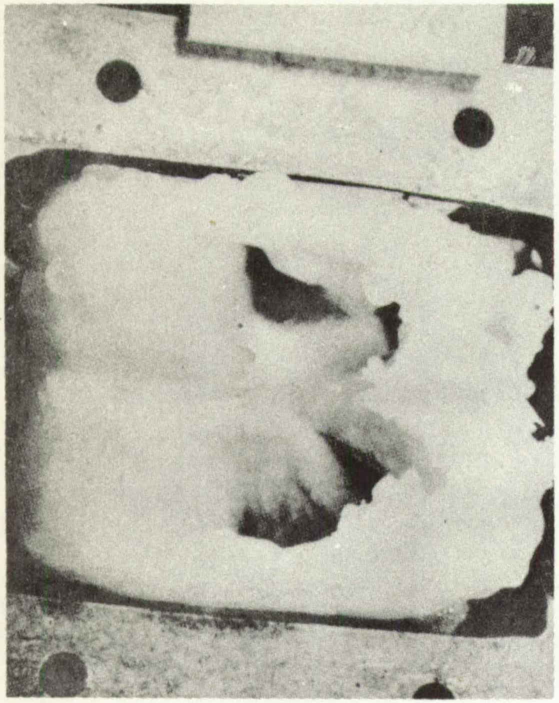

Figure 11.- Ice formation in adapter after run no. 16.(See figure 17.)

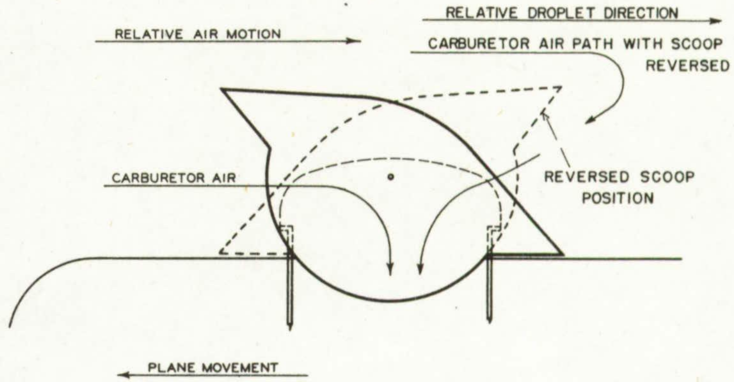

Figure 12.- Outline of a reversible air scoop.

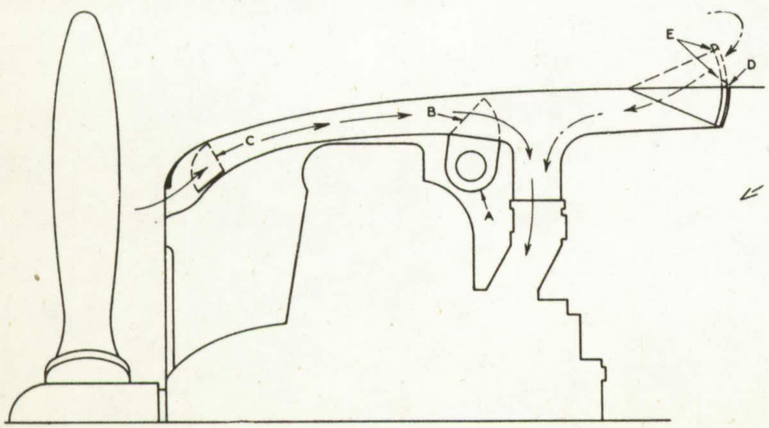

Figure 13.- Precipitation shield applied to provide an alternate air source for installation with cowl scoop.
A, warm air muff
B, warm air valve
C, valve to close off wet air
D, dry cold air intake (solid lines indicate closed position; dotted lines, open position)
E, drain lip for removal of water in stagnation layer

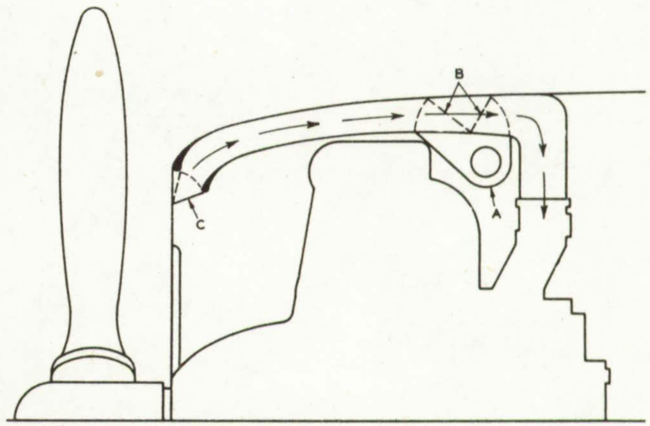

Figure 14.- Principle of inertia separation applied to cowl scoop. A, warm air muff; B, warm air valves; C, flapper valve.

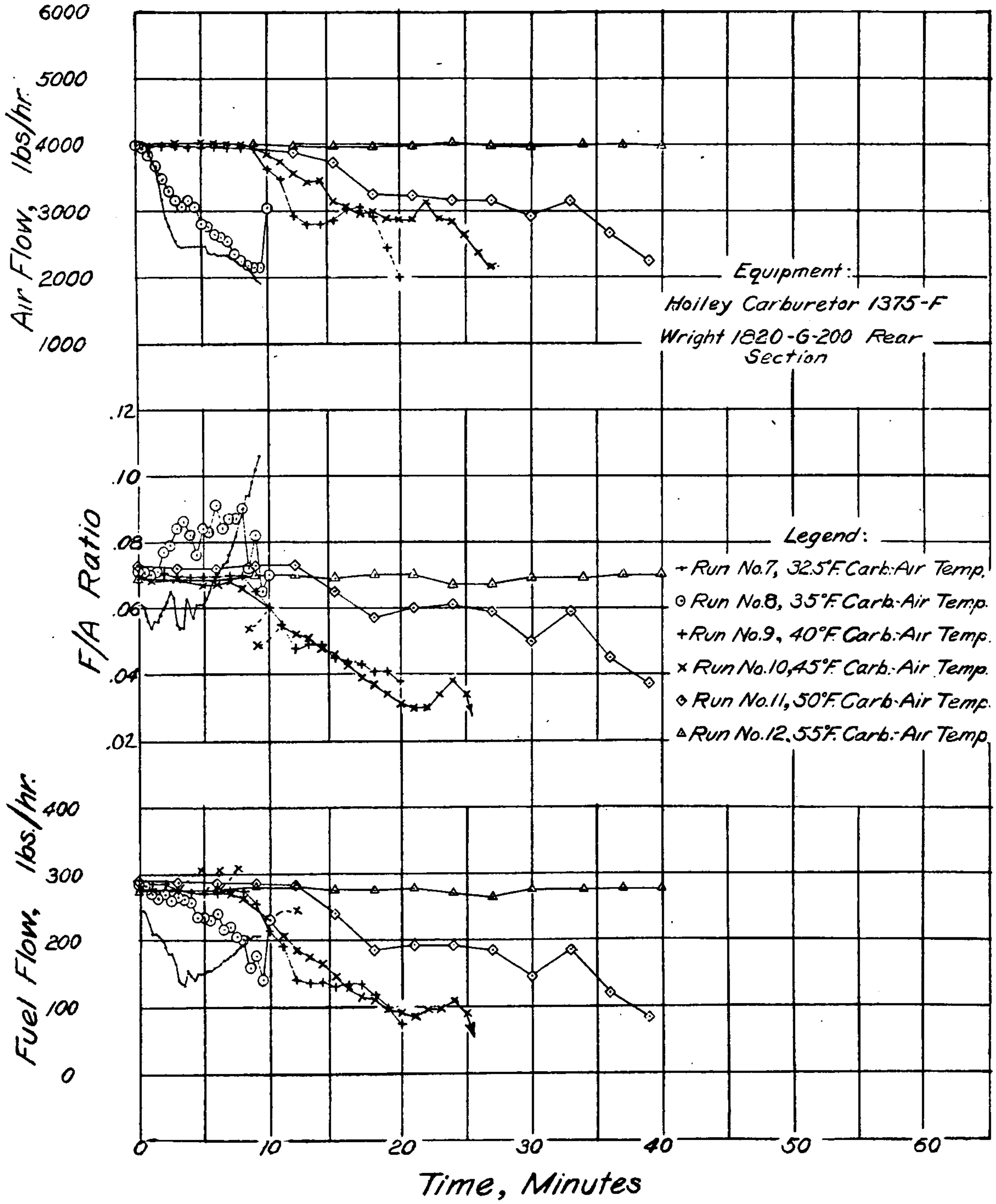

Figure 15.- Effect of varying carburetor-air temperature with initial moisture content 100 percent R.H. + 10g/m^3.

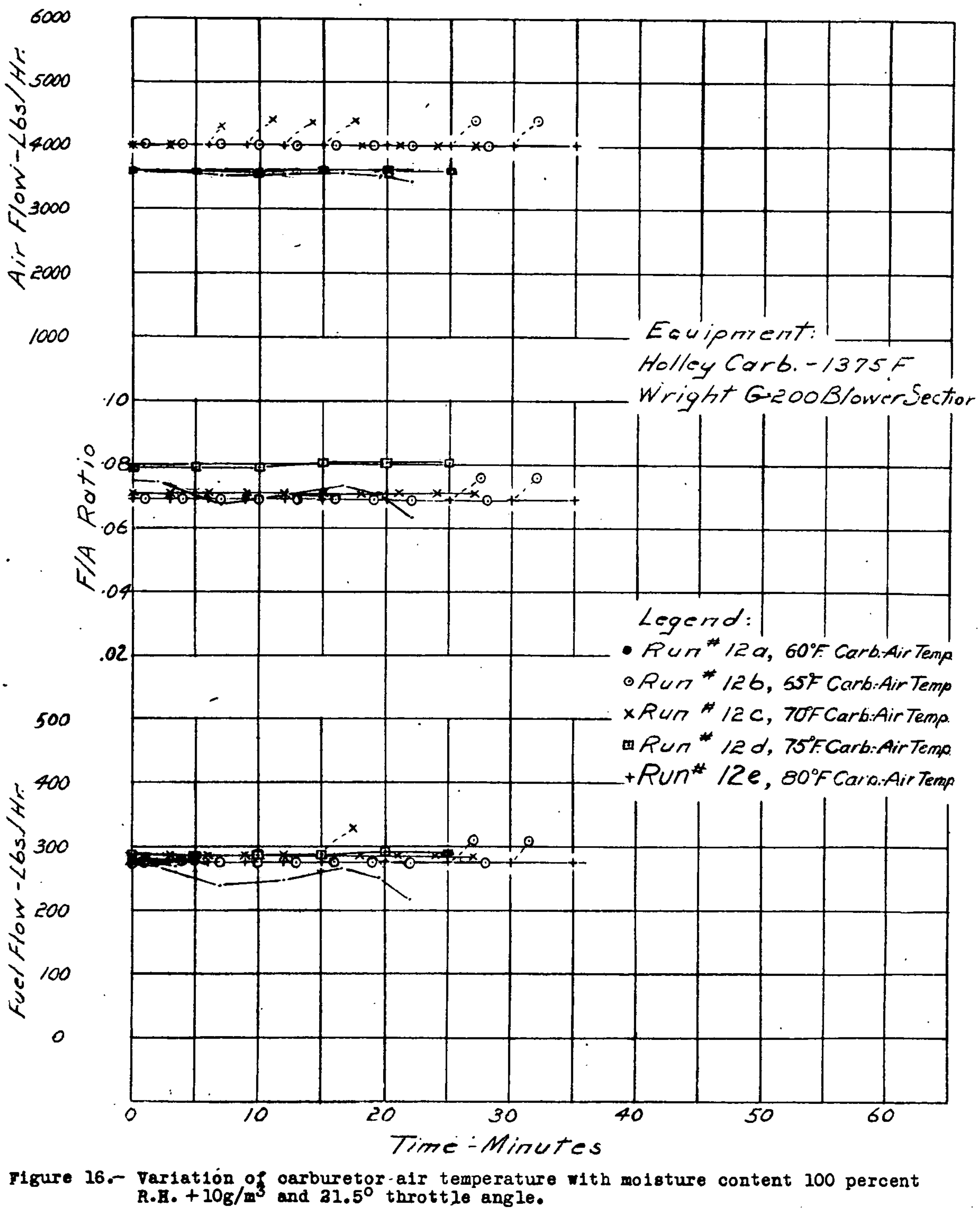

Figure 16.- Variation of carburetor-air temperature with moisture content 100 percent R.H. + 10g/m^3 and 21.5° throttle angle.

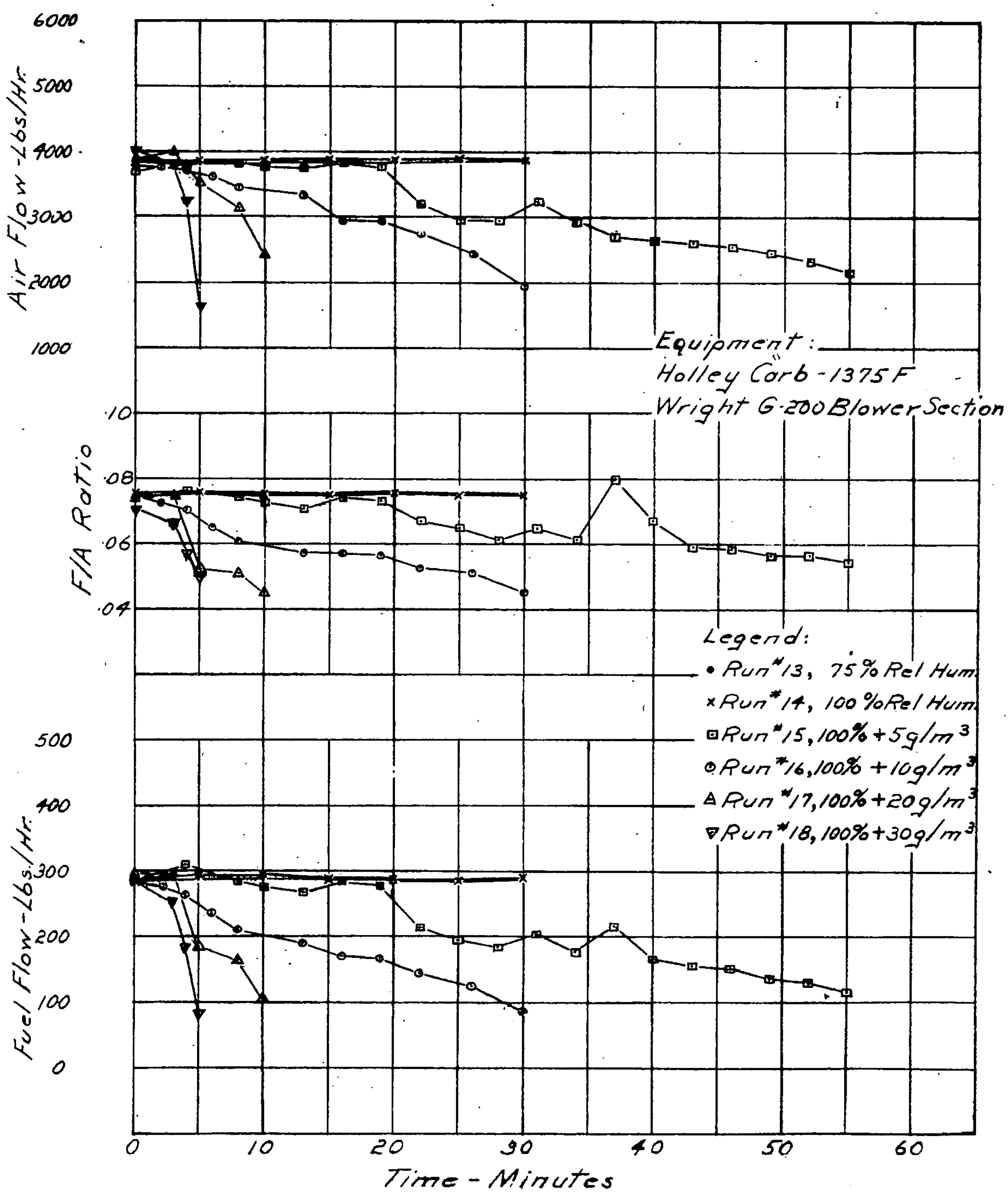

Figure 17.- Effect of rain ingestion at 40°F C.A.T., and 21.5° throttle angle.

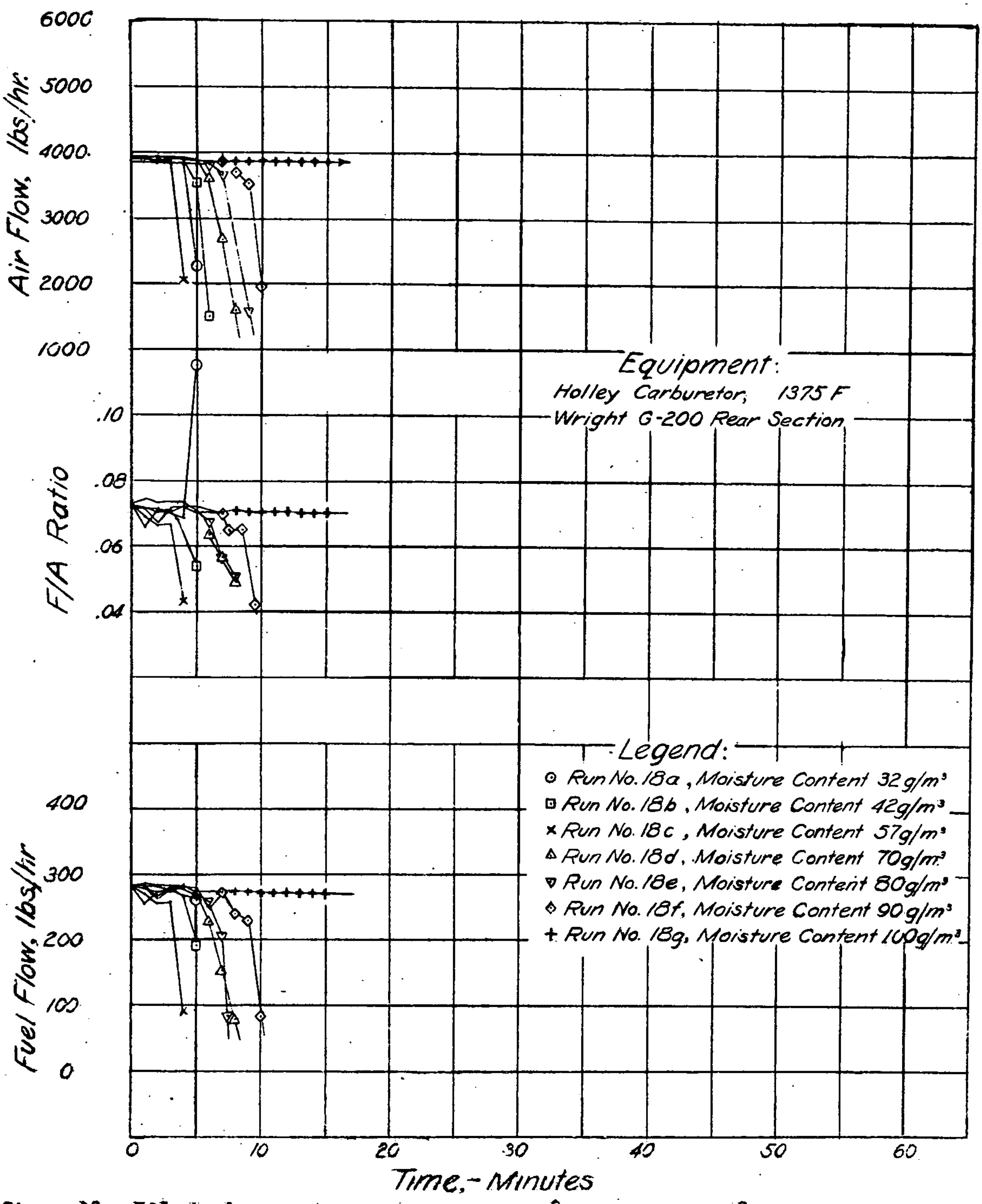

Figure 18.- Effect of extreme rain ingestion at 40°F C.A.T., and 22° throttle angle.

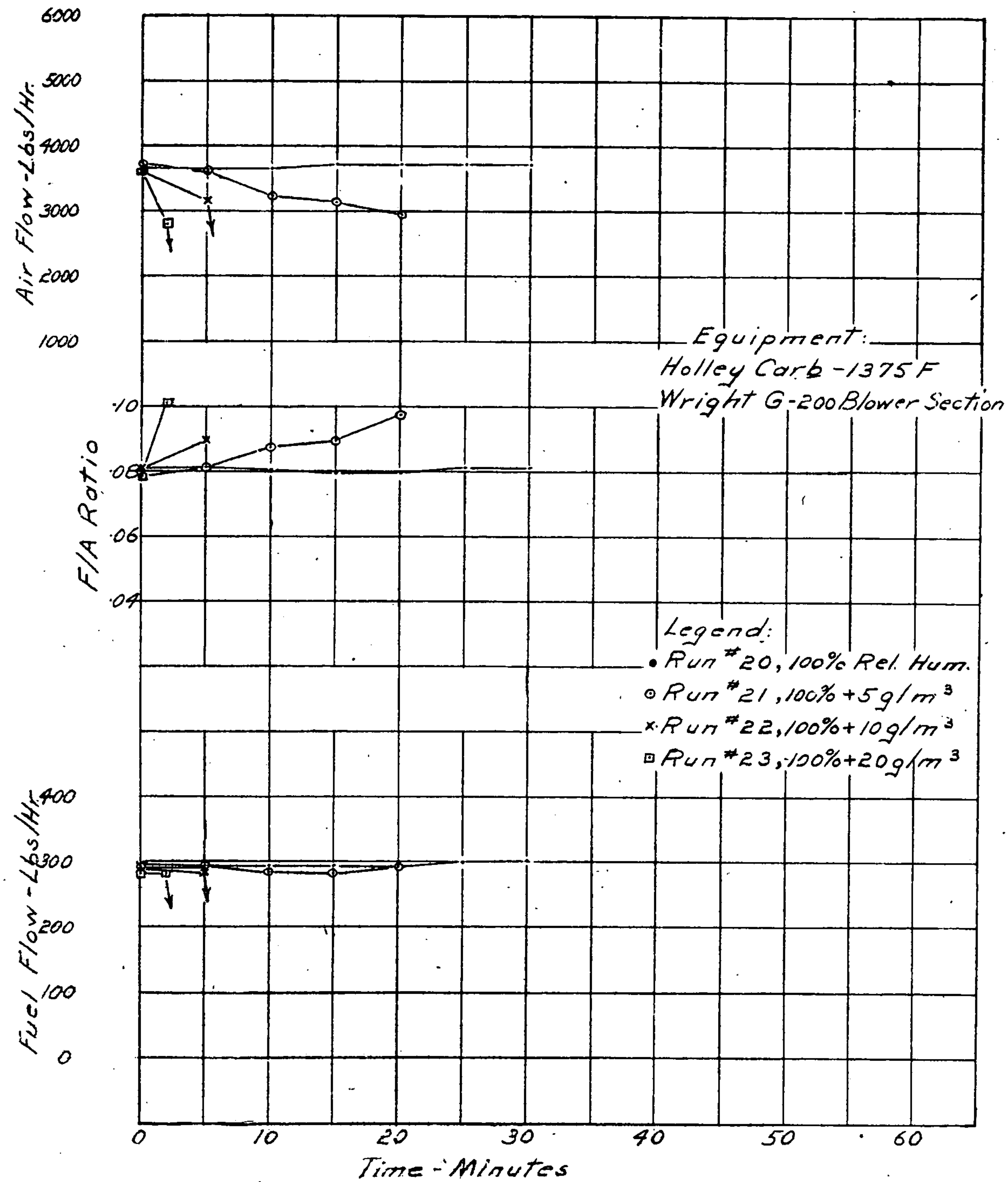

Figure 19.- Effect of rain ingestion at 35°F C.A.T., and 20° throttle angle.

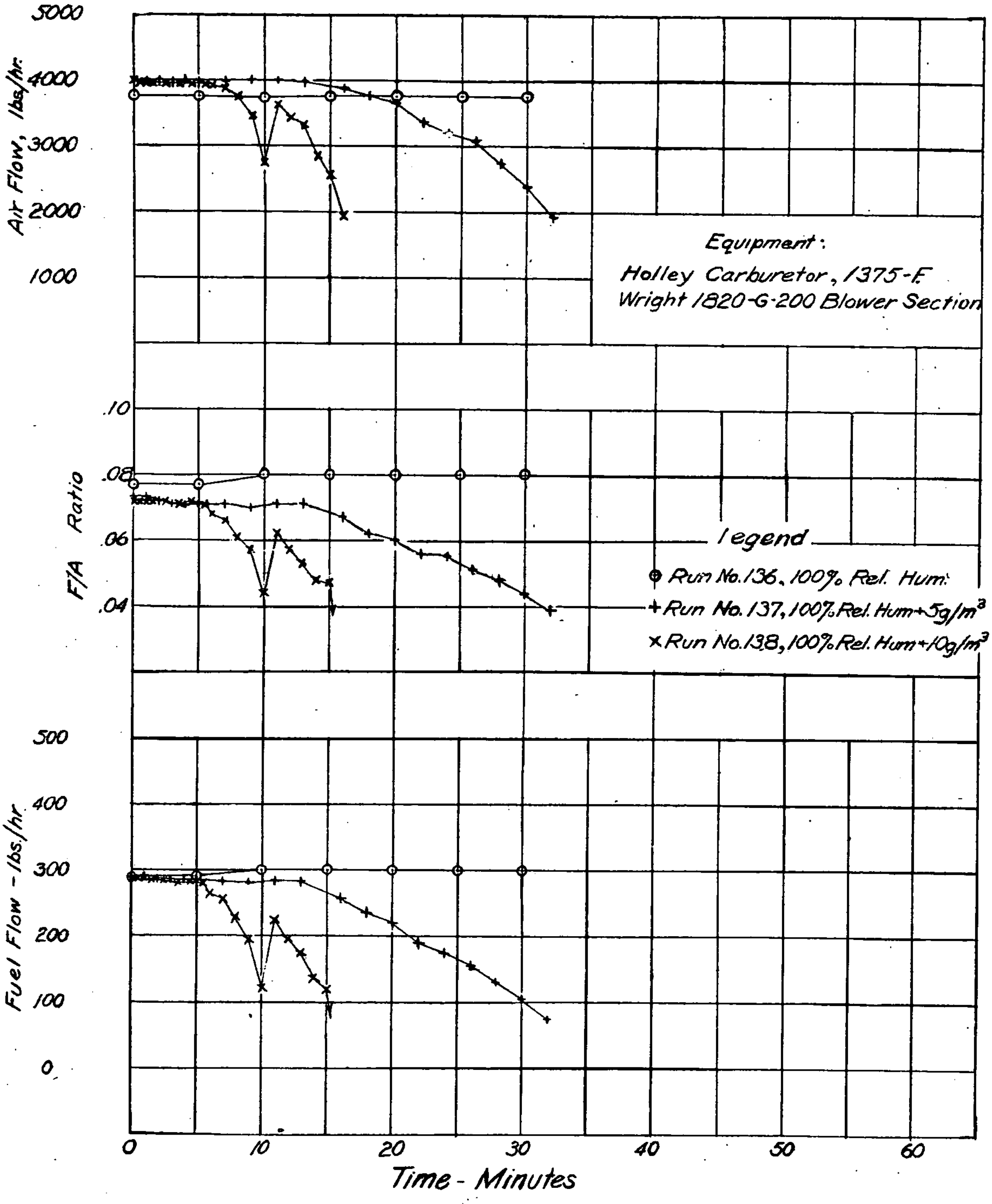

Figure 20.- Effect of rain ingestion at 40°F C.A.T., and 31° throttle angle.

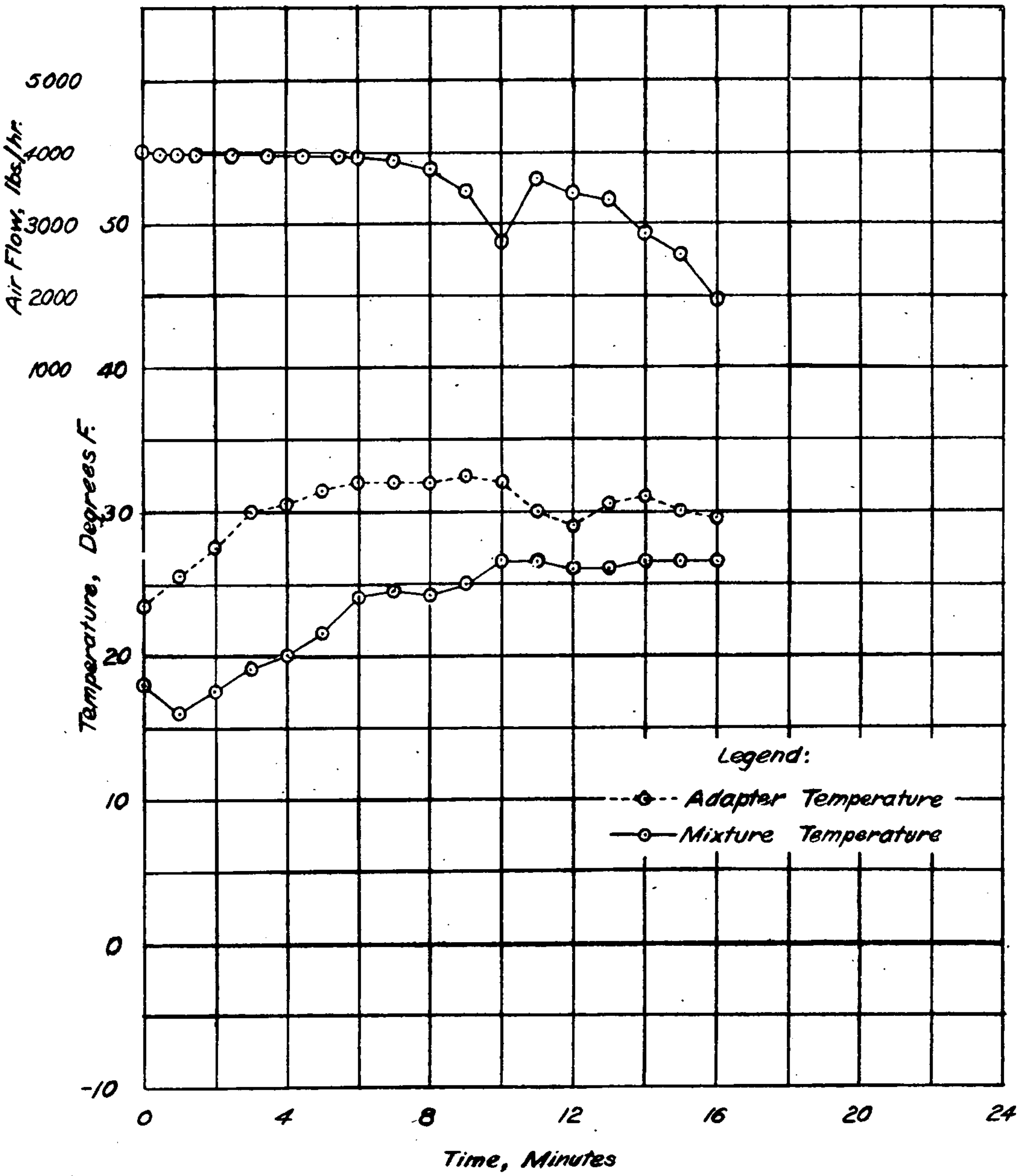

Figure. 21. - Variation of Mixture and Adapter Temperatures During Icing, Run No. 138

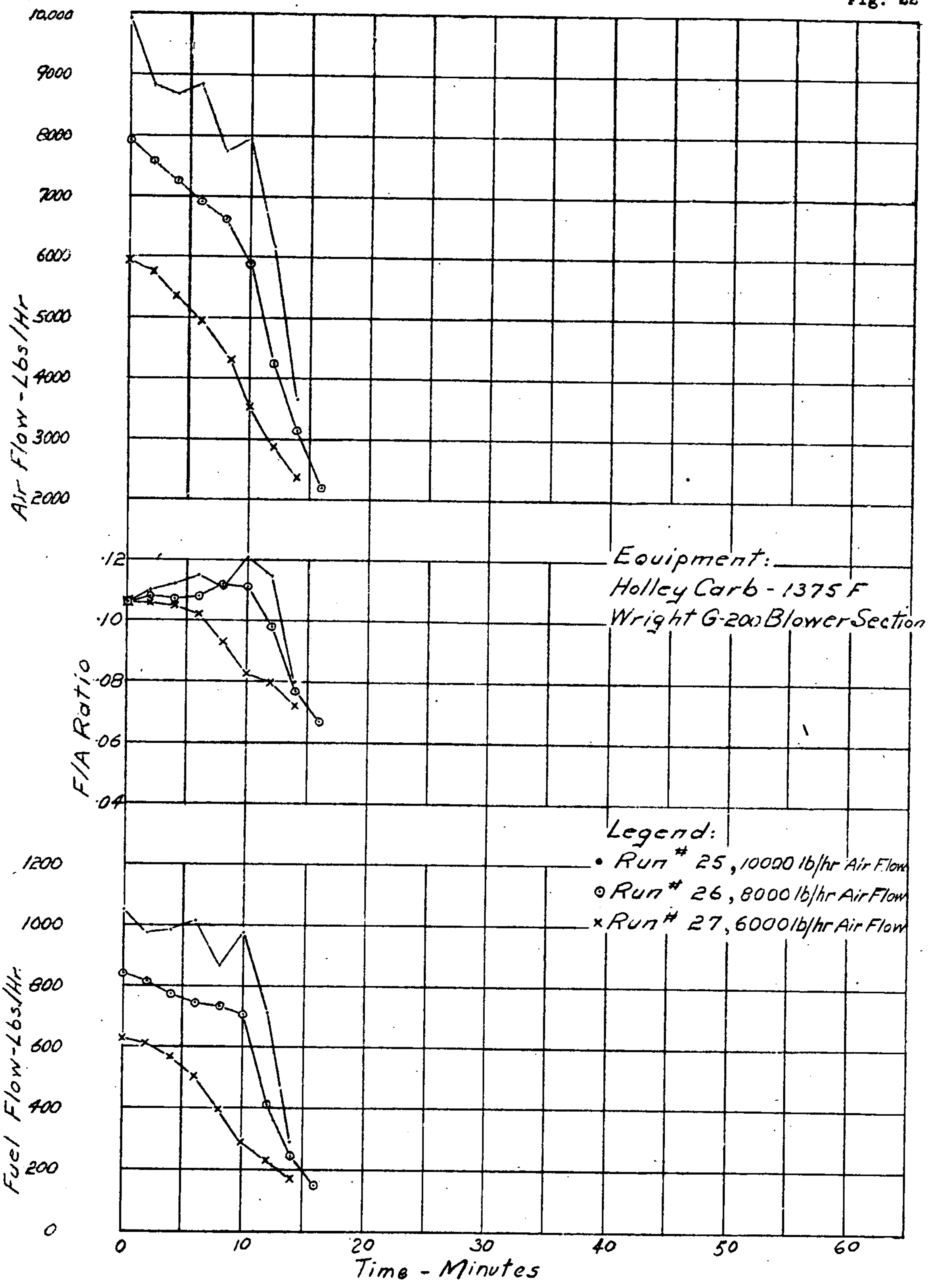

Figure 22.- Icing at various initial rates of air flow at 35°F C.A.T., moisture content 100 percent R.H.+ 5g/m³ and 73° throttle angle.

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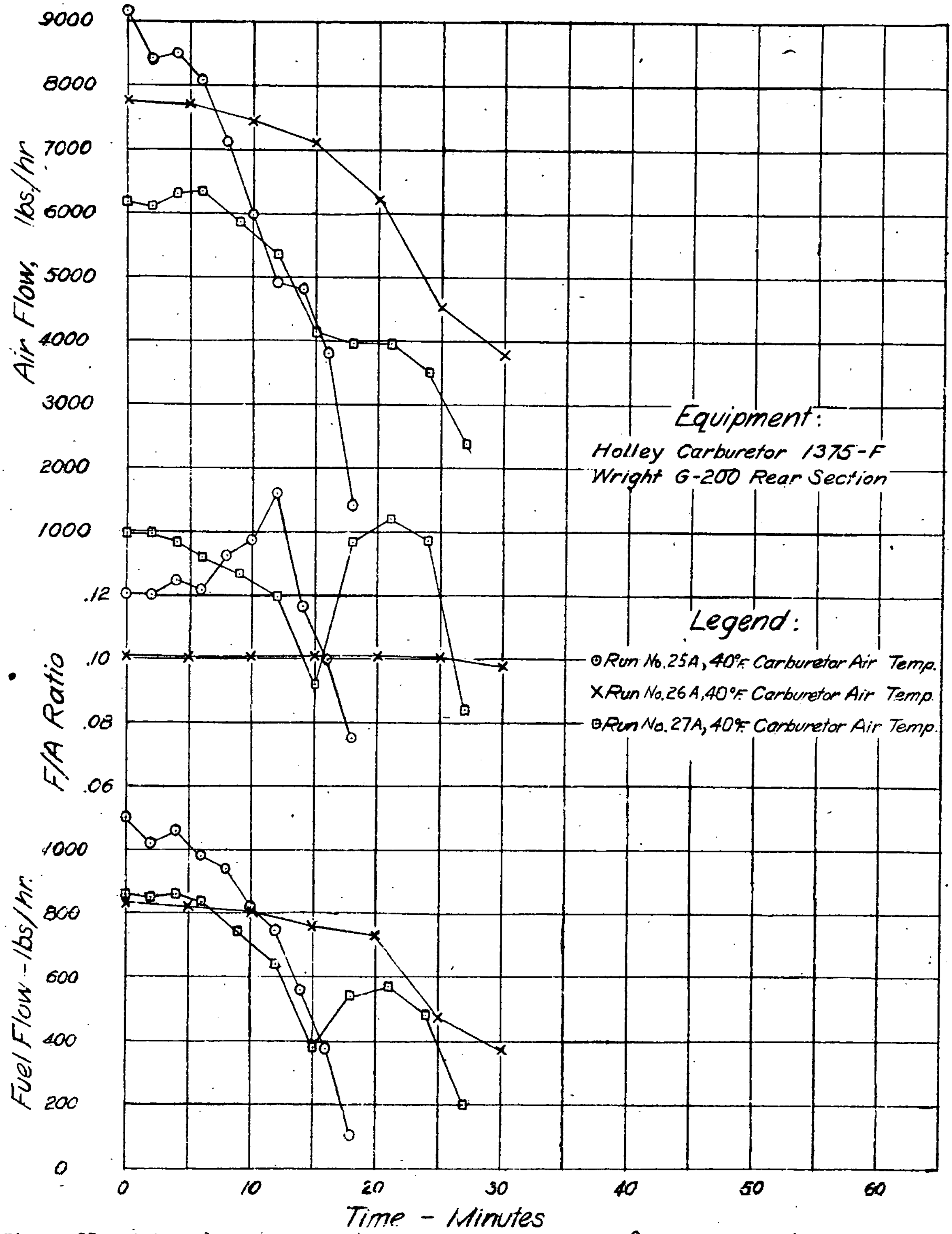

Figure 23.- Icing at various initial rates of airflow at 40°F C.A.T., moisture content 100% R.H. + 5g/m^3, and 73° throttle angle.

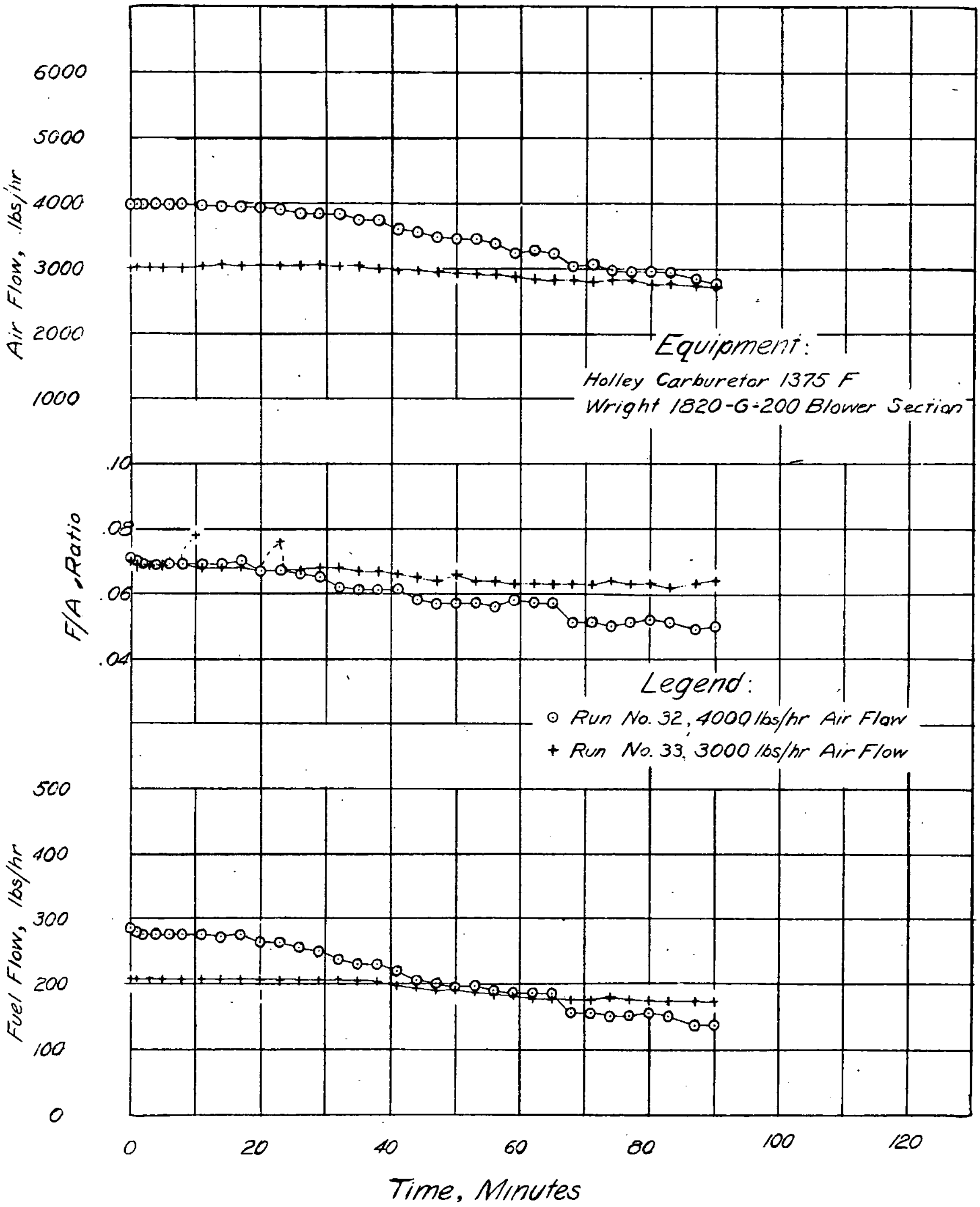

Figure 24.- Effect of varying initial rate of air flow at 40°F C.A.T., moisture content 100 percent R.H. + 5g/m^3 and 20° throttle angle

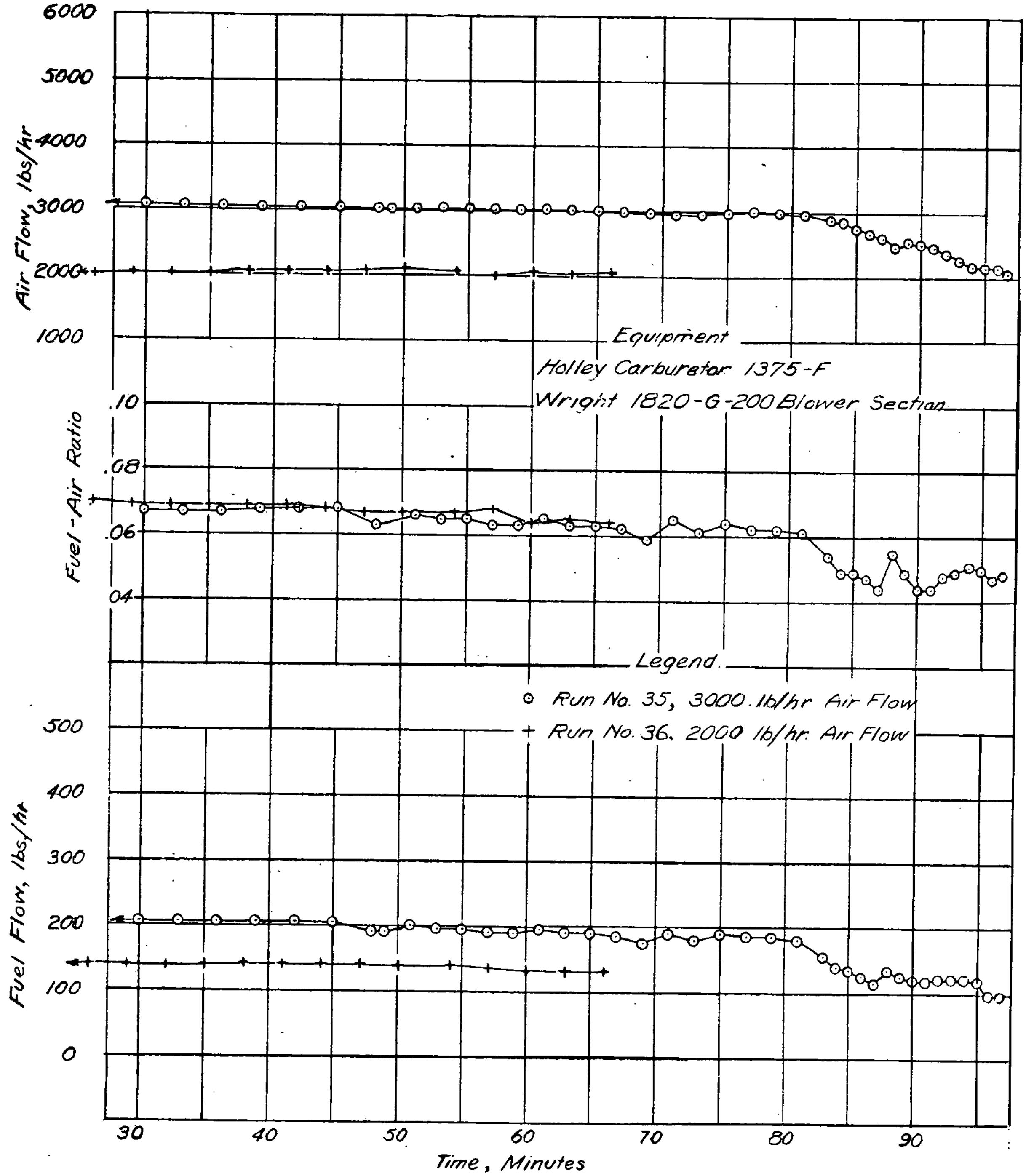

Figure 25.- Effect of varying initial rate of air flow at 40°F C.A.T., moisture content 100 percent R.H.+ 5g/m^3 and 15° throttle angle.

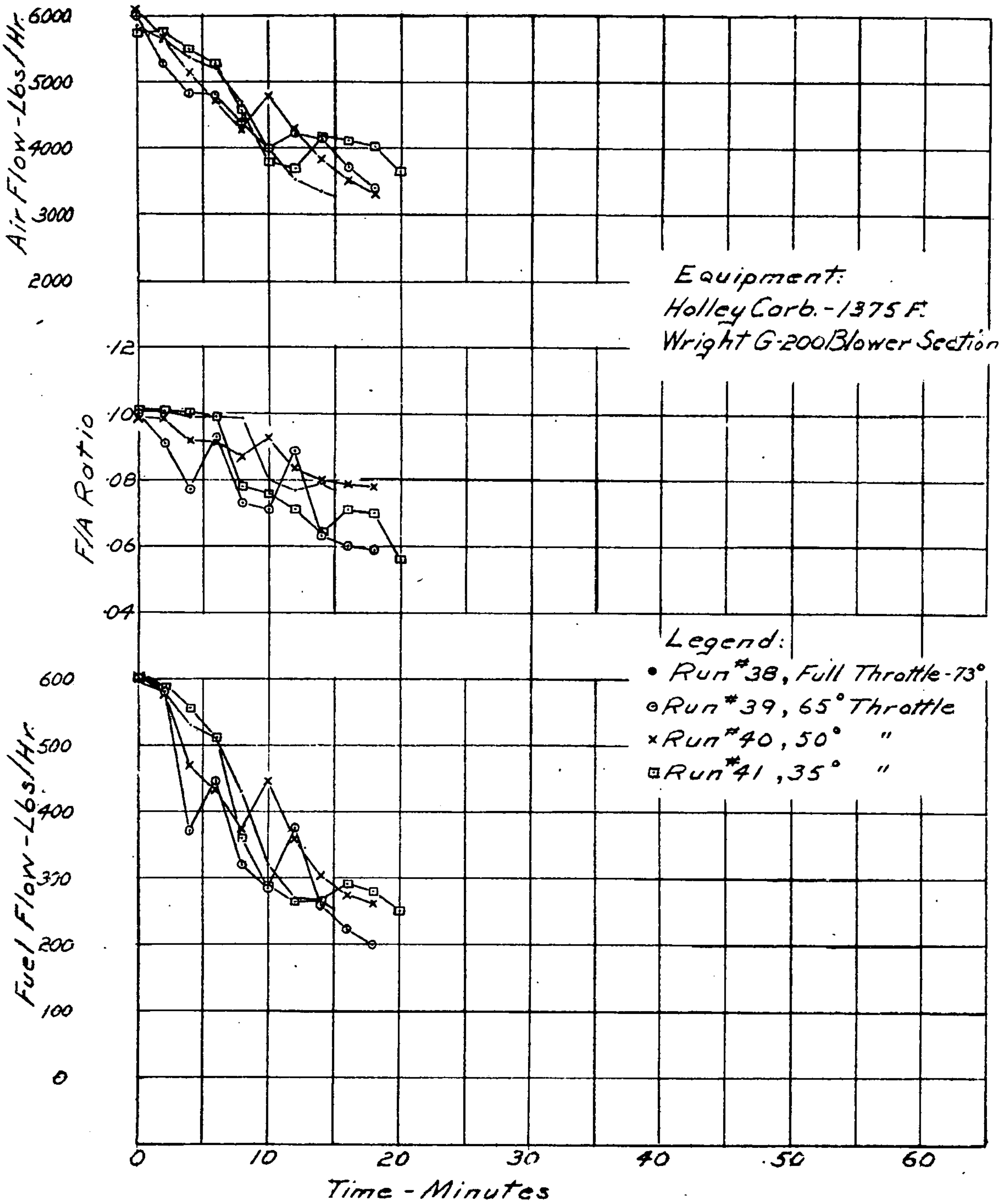

Figure 26. Effect of varying throttle angle at 35°F C.A.T., and moisture content 100 percent R.H. + 5g/m³.

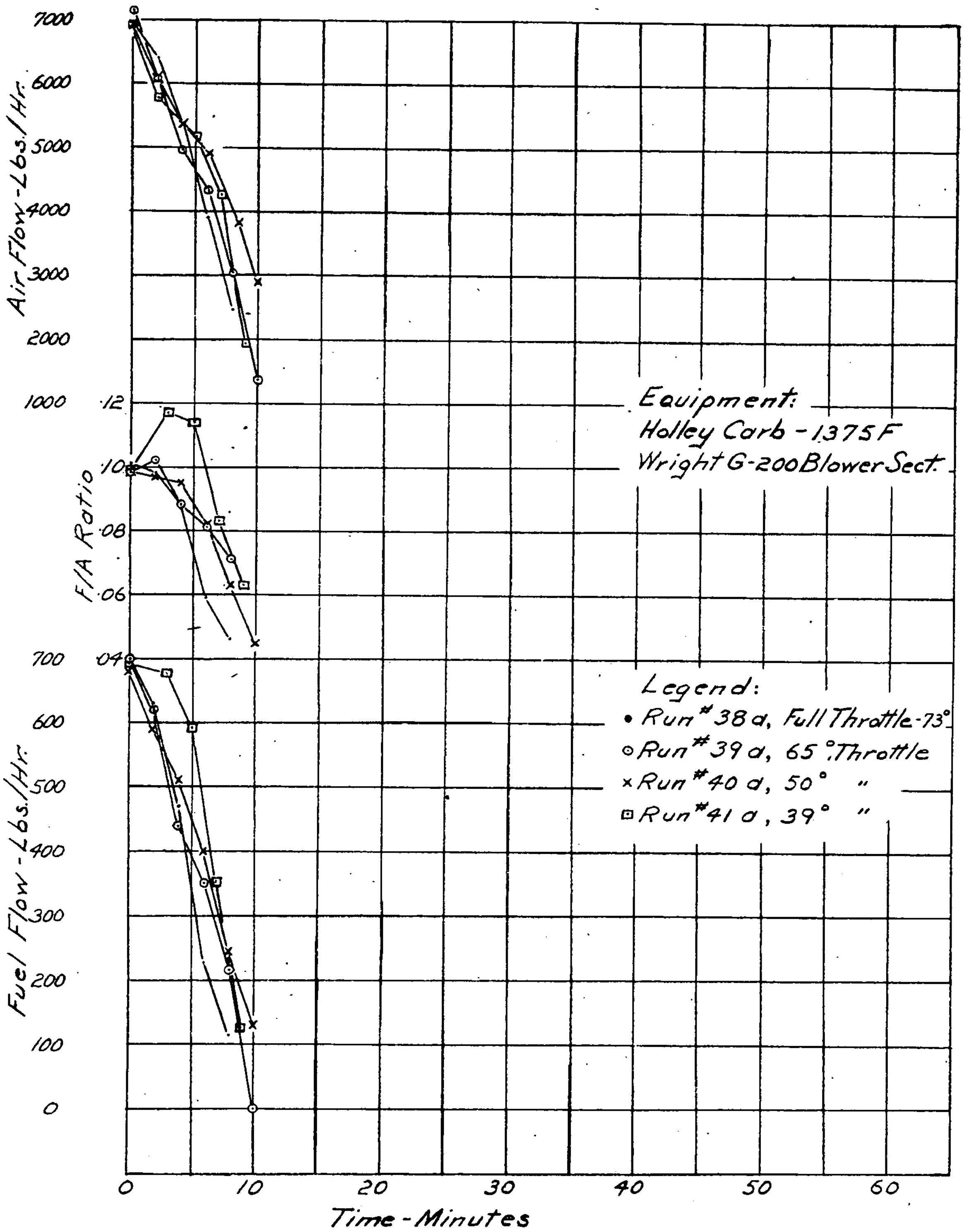

Figure 27.- Effect of varying throttle angle at 35°F C.A.T., and moisture content 100 percent R.H.+ 5g/m³.

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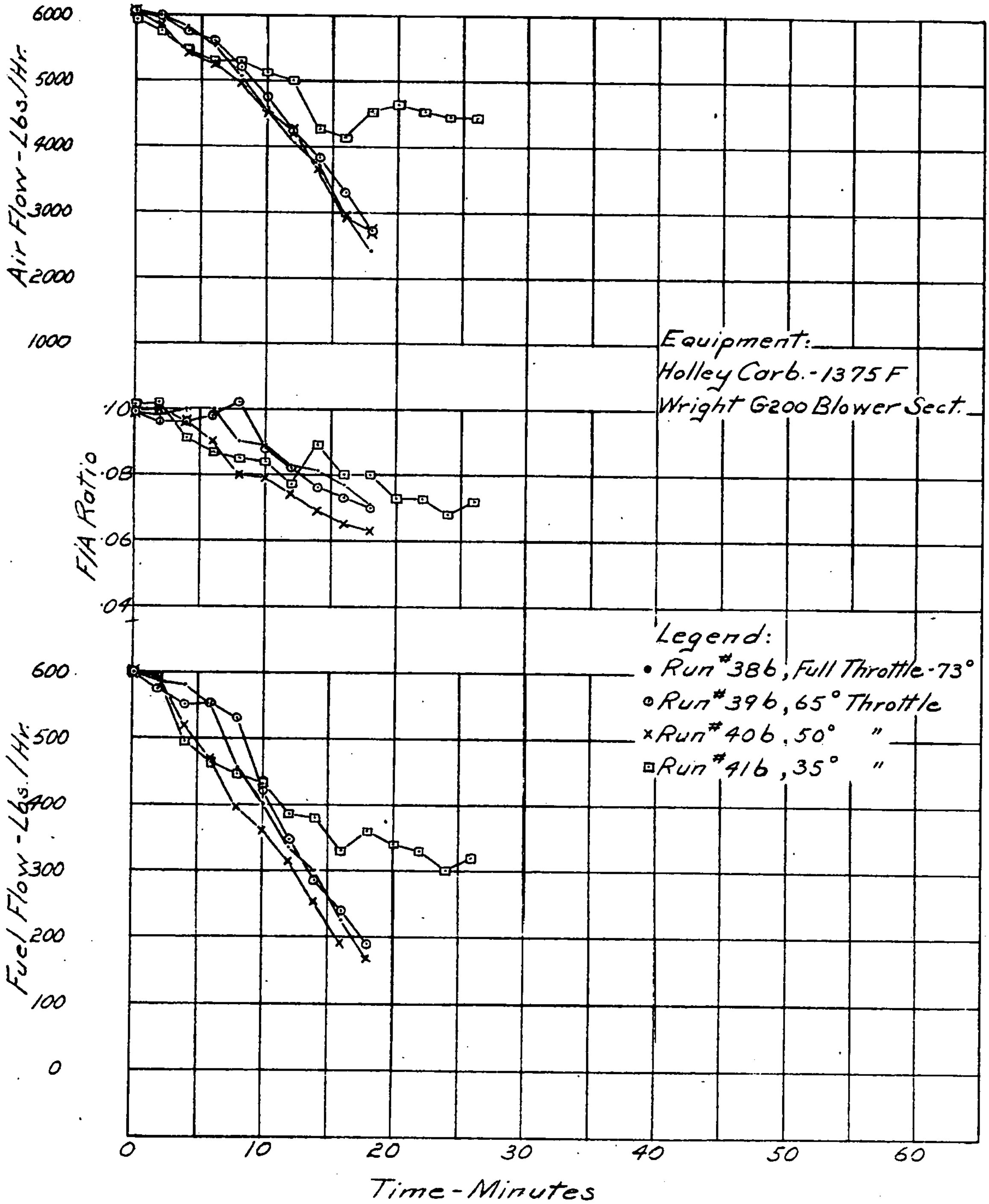

Figure 28.- Effect of varying throttle angle at 40°F C.A.T., and moisture content 100 % R.H. + 5g/m³.

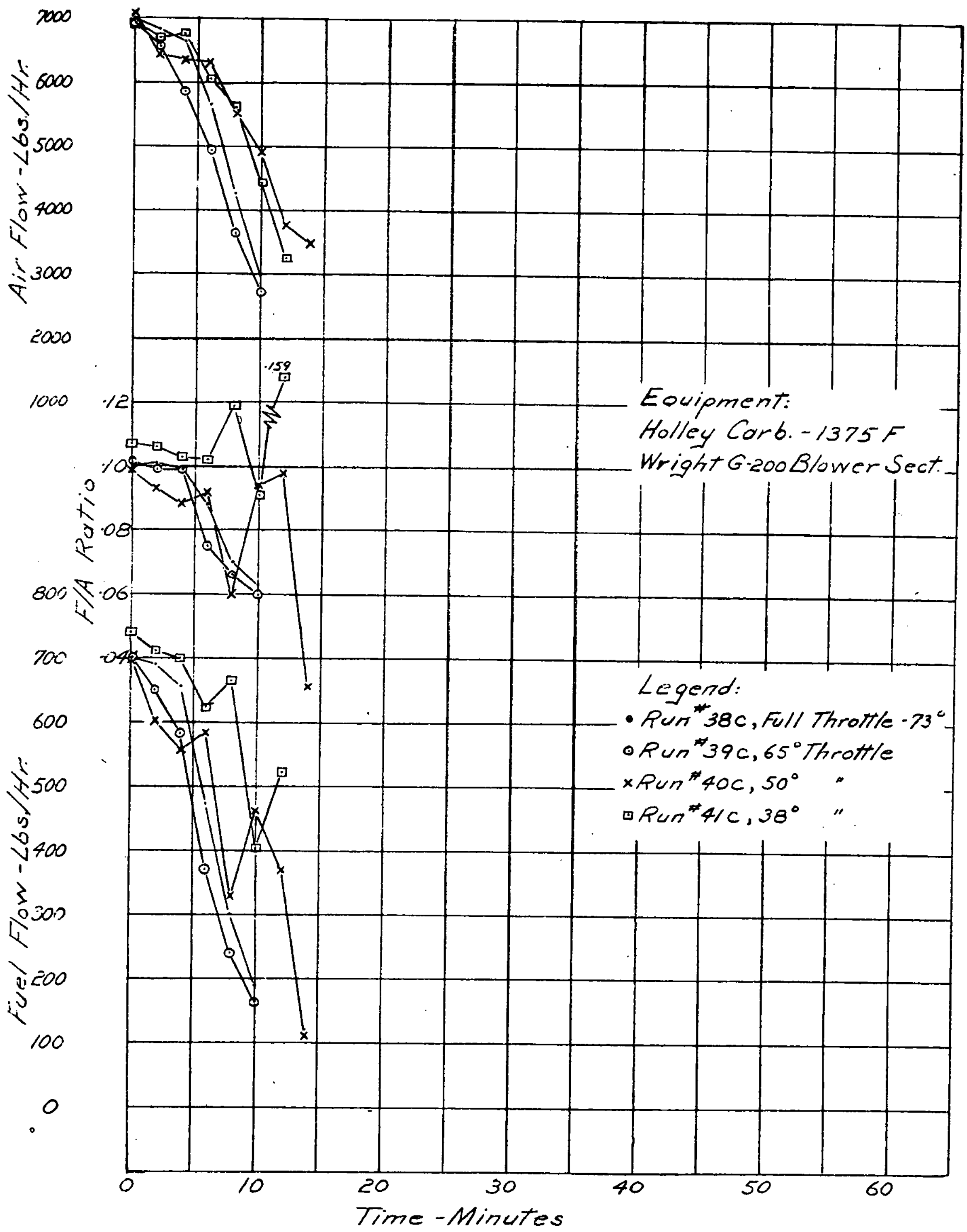

Figure 39.— Effect of varying throttle angle at 40°F C.A.T., and moisture content 100 percent R.H. +5g/m³.

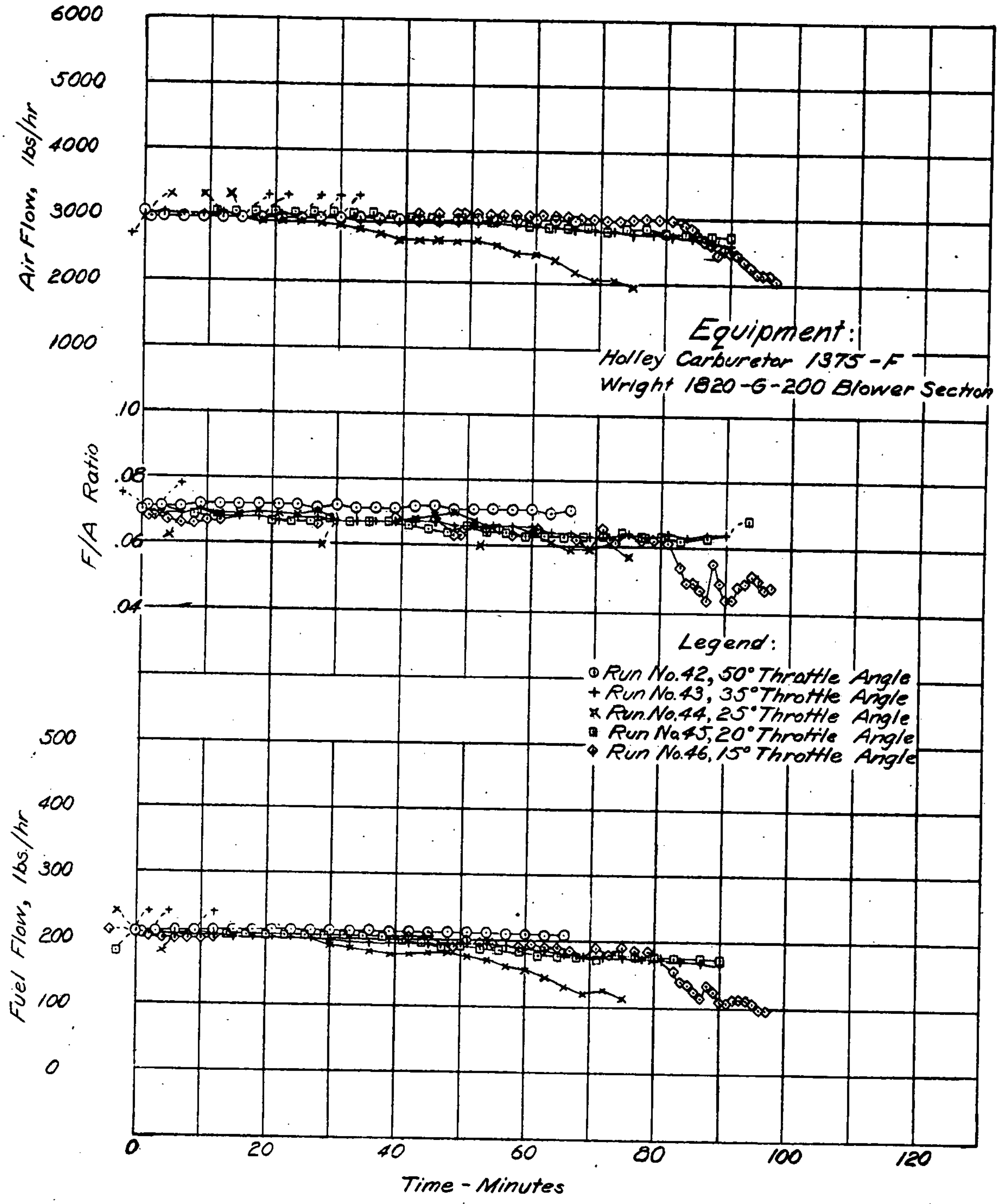

Figure 30.- Effect of varying throttle angle at 40°F C.A.T., and moisture content 100 percent R.H.+ $5 g/m^3$.

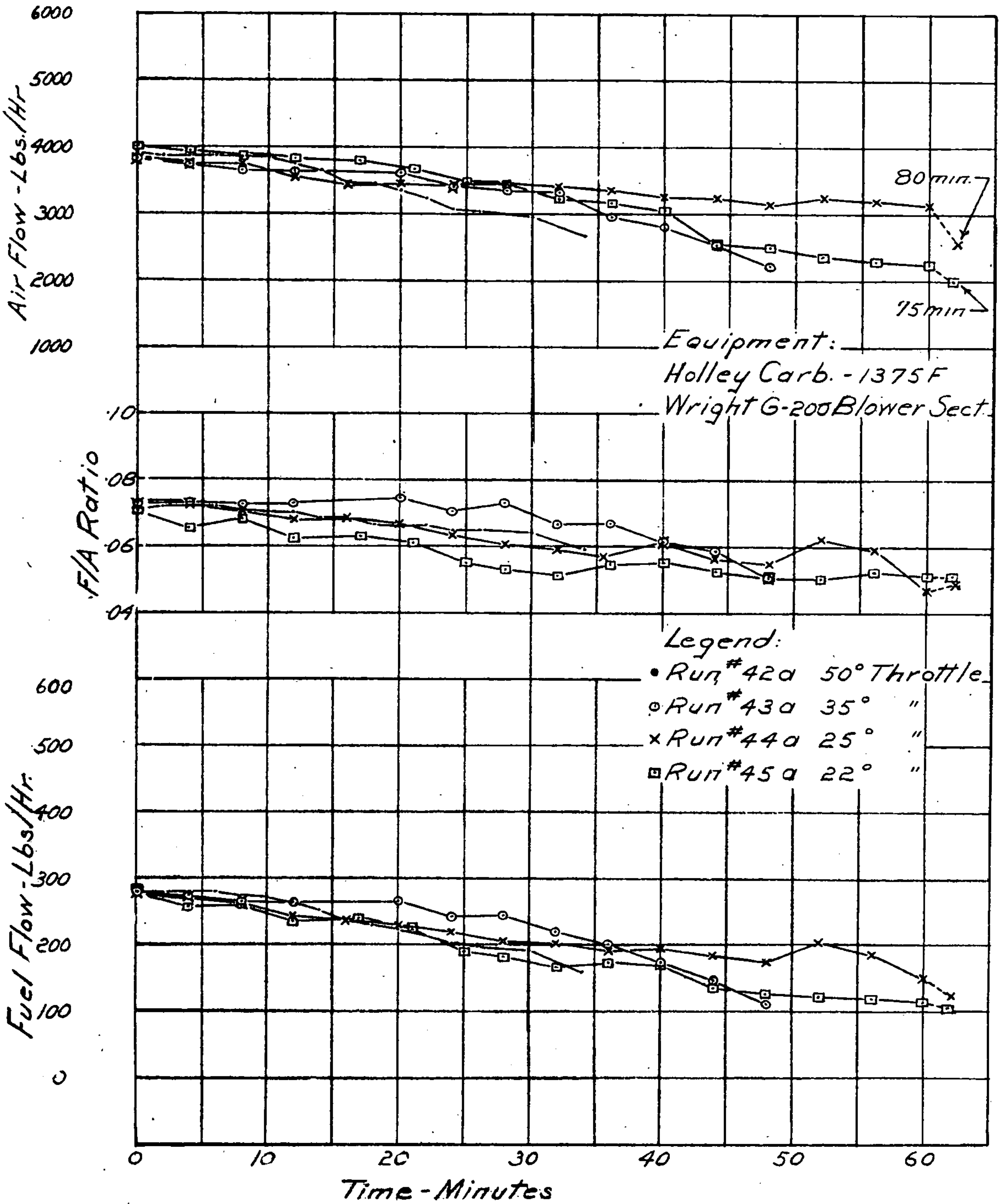

Figure 31.- Effect of varying throttle angle at 40°F C.A.T., and moisture content 100 percent + 5g/m³.

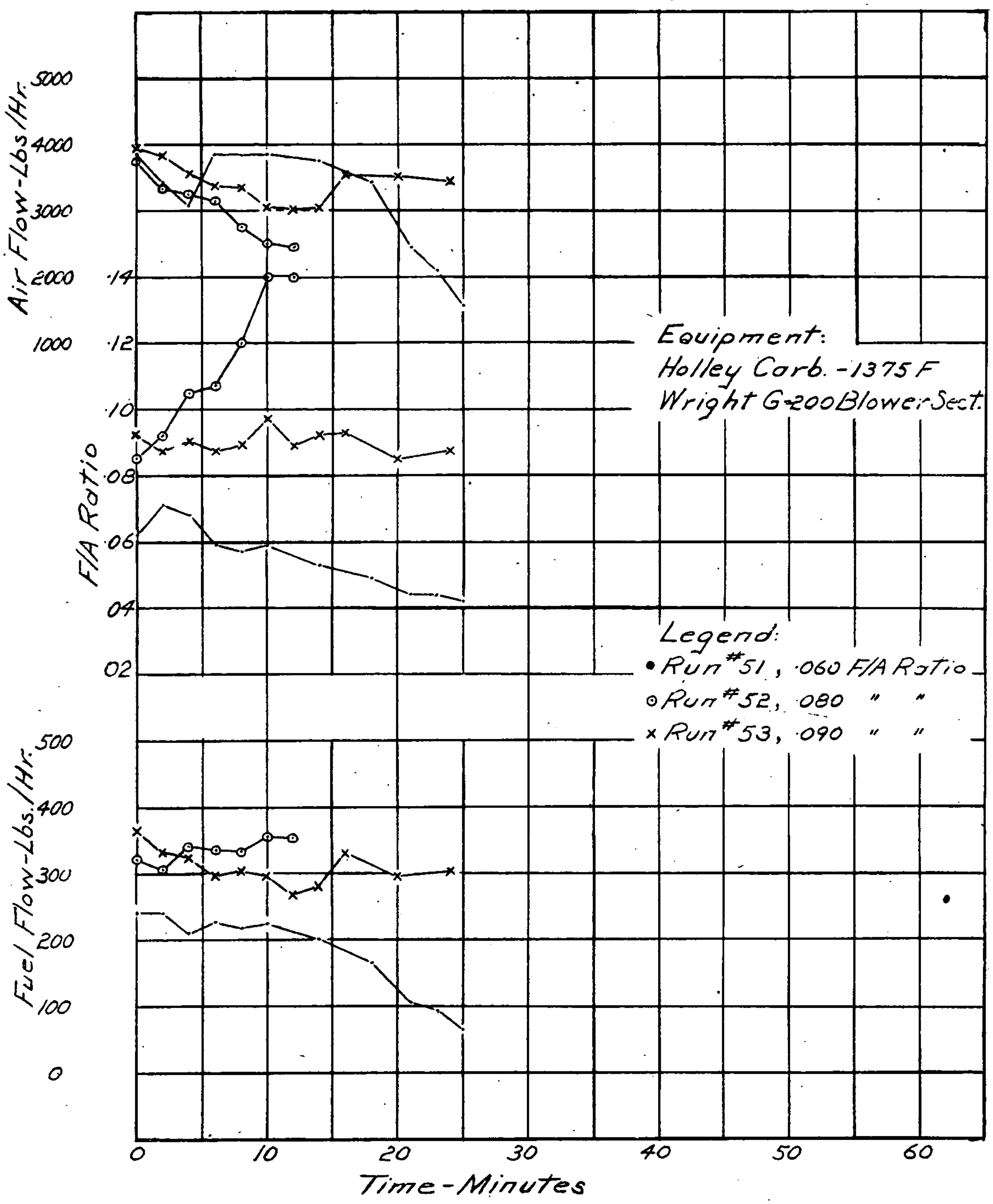

Figure 32.- Effect of varying fuel-air ratio at 40°F C.A.T., moisture content 100 percent R.H. + 5g/m^3, and 21° throttle angle.

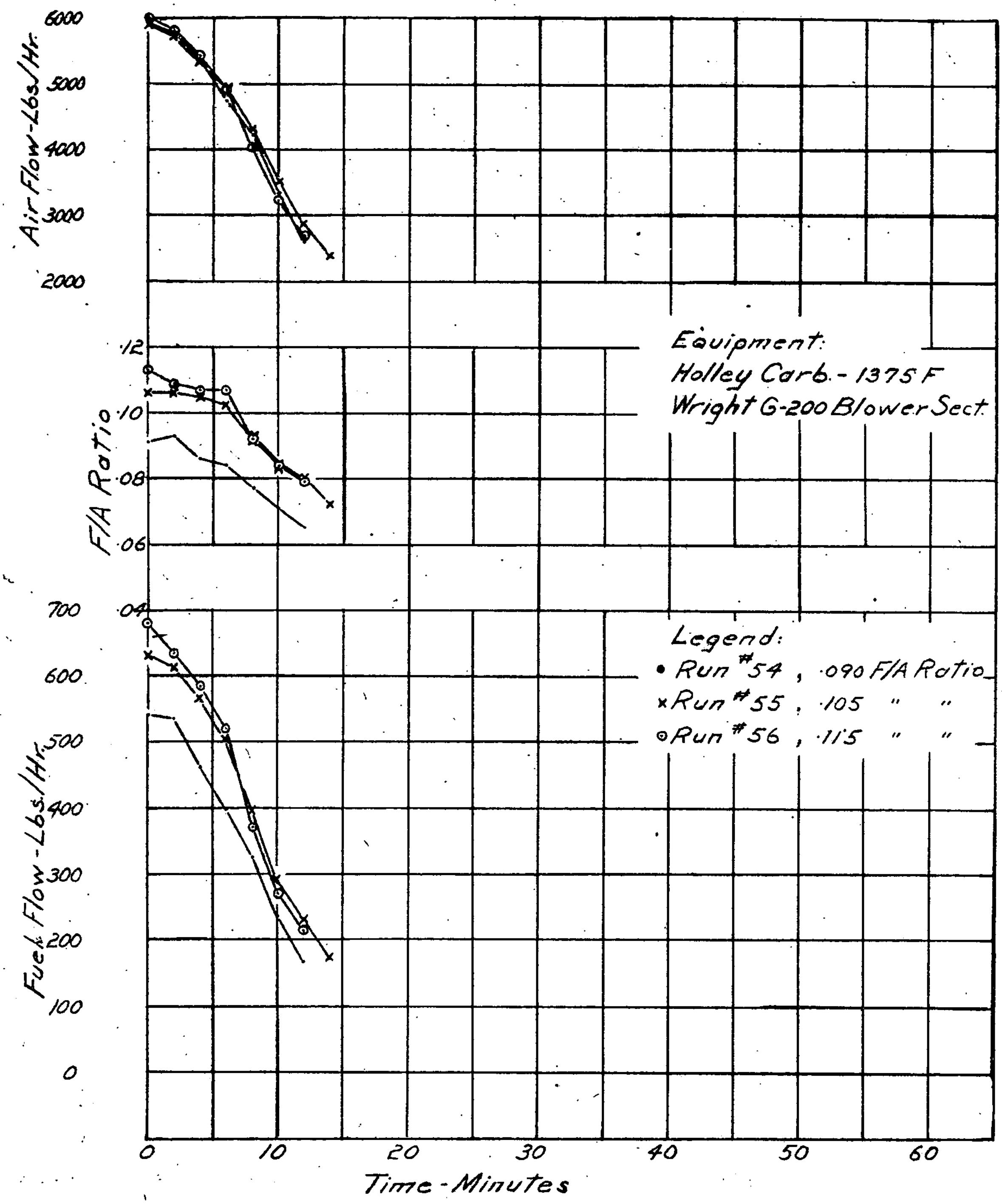

Figure 33.- Effect of varying fuel-air ratio at 35°F C.A.T., moisture content 100 percent R.H.+ 5g/m³ and 73° throttle angle.

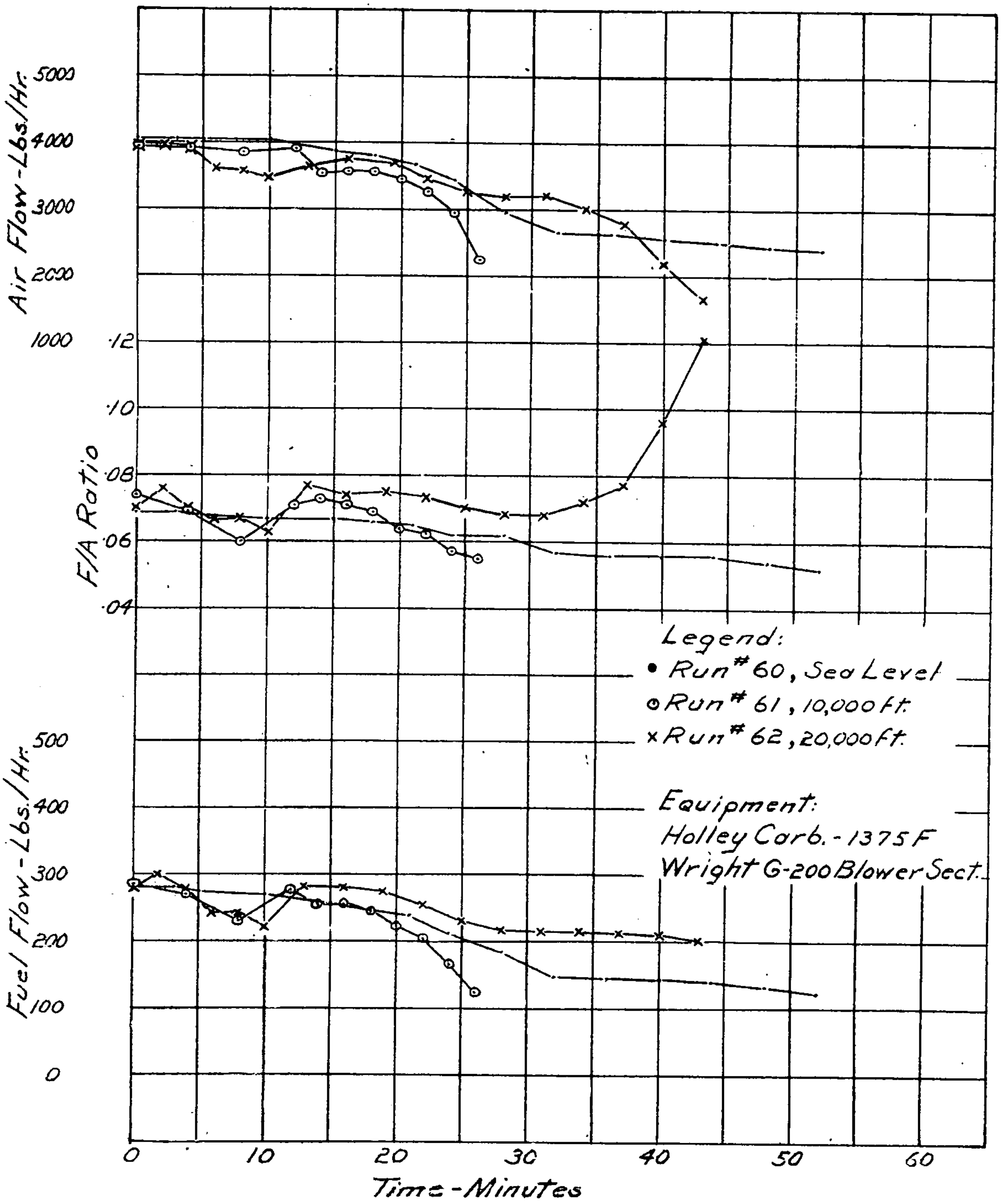

Figure 34.- Effect of varying altitude with 35°F C.A.T., moisture content 100 percent R.H. +5g/m³, and 73° throttle angle.

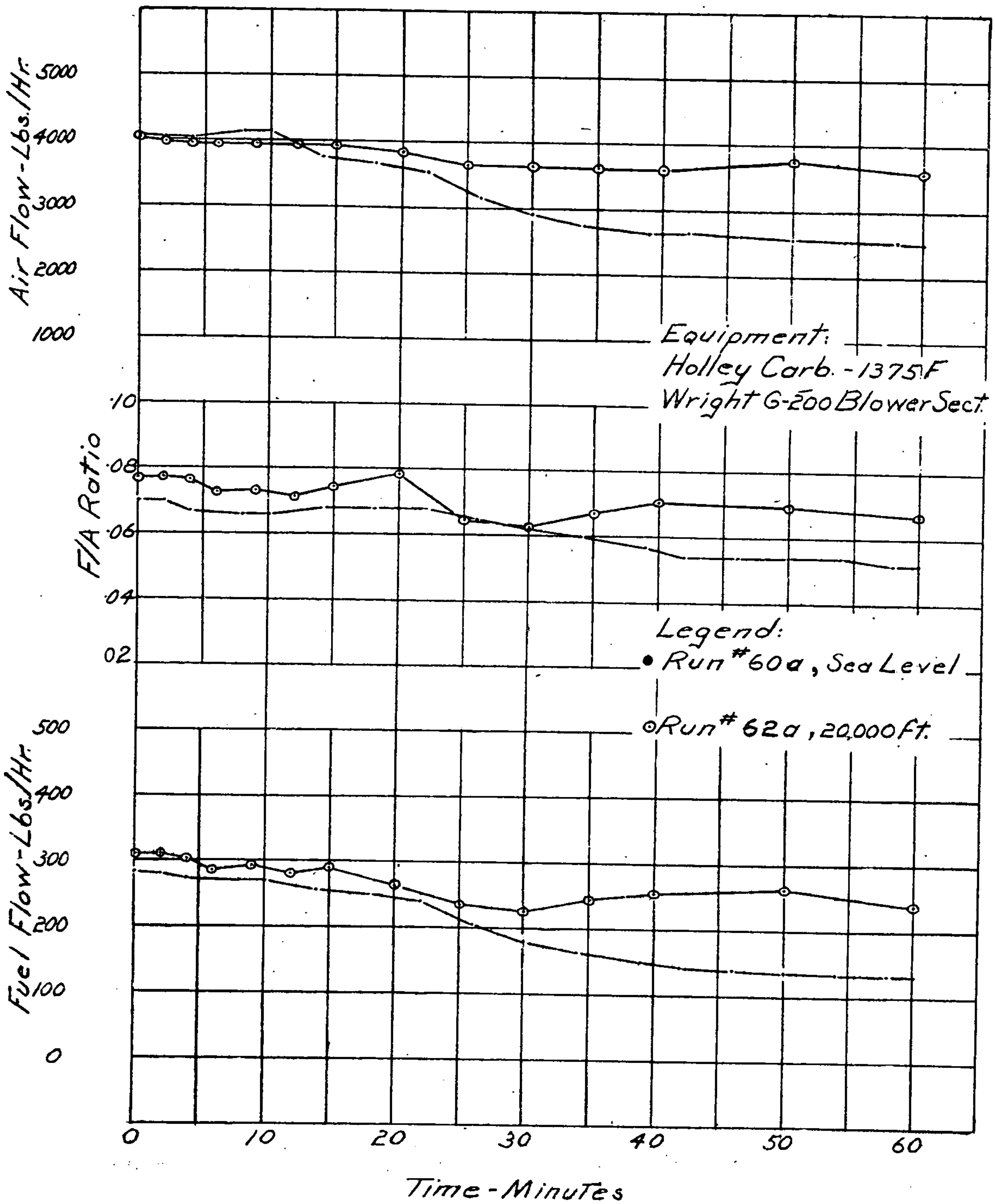

Figure 35.– Effect of varying altitude with 40°F C.A.T., moisture content 100 percent R. H. + 5g/m^3, and 73° throttle angle.

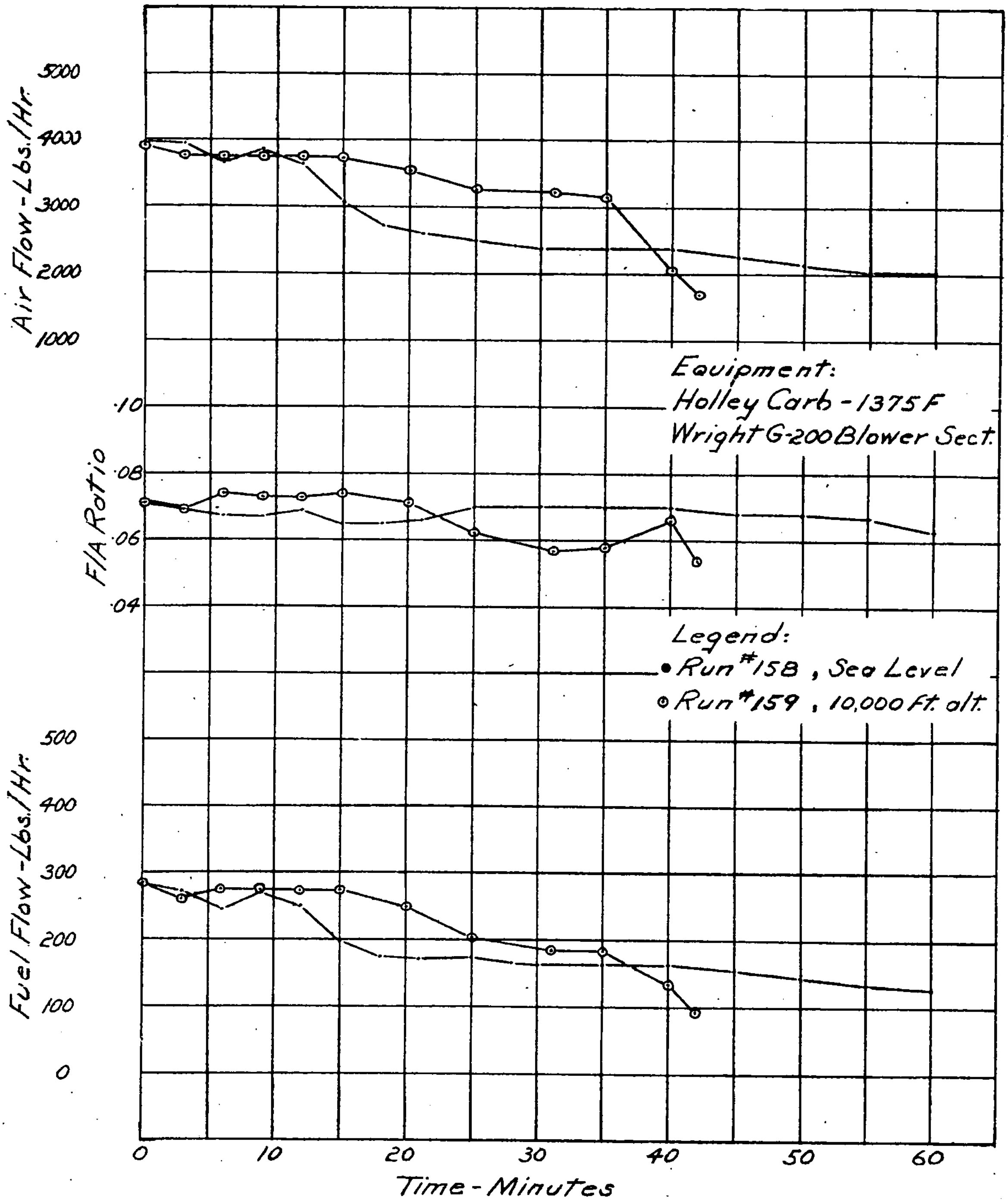

Figure 36.- Effect of varying altitude with 40°F C.A.T., moisture content 100 percent R.H. + 5g/m³, and 35° throttle angle.

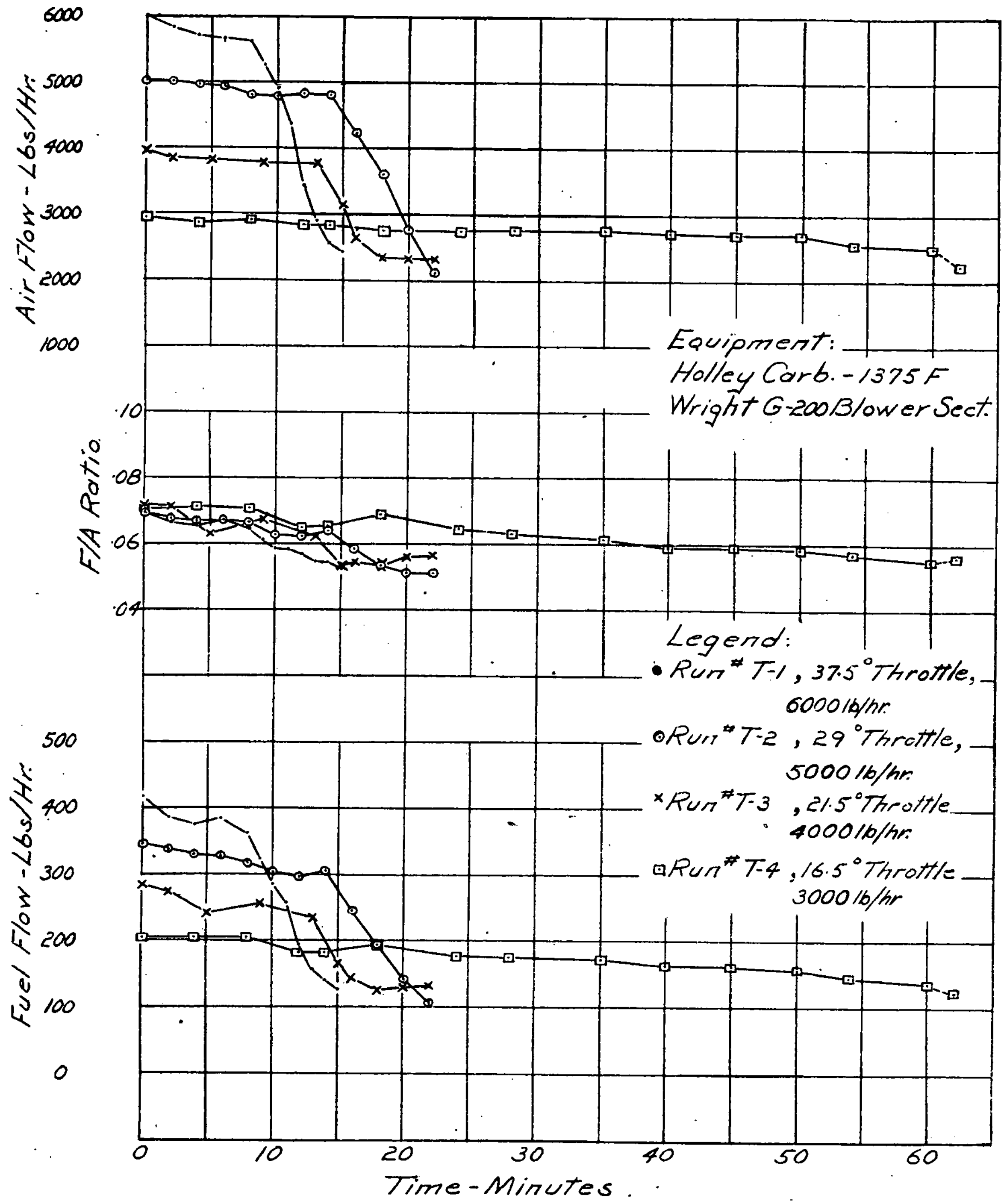

Figure 37.– Effect of propeller load curve conditions at 40°F C.A.T., and moisture content 100 percent R.H. + 5g/m^3.

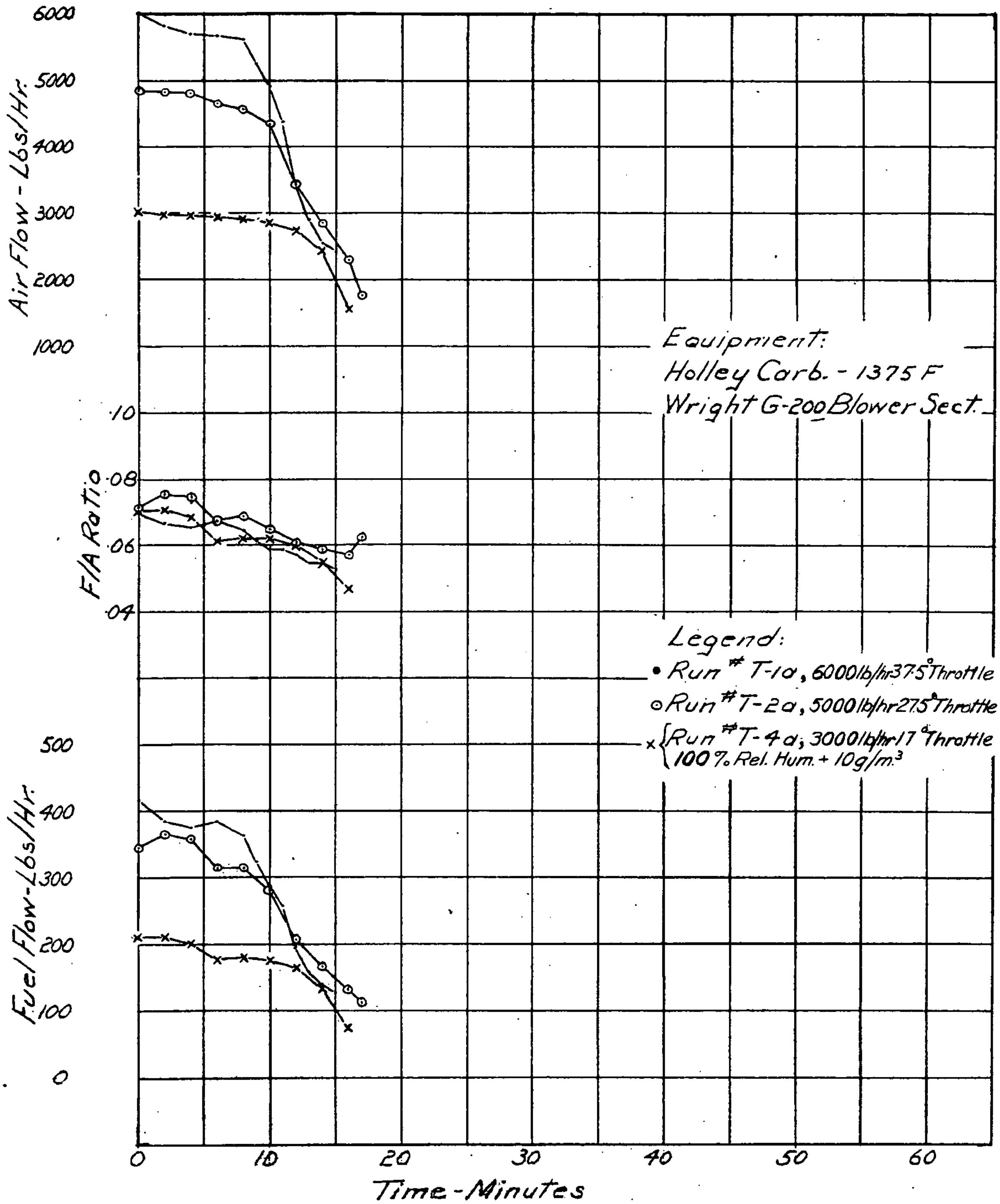

Figure 38.- Effect of propeller load curve conditions at 40°F C.A.T., and moisture content 100 percent R.H.+ 5g/m^3.

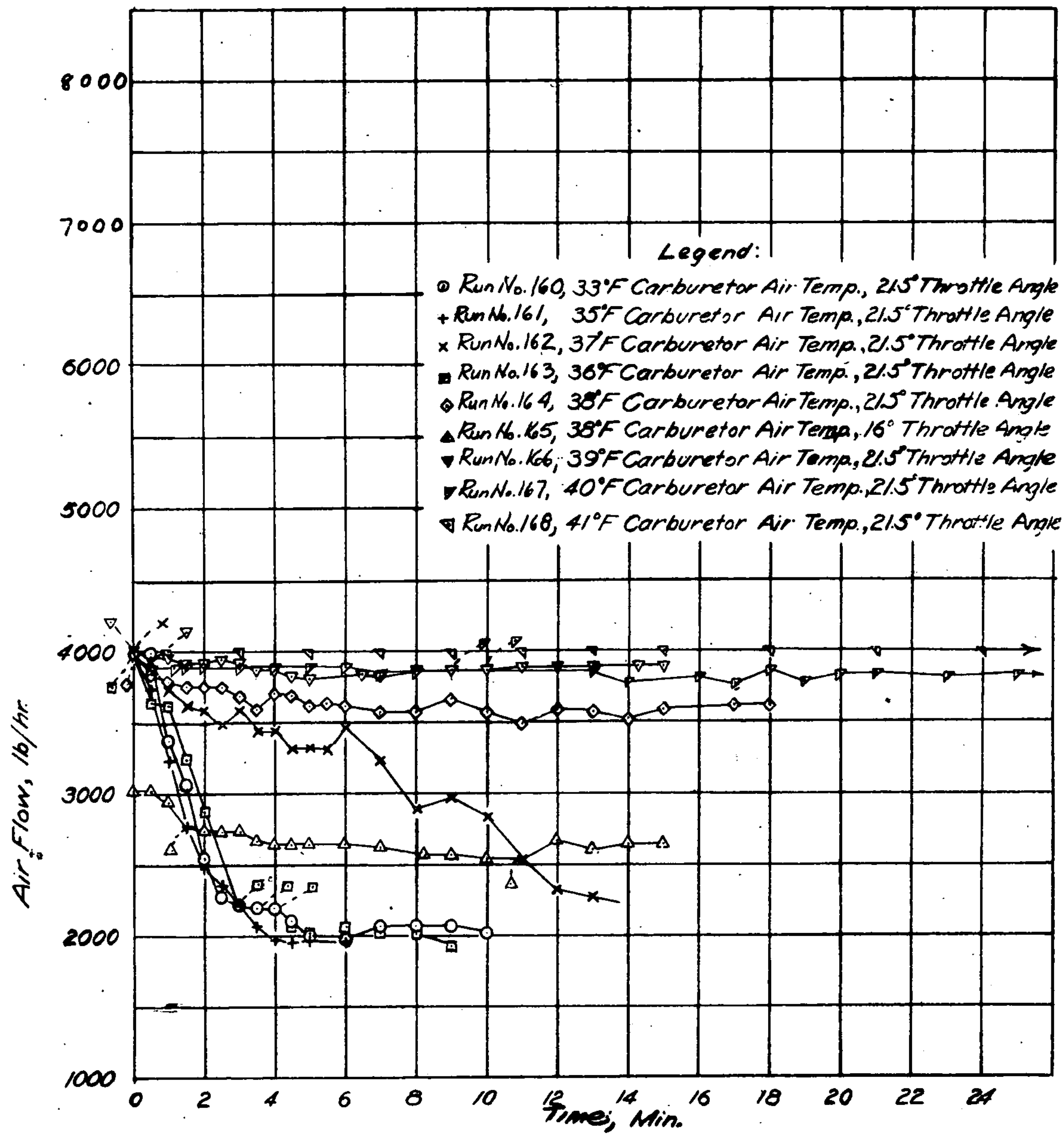

Figure 39.- Effect of throttle icing on air flow at moisture content 100 percent R.H. + 10g/m³.

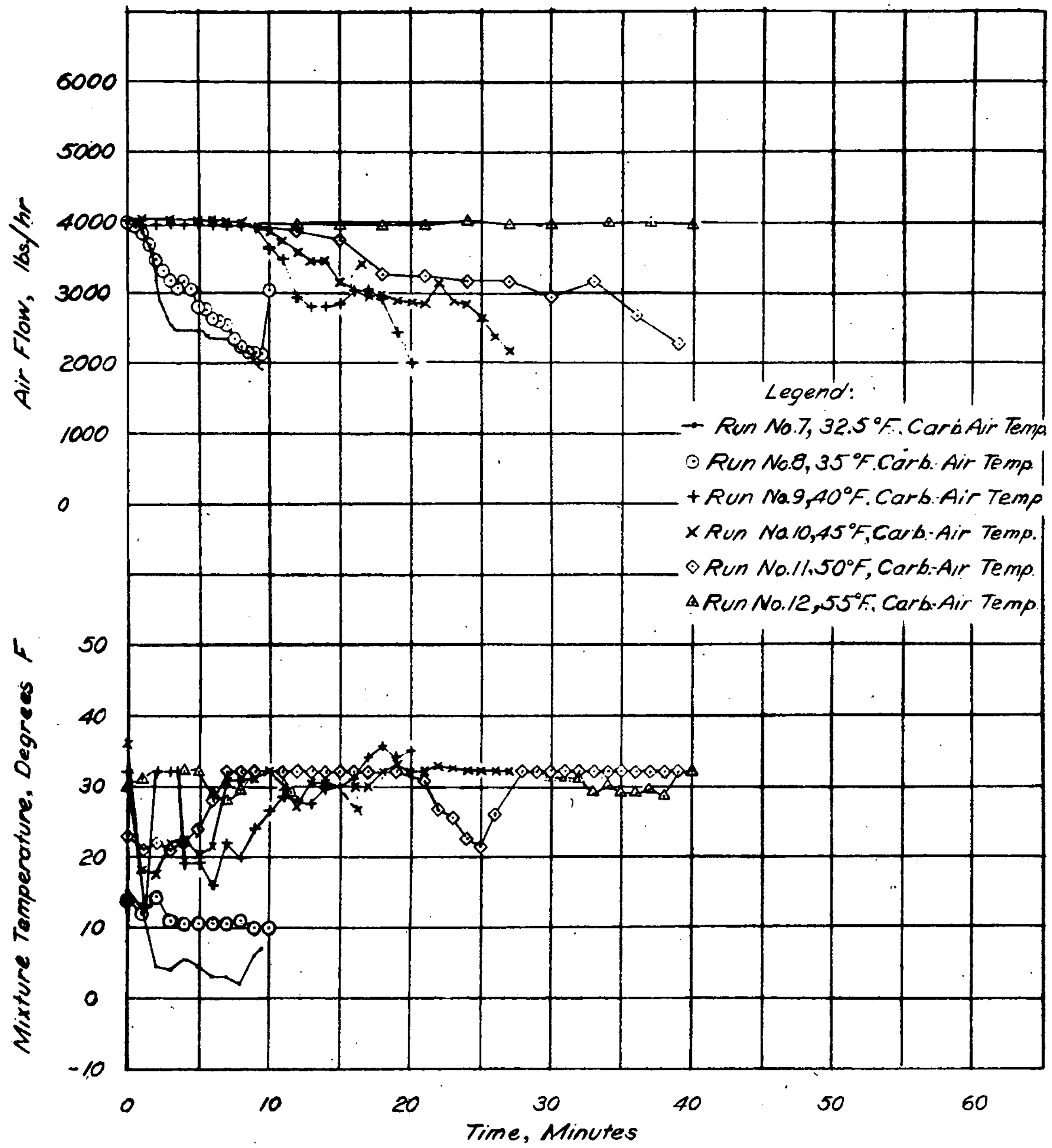

Figure 40.- Mixture temperature fluctuations during icing at moisture content of 100 percent R.H. + 10g/m³.

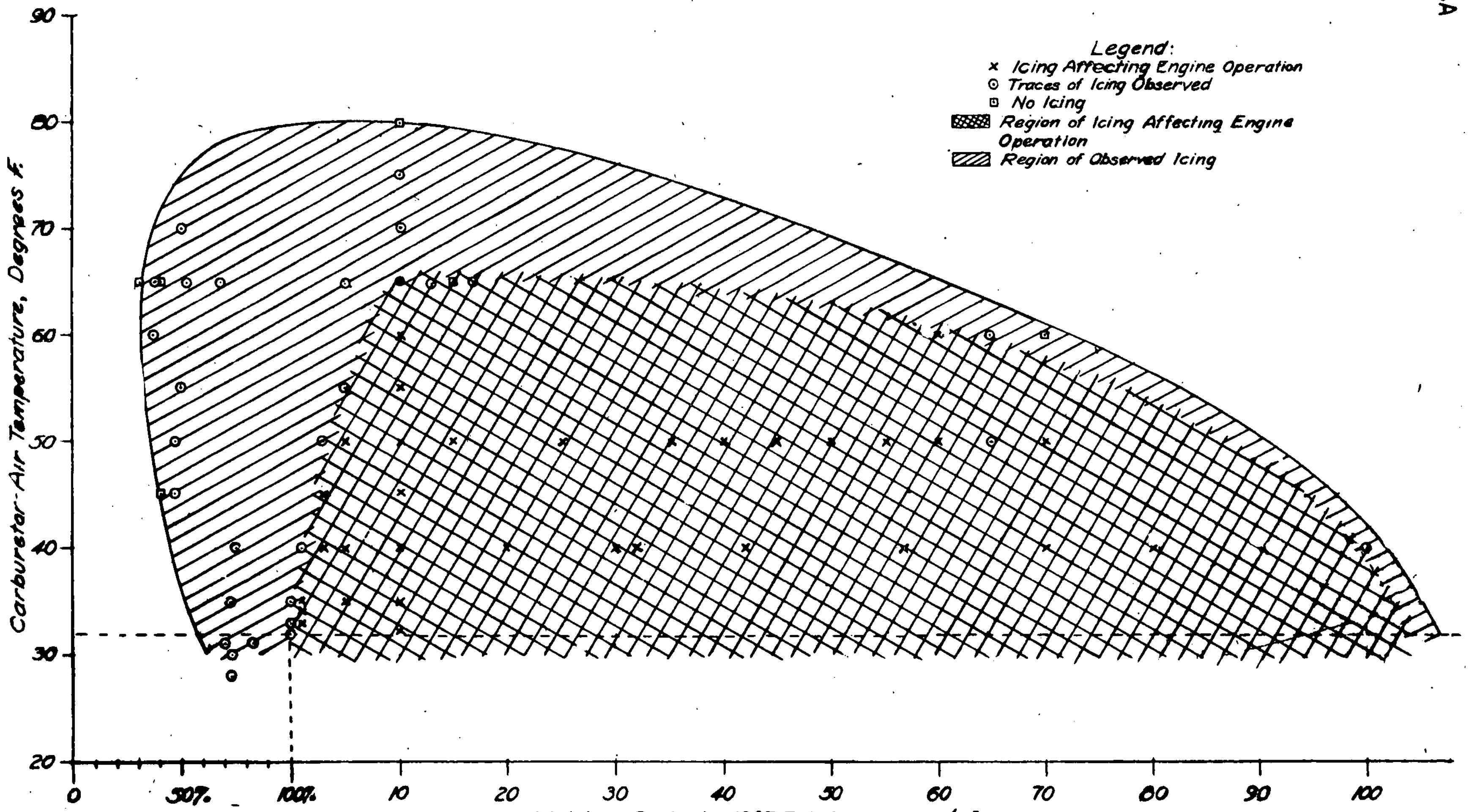

Figure 41, Limiting Icing Conditions
Holley 1375-F Carburetor, Wright 1820-G-200 Blower Section