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RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

AN INVESTIGATION OF THE ICING AND HEATED-AIR DE-ICING CHARACTERISTICS OF THE R-2600-13 INDUCTION SYSTEM

By Gilbert E. Chapman

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

A laboratory investigation was made on a Holley 1685-HB carburetor mounted on an R-2600-13 supercharger assembly to determine the icing characteristics and the heated-air de-icing requirements of this portion of the B-25D airplane induction system. Icing has been found to be most prevalent at relatively small throttle openings and, consequently, all runs were made at simulated 60-percent normal rated power condition. Icing characteristics were determined during a series of 15-minute runs over a range of inlet-air conditions. For the de-icing investigation severe impact ice was allowed to form in the induction system and the time required for the recovery of 95 percent of the maximum possible air flow at the original throttle setting was then determined for a range of wet-bulb temperatures.

Results of these runs showed that ice on the walls of the carburetor adapter and on the rim of the impeller-shroud portion of the supercharger diffuser plate did not affect engine operation at 60-percent normal rated power. Ice that adversely affected the air flow and the fuel-air ratio was formed only on the central web of the carburetor and then only when the inlet air was saturated or contained free moisture in excess of saturation. No serious ice formations were observed at inlet-air temperatures above 66° F or with an inlet-air enthalpy greater than 34 Btu per pound. The maximum temperature at which any trace of icing could be detected was 111° F with a relative humidity of approximately 28 percent. The air-flow recovery time for emergency de-icing was 0.3 minute for an enthalpy of 35 Btu per pound or wet-bulb temperature of 68° F. Further increase in enthalpy and wet-bulb temperature above these values resulted in very slight

improvement in recovery time. The fuel-air ratio restored by a 5-minute application of heated air was approximately 7 percent less than the initial value for cold-air conditions.

INTRODUCTION

As a part of the induction-system icing program requested by the Air Materiel Command, Army Air Forces, a laboratory investigation was made at the NACA Cleveland laboratory to determine the characteristics of ice formation and elimination in the induction system of the B-25D airplane. Icing and de-icing tests were conducted on that part of the induction system incorporating a Holley 1685-HB variable-venturi carburetor mounted on an R-2600-13 supercharger assembly. This research investigation had two objectives: (1) to determine the icing characteristics of the engine-carburetor induction system and thus to determine the requirements for ice prevention, and (2) to determine the heated-air requirements for the emergency removal of ice from the system.

The severity and rate of ice accumulation in a given aircraft induction system operating at a constant-power condition is primarily a function of inlet-air enthalpy and humidity ratio. Consequently, the investigation of the icing characteristics of the B-25D airplane induction system required the determination of (1) the specific combinations of inlet-air enthalpy and humidity ratio that would result in the formation of induction-system ice and (2) the location and effects of the ice accretions.

As was found in a previous study of the P-38J airplane induction system (reference 1), icing was most prevalent at relatively small throttle openings. In order to cover the maximum range of conditions at which icing was likely to be encountered, all runs were made at simulated low cruising power. The variables of inlet-air temperature and humidity ratio were controlled at or near the carburetor top deck and covered the full range of conditions expected to be encountered in flight. The results of the investigation are therefore based on the conditions existing in the air stream at the carburetor.

Icing characteristics were investigated at air temperatures above freezing in order to produce ice of the fuel-evaporation and throttling types. Below-freezing temperatures were avoided in this investigation because an accurate study of impact icing necessitates the use of the entire induction system. Impact-icing conditions were used, however, to produce severe ice formations for the de-icing runs.

The icing characteristics are presented as the conditions of inlet-air temperature or enthalpy and humidity ratio at which ice was observed to form in the system; ice that reduced the air flow 100 pounds per hour or altered the fuel-air ratio 0.005 within 15 minutes is classified as serious. The evaluation of results was aided by a visual inspection of the carburetor and supercharger inlet passage at the end of each 15-minute run.

APPARATUS

The apparatus used in the icing and de-icing investigation of a Holley 1685-HB variable-venturi carburetor mounted on an R-2600-13 supercharger assembly was the same as that described in reference 2 with the exception of a special inlet adapter and a 14-tube discharge system. Air flow, carburetor-deck pressure, inlet-air temperature, humidity, simulated-rain content, and fuel and water temperatures were accurately controlled during each run.

The laboratory installation of the induction system is shown in figure 1. Provision was made for rapidly dismantling the carburetor to permit photographing and inspection of ice formations. Plastic windows in the sides and rear of the carburetor adapter facilitated inspection during operation. An electric dynamometer coupled to the R-2600-13 accessory drive shaft drove the supercharger impeller at a speed corresponding to the 60-percent normal rated power condition.

PROCEDURE

All runs were made at simulated 60-percent normal rated power with a carburetor deck pressure of 24.89 inches of mercury absolute corresponding to a pressure altitude of 5000 feet. These simulated low-cruise-power conditions are: air flow, 5700 pounds per hour; engine speed, 2000 rpm; absolute manifold pressure, 29.5 inches of mercury; fuel-air ratio, 0.079. Inasmuch as previous research (reference 1) has indicated that variations in fuel and water temperatures do not appreciably affect icing characteristics, no attempt was made to vary the fuel and water temperatures from the arbitrarily selected value of 40° F. The icing and de-icing procedures used were similar to those described in reference 2.

Icing runs. - When the desired inlet-air pressure, temperature, humidity, and air flow were established, fuel and water used for simulating rain were diverted from their bleed lines and injected into the air stream at predetermined rates. Measurements of air flow, fuel flow, and inlet-air conditions were recorded at regular intervals during each 15-minute run. At the end of each run a visual inspection of the induction passage was made either through the plastic windows located in the sides and rear of the carburetor adapter or by dismantling the induction system. The ice formations were then properly classified in accordance with the criterions previously described.

De-icing runs. - The induction system was permitted to ice at an inlet-air temperature of 28° F, relative humidity of 100 percent, and simulated-rain injection of 100 grams per minute until the air flow was reduced to 2000 pounds per hour. The system was then instantly switched to operation with heated de-icing air of predetermined temperature and humidity at the same air flow. Measurements of air flow and fuel flow were recorded at intervals of 0.1 minute during the first minute, 0.2 minute during the second minute, and 0.5 minute during the remainder of the 5-minute de-icing period. The throttle setting was held constant throughout each run.

RESULTS AND DISCUSSION

Icing Runs

Presentation of results. - The data obtained from the icing runs are plotted on coordinates of inlet-air enthalpy and humidity ratio in figure 2. The values of enthalpy used were computed from data taken from reference 3. Lines of constant relative humidity and simulated-rain injection are superimposed upon the figure to facilitate interpretation of the data. All runs in which simulated-rain injection was used were made with saturated air. The conditions at which icing was encountered within 15 minutes are indicated by the region beneath the upper limiting curve; serious icing occurred at conditions beneath the lower curve. The sharp drop of the upper icing curve, which occurs when simulated rain is injected into the air stream, is attributed to the observed tendency of water to erode ice from the induction-system walls. At carburetor-deck conditions that lie between the two limiting curves, icing may become serious as the operating time at these conditions is increased beyond 15 minutes.

In figure 3 the results of the icing runs are presented with the commonly used coordinates of inlet-air temperature and humidity ratio. Icing occurred at temperatures up to 111° F at a relative humidity of 28 percent and at relative humidities as low as 14 percent. Serious icing was encountered only when the inlet air was saturated or contained free moisture in excess of saturation and occurred up to a maximum temperature of 66° F and a corresponding enthalpy of 34 Btu per pound.

Location and effect of ice formations. - Most of the ice accretions were formed on three parts of the induction system: the walls of the carburetor adapter, the rim of the impeller-shroud portion of the supercharger diffuser plate, and the carburetor fuel-discharge nozzle. Light frost occasionally formed on the lower portion of the throttles. The walls of the induction passage below the carburetor adapter were kept reasonably free of ice by heat transferred from the oil in the accessory housing. Typical ice formations are shown in figures 4 to 6 and their relative location and magnitude are illustrated in the schematic diagram of the induction system in figure 7.

The exposed carburetor adapter, unlike the lower portions of the induction passage, was not heated by the engine oil and large quantities of ice readily adhered to the adapter walls (figs. 4(b) and 7). The cross-sectional area of the adapter passage was, however, sufficiently large to permit a considerable decrease in size without appreciably restricting the air flow. During the 15-minute icing runs, none of the adapter ice formations reduced air flow. With extended periods of operation, however, restrictive ice formations may accumulate in the adapter.

The rim of the impeller-shroud portion of the supercharger diffuser plate was subject to serious icing (figs. 5(b) and 7) because of its exposed location in the air stream. As in the case of the carburetor adapter, the area of the induction system at the impeller entrance was relatively large and ice formations in this region, though quite heavy, did not affect engine operation within 15 minutes.

The throat of the variable-venturi carburetor, formed by the throttles and a central web containing the fuel-discharge nozzles, was found to be the most critical icing region in the induction system. Ice was formed on the central web from the fuel-outlet holes down to the tip of the web (figs. 4(a), 5(a), 6(a), and 7) and altered either air flow, fuel-air ratio or both. The contraction of the air passage between the carburetor throttles and central web presented an area that was readily restricted by relatively small ice accretions. As the throttle opening was increased, the air-flow restriction caused by ice on the discharge nozzle was correspondingly reduced. Carburetor ice formations, in addition to restricting the air flow, frequently caused a change in the fuel-discharge pressure and a consequent upset in fuel metering.

De-Icing Runs

The heated-air de-icing process involves melting only the inner face of the ice deposits until the bond to the metal surfaces is sufficiently weakened to permit the ice to be swept away by the air stream. Thus the process is primarily governed by the enthalpy of the de-icing air and, as indicated by the investigations reported in reference 4, is affected by the location, type, and magnitude of the ice formations. The relative effect of each characteristic varies with different induction systems.

A severe icing condition was simulated in order to determine the maximum amount of heat required to satisfactorily de-ice the induction system in an emergency. No attempt was made to determine the variations of de-icing effectiveness resulting from changes in the characteristics of the ice accretions.

Criterion of de-icing effectiveness. - Because of the variation of air density with changes in temperature, initial values of cold air flow could not be fully recovered during the heated-air de-icing process. The variation of air flow with temperature, as determined from runs made at constant speed, throttle angle, and carburetor-deck pressure, is plotted in figure 8. The criterion for de-icing effectiveness was chosen as the time required to recover 95 percent of the maximum possible heated-air flow.

Presentation of results. - The results of the de-icing investigation are presented in table I and in figure 9. As shown by figure 9, the air-flow recovery time rapidly decreased as the enthalpy of the de-icing air was increased to a value of 35 Btu per pound and very slightly decreased with further increases of enthalpy. Although the de-icing process was primarily dependent upon the enthalpy of the de-icing air, it was necessary for satisfactory de-icing to maintain the humidity ratio at values such that the inlet-air conditions would not lie within the serious-icing region indicated in figure 2.

Because atmospheric air may be treated as a mixture of perfect gases without serious error, the perfect gas laws may be applied and the enthalpy of wet air is very closely related to wet-bulb temperature. The time required for the removal of ice therefore becomes a function of the wet-bulb temperature of the de-icing air and makes this property a desirable basis for the establishment of heated-air de-icing requirements. Consequently, equivalent values of wet-bulb temperature have been indicated on the abscissa of figure 9. Thus, with wet-bulb temperatures of more than 68° F, 95 percent of the maximum possible heated-air flow was recovered within 0.3 minute. With wet-bulb temperatures of less than 44° F, air-flow recovery could not be obtained within 5 minutes.

Recovery of fuel-air ratio. - During icing the mixture was enriched from an initial fuel-air ratio of about 0.079 to as high as 0.223 (table I). During de-icing the fuel-air ratio was between 0.054 and 0.093 when 95 percent of the maximum heated-air flow had been reestablished and approximately half of the tests resulted in a fuel-air ratio that was within 6 percent of the initial value of 0.079. After a de-icing period of 5 minutes, the fuel-air ratio was generally stabilized at a value somewhat lower than that for the initial cold-air condition; the lowest value after 5 minutes was 0.066, the highest 0.082, and the average 0.074 or 6.6 percent lower than the initial value for cold air. These deviations of the fuel-air ratio may have occurred because of errors and lag inherent in the carburetor-temperature compensator or because water may have collected in the temperature compensating unit while the system was being iced and prevented proper temperature compensation during the de-icing period.

SUMMARY OF RESULTS

The following results are applicable to the Holley 1685-HB carburetor mounted on the R-2600-13 supercharger assembly when operated under the conditions of this investigation:

1. Most of the ice accretions were formed on the carburetor fuel-discharge nozzle, the walls of the carburetor adapter, and the rim of the impeller-shroud portion of the supercharger-diffuser plate.

2. Ice that seriously affected air flow and fuel-air ratio in 15 minutes formed only on the central web and then only when the inlet air was saturated or contained free moisture in excess of saturation.

3. Serious-ice formations were observed at inlet-air temperatures below 66° F or with an inlet-air enthalpy less than 34 Btu per pound.

4. The maximum temperature at which icing occurred was 111° F with a relative humidity of approximately 28 percent.

5. The air-flow recovery time for emergency de-icing was 0.3 minute for an enthalpy of 35 Btu per pound or a wet-bulb temperature of 68° F; further increase in enthalpy and wet-bulb temperature resulted in very slight improvement in recovery time.

6. The average fuel-air ratio after application of heated air for 5 minutes was 6.6 percent lower than the initial value for cold-air conditions.

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2. Mulholland, Donald R., Rollin, Vern G., and Galvin, Herman B.: Laboratory Investigation of Icing in the Carburetor and Supercharger Inlet Elbow of the Lockheed P-38J Airplane. I - Description of Setup and Testing Technique. NACA MR No. E5L13, Army Air Forces, 1945.

3. Anon.: Heating Ventilating Air Conditioning Guide 1944. Vol. 22. Am. Soc. Heating and Ventilating Engineers (New York), 22 ed., 1944, pp. 10-17.

4. Essex, Henry A., and Galvin, Herman B.: A Laboratory Investigation of Icing and Heated-Air De-Icing of a Chandler-Evans 1900 CPB-3 Carburetor Mounted on a Pratt & Whitney R-1830-C4 Intermediate Rear Engine Section. NACA ARR No. E4J03, 1944.

TABLE I - RESULTS OF HEATED-AIR DE-ICING INVESTIGATION ON HOLLEY 1685-HB CARBURETOR IN R-2600-13 SUPERCHARGER ASSEMBLY

[Initial icing conditions: air flow, 5700 lb/hr; fuel-air ratio, 0.079; carburetor-deck pressure, 24.89 in. Hg absolute; inlet-air temperature, 28° F; relative humidity, 100 percent; simulated-rain injection, 100 gram/min. Air flow at start of de-icing, 2000 lb/hr.]

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Run	De-icing air at carburetor				95-percent maximum possible warm air flow (lb/hr)	Time for 95-percent warm air-flow recovery (min)	Air flow at 5 minutes after start of de-icing (lb/hr)	Fuel-air ratio at start of de-icing	Fuel-air ratio at 95-percent air-flow recovery time	Fuel-air ratio 5 minutes after start of de-icing
	Wet-bulb temperature (°F)	Dry-bulb temperature (°F)	Relative humidity (percent)	Enthalpy (Btu/lb dry air)						
a1	--	--	--	--	--	--	--	--	--	--
2	41	51	44	16.71	5263	(b)	4183	0.181	(b)	0.117
3	45	49	75	19.07	5282	3.0	5375	.175	0.066	.073
4	44	50	64	18.25	5273	2.5	5315	.177	.073	.073
5	48	50	88	20.87	5273	1.2	5679	.179	.069	.071
6	50	52	88	22.06	5256	1.4	5140	.214	.067	.067
7	52	55	83	23.15	5232	.9	5735	.221	.071	.074
8	50	55	72	21.74	5232	1.4	5880	.181	.085	.071
9	53	56	83	23.79	5223	1.4	5565	.168	.059	.073
10	55	57	89	25.26	5216	.7	5535	.172	.054	.071
11	55	59	79	24.91	5197	.5	5840	.187	.061	.069
12	60	66	72	28.82	5140	.4	5795	.176	.084	.078
13	64	67	86	32.24	5130	.5	5800	.136	.058	.074
14	69	72	87	36.63	5089	.3	5750	.136	.071	.074
15	75	80	80	42.33	5023	.3	5565	.103	.064	.075
16	80	84	85	48.66	4990	.3	5370	.106	.073	.079
17	86	92	79	57.16	4924	.3	5415	.122	.066	.066
18	93	102	72	67.50	4841	.3	5230	.084	.081	.076
19	97	112	59	74.57	4759	.2	5245	.073	.072	.075
20	97	109	65	75.39	4783	.2	5565	.089	.079	.074
21	83	93	66	51.93	4915	.2	5680	.107	.077	.072
22	74	81	73	41.78	5016	.3	5825	.156	.079	.074
23	68	77	65	35.29	5047	.3	5880	.147	.092	.075
24	63	73	60	31.02	5083	.3	5900	.134	.069	.075
25	55	67	48	25.01	5130	.7	5885	.152	.067	.072
26	54	65	51	24.18	5147	.4	5610	.141	.082	.074
27	62	66	81	30.33	5139	.4	5710	.113	.065	.077
28	54	65	51	24.18	5147	.6	5705	.153	.088	.069
29	57	65	63	26.38	5147	.7	5850	.159	.093	.066
30	50	60	52	21.73	5189	.9	5670	.141	.077	.074
31	47	58	46	19.95	5206	1.0	5679	.161	.088	.078
32	48	58	50	20.45	5206	1.2	5735	.159	.087	.077
33	46	55	53	19.45	5232	3.5	5570	.139	.082	.082
34	44	54	47	18.29	5239	5.0	5670	.191	.081	.081
35	42	51	49	17.14	5263	4.0	5690	.149	.073	.075
36	40	48	52	16.20	5290	(b)	2775	.154	(b)	.124
37	42	51	49	17.14	5263	3.5	5660	.207	.074	.076
38	42	51	49	17.14	5263	(b)	4430	.189	(b)	.087
39	45	51	65	18.99	5263	(b)	5236	.223	(b)	.093
40	46	56	49	19.46	5224	2.5	5538	.195	.067	.067

[a] Conditions varied during run.

[b] 95-percent recovery not attained.

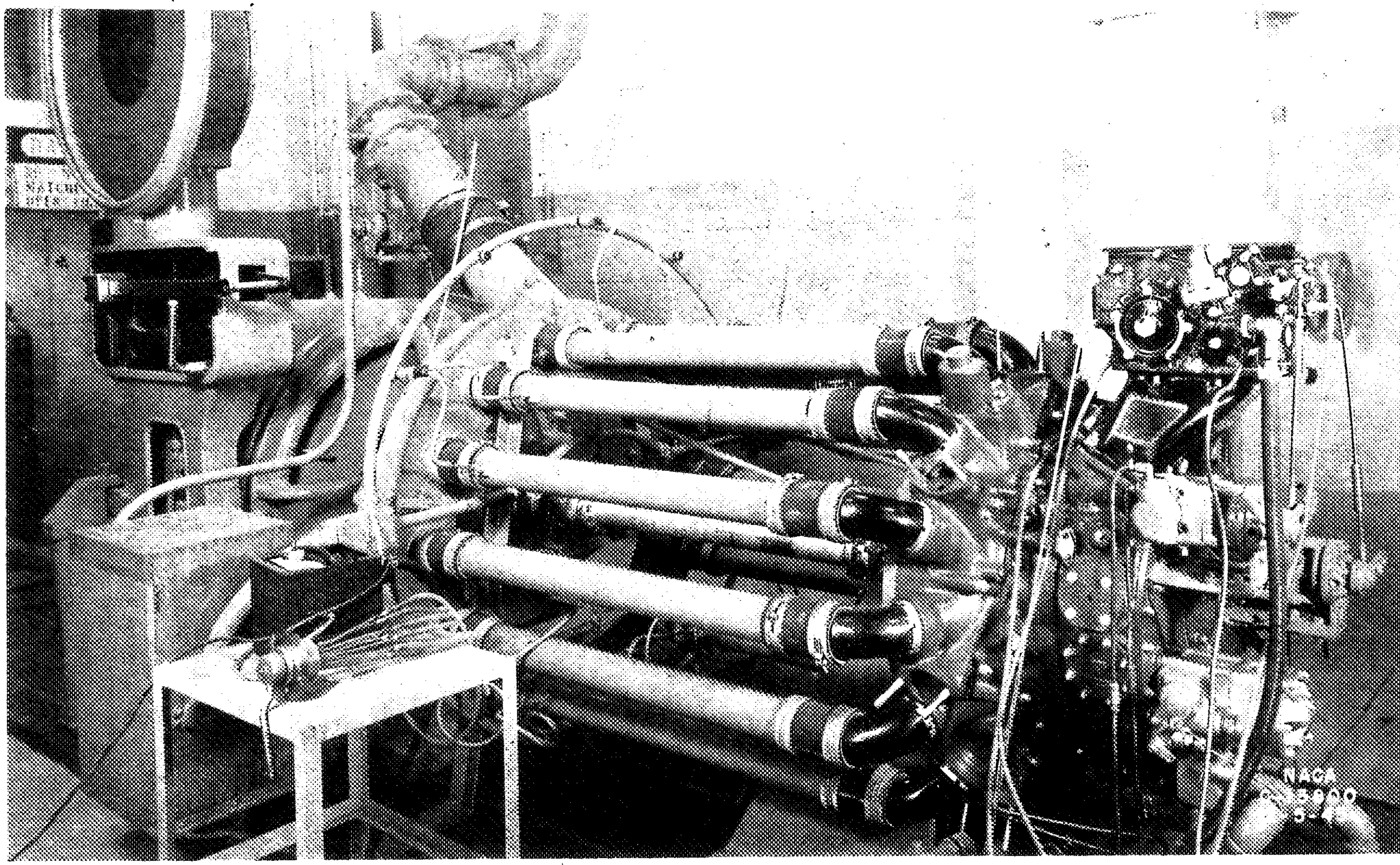


Figure 1. - General view of setup used for icing investigation of induction system. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.

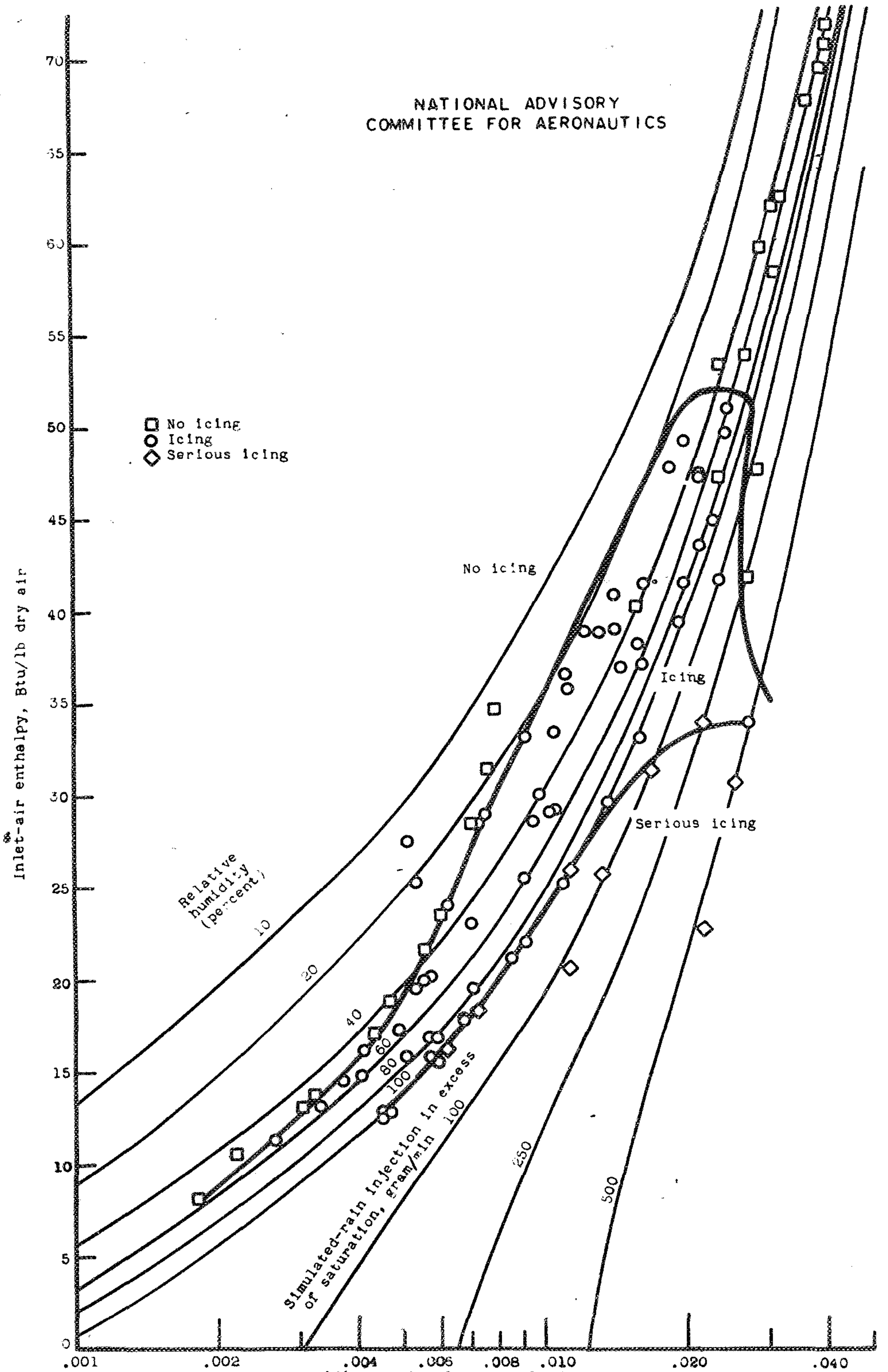


Figure 2. - Limiting-icing conditions of inlet-air enthalpy and water content. Simulated normal rated power, 60 percent. Initial icing conditions: air flow, 5700 pounds per hour fuel-air ratio, 0.079; carburetor-deck pressure, 24.89 inches mercury absolute. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.

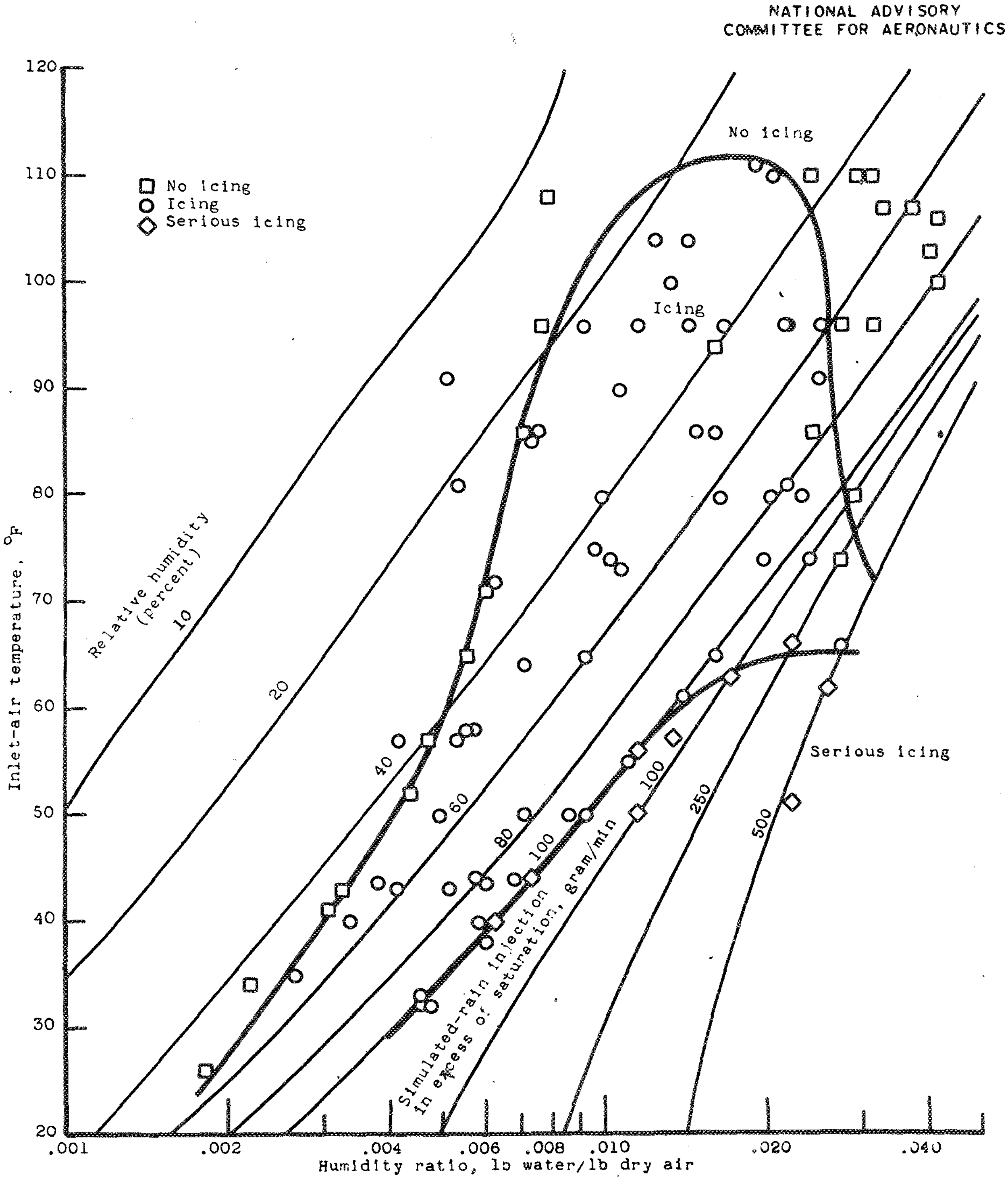
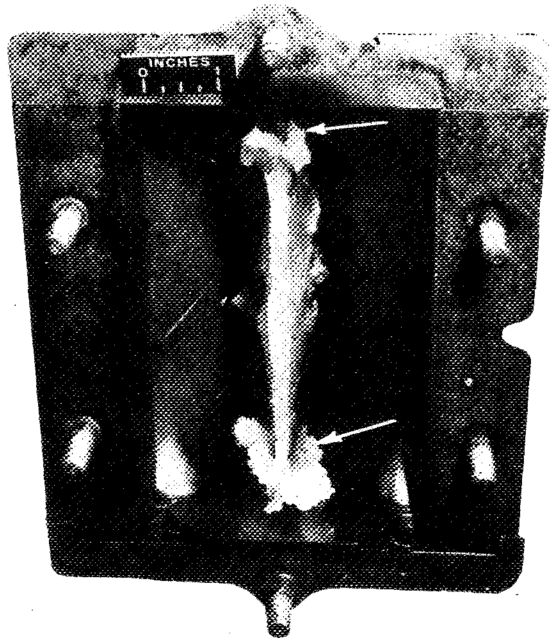
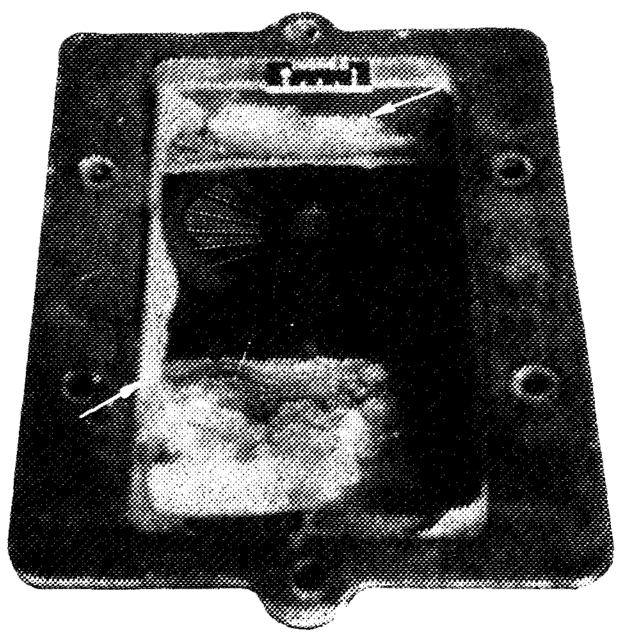


Figure 3. - Limiting-icing conditions of inlet-air temperature and water content. Simulated normal rated power, 60 percent. Initial icing conditions: air flow, 5700 pounds per hour; fuel-air ratio, 0.079; carburetor-deck pressure, 24.89 inches mercury absolute. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.



(a) Bottom view of carburetor.



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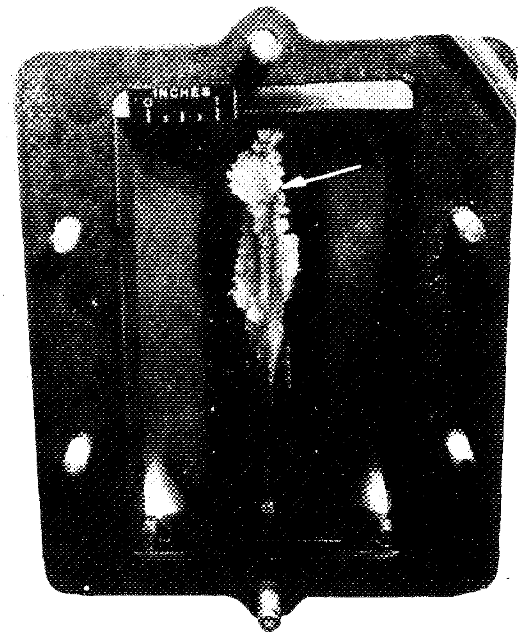
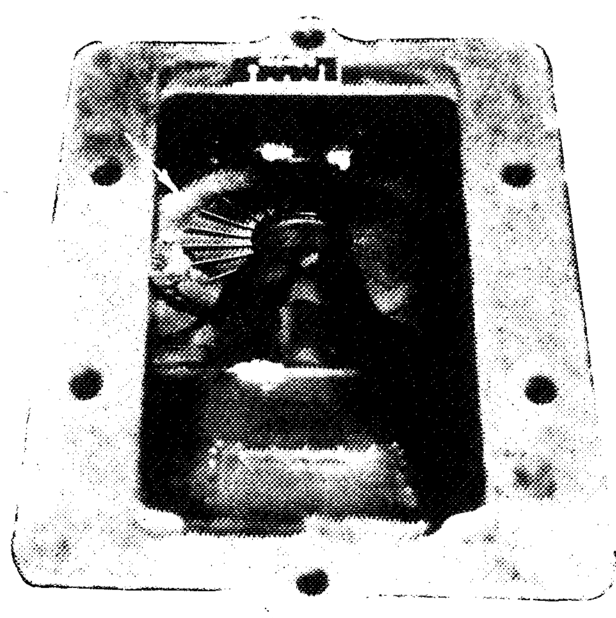
(b) Top view of supercharger inlet passage.

Figure 4. - Induction-system ice formations after 4-minute icing period. Inlet-air temperature, 40° F; relative humidity, 100 percent; simulated-rain injection, 250 grams per minute; initial air flow, 5750 pounds per hour; final air flow, 4600 pounds per hour; initial fuel-air ratio, 0.079; final fuel-air ratio, 0.065. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.



(a) Bottom view of carburetor.



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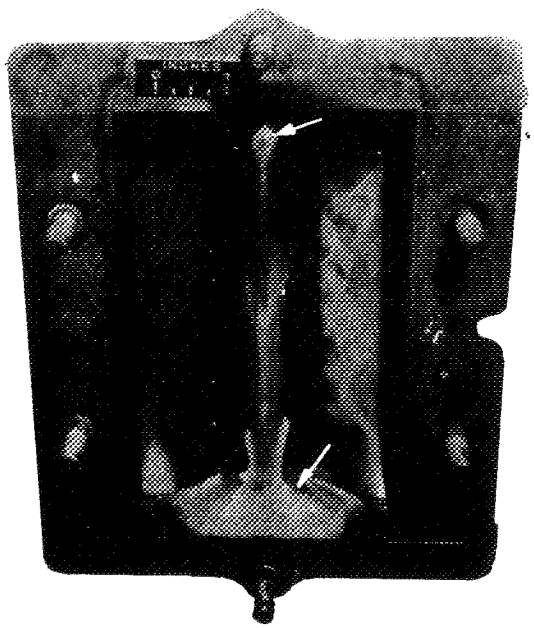
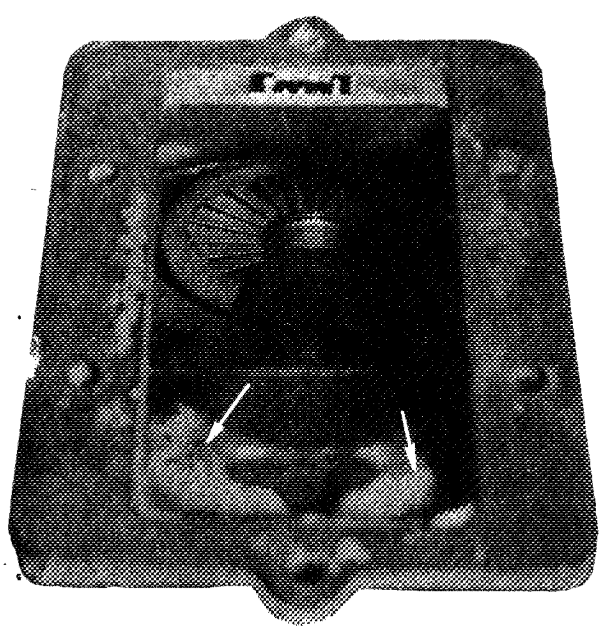
(b) Top view of supercharger inlet passage.

Figure 5. - Induction-system ice formations after 3-minute icing period. Inlet-air temperature, 44° F; relative humidity, 100 percent; simulated-rain injection, 500 grams per minute; initial air flow, 5720 pounds per hour; final air flow, 4890 pounds per hour; initial fuel-air ratio, 0.078; final fuel-air ratio, 0.075. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.



(a) Bottom view of carburetor.



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(b) Top view of supercharger inlet passage.

Figure 6. - Induction-system ice formations after 9-minute icing period. Inlet-air temperature, 35° F; relative humidity, 100 percent; simulated-rain injection, 0 grams per minute; initial air flow, 5630 pounds per hour; final air flow, 5420 pounds per hour; initial fuel-air ratio, 0.080; final fuel-air ratio, 0.092. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.

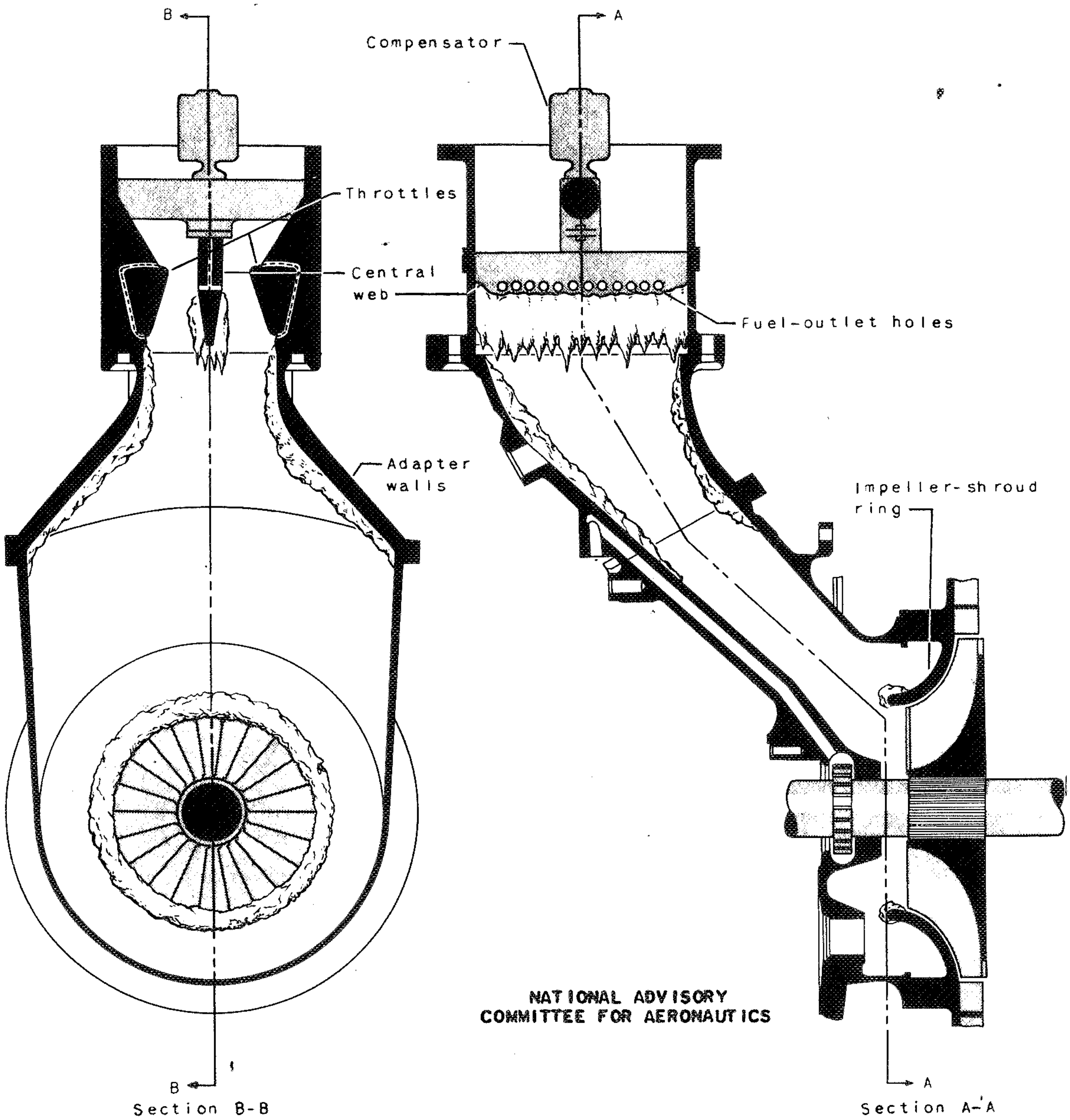

Figure 7. - Schematic diagram indicating relative location and magnitude of ice formations in induction system. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.

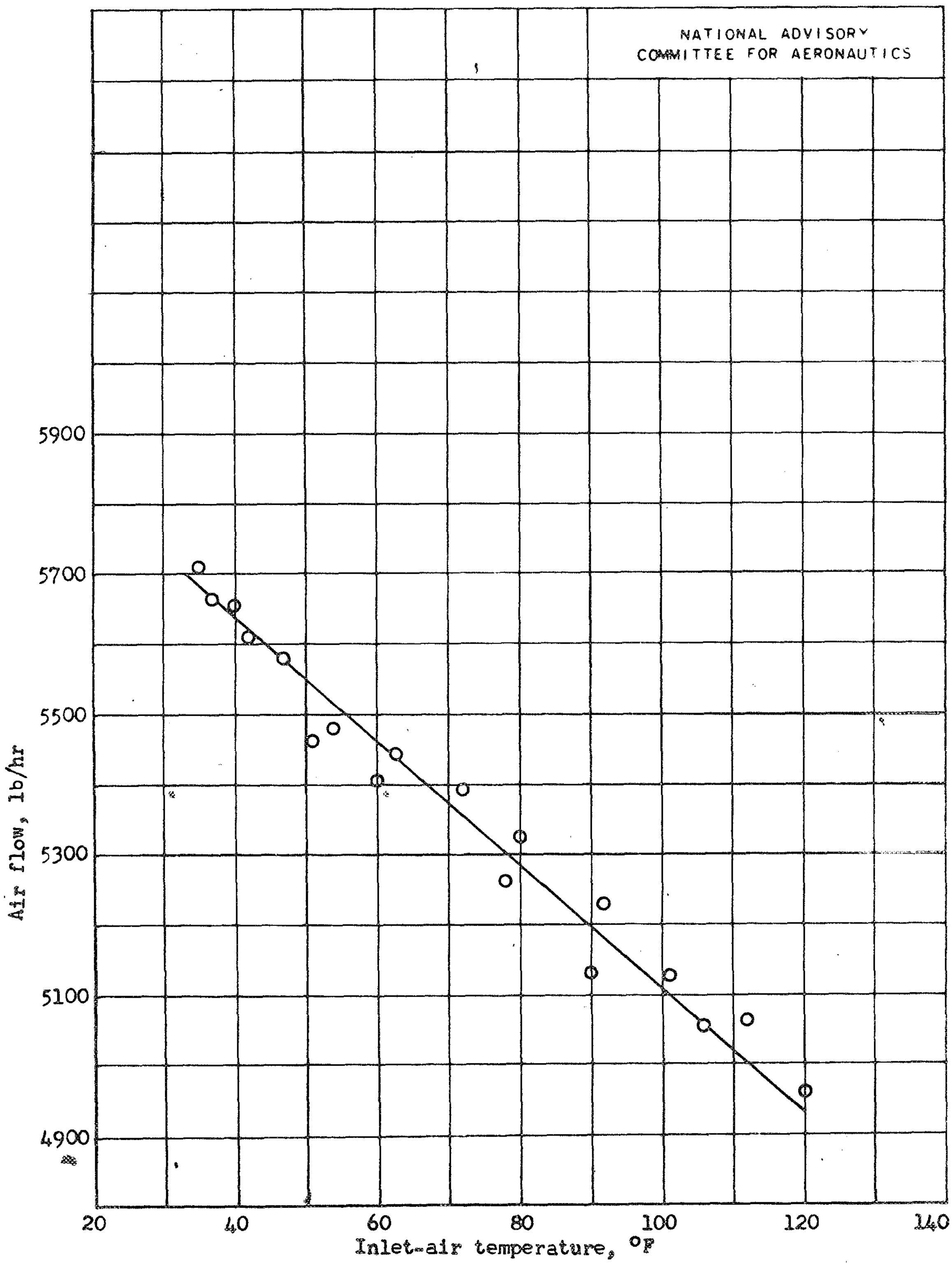

Figure 8. - Variation of air flow with temperature. Engine speed, 2000 rpm; throttle angle, constant; carburetor-deck pressure, 24.89 inches mercury absolute. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.

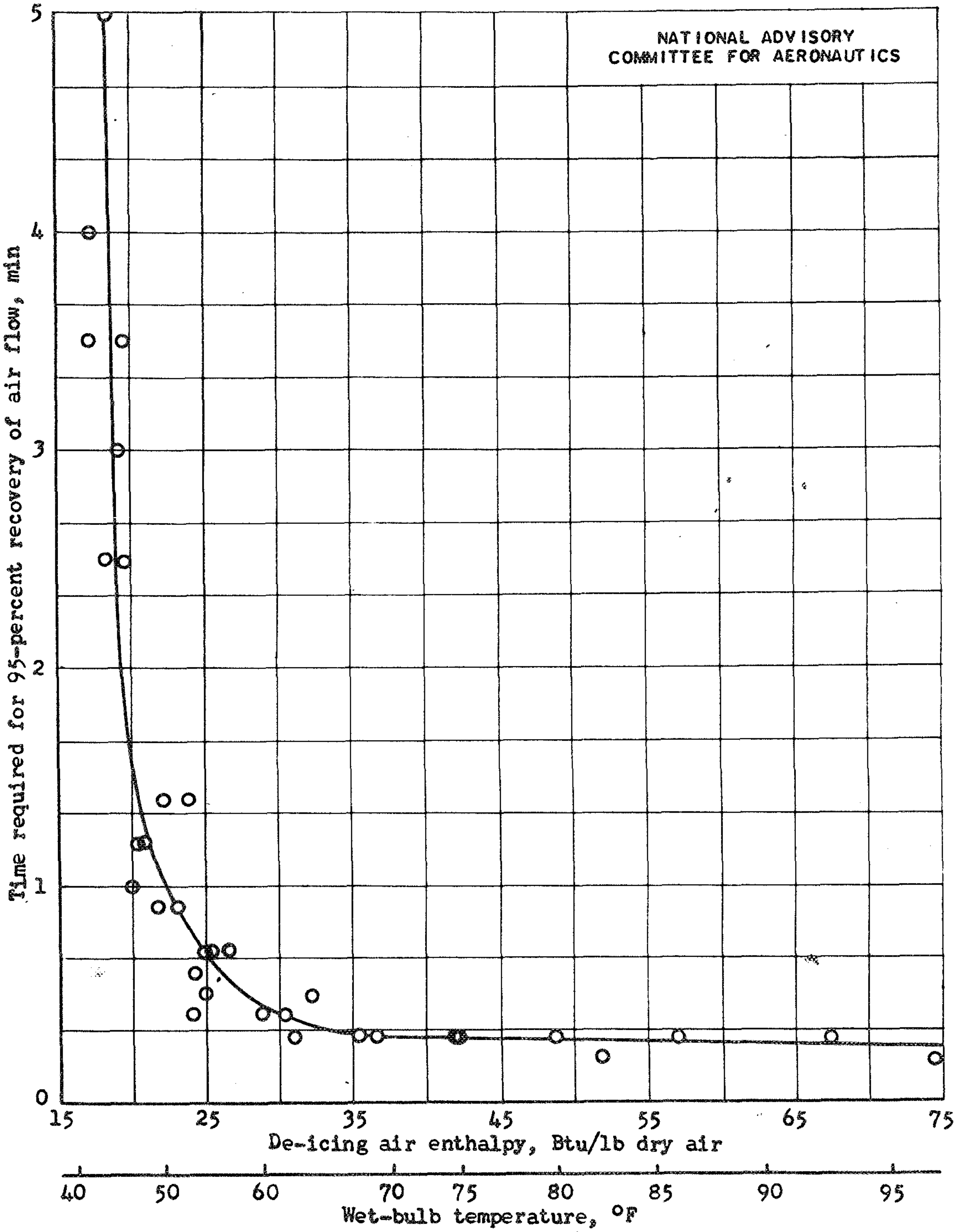

Figure 9. - Variation of air-flow recovery time with de-icing air enthalpy and wet-bulb temperature. Throttle, fixed. Initial icing conditions: air flow, 5700 pounds per hour; fuel-air ratio, 0.079; carburetor-deck pressure, 24.89 inches mercury absolute; inlet-air temperature, 28° F; relative humidity, 100 percent; simulated-rain injection, 100 grams per minute. Air flow at start of de-icing, 2000 pounds per hour. Holley 1685-HB carburetor; R-2600-13 supercharger assembly.