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INVESTIGATION OF ICE FORMATION IN THE INDUCTION SYSTEM OF AN AIRCRAFT ENGINE

I - GROUND TESTS

By Henry A. Essex, Edward D. Zlotowski
and Carl Ellisman

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NACA

WASHINGTON

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NACA AIRCRAFT ENGINE RESEARCH LABORATORY

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

INVESTIGATION OF ICE FORMATION IN THE INDUCTION SYSTEM OF AN AIRCRAFT ENGINE

I - GROUND TESTS

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SUMMARY

Ground tests were conducted on a twin-engine fighter airplane to study icing of an induction system incorporating an exhaust-driven turbosupercharger. The ground tests were made to determine the disposition of free water in the induction system of the airplane, to determine the charge-air heat rise available from the turbosupercharger, and to correlate actual airplane-test results with those of laboratory tests.

The icing characteristics of the airplane were studied at engine powers that varied from idling to take-off power with simulated-rain conditions of moderate, heavy, and excessive rain. The effect of the intercooler on the heat content of the charge air was studied at three power settings representative of the full range of engine power. Ambient-air temperature varied from 23° to 37° F.

The results obtained in the ground tests indicate that the induction system is susceptible to serious icing only at low engine powers with high water-ingestion rates. The configuration of the induction system is such that the water is removed from the charge air before it reaches the carburetor deck, except when the engine is operated at manifold pressures of 40 inches of mercury and above in simulated excessive rainfall (2 grams/cu m).

The ground-test results were in agreement with the curves of limiting-icing conditions of temperature and humidity determined in the laboratory. In the ground-test runs during which the intercooler flap was closed, approximately 85 percent of the heat added to the charge air by the turbosupercharger was available for ice prevention or de-icing at the curburetor deck.

INTRODUCTION

Induction-system icing has been experienced in airplane induction systems that incorporate turbosuperchargers. The susceptibility to icing of an induction system with an exhaust-driven turbosupercharger has not been previously investigated. At the request of the Air Technical Service Command, Army Air Forces, laboratory tests were conducted at the NACA Cleveland laboratory of the carburetor and engine supercharger section of the fighter airplane induction system (reference 1). The tests of reference 1 and unpublished tests on a complete engine have demonstrated that dangerous ice formations can occur over a wide range of carburetor-air temperature and humidity.

The ground tests reported herein were made prior to flight tests with the following objectives: (a) to determine what happens to the simulated rain that is sprayed into the induction-system entrance; (b) to obtain data for the determination of the heat rise through the induction system from the turbosupercharger; and (c) to provide data for a preliminary correlation of laboratory and airplane test results. The tests were made from December 1944 to February 1945 in order that the free-air temperatures would be as close to 32° F as possible. Water was injected into the air scoop at rates of 0.275, 0.550, and 1.10 pounds per minute to simulate flight through moderate, heavy, and excessive rain, respectively. The icing characteristics of the airplane induction system were studied at engine powers that varied from idling to take-off.

APPARATUS AND INSTRUMENTATION

The right engine installation of a twin-engine fighter airplane was selected for testing because the single generator of the electrical system is driven by the left engine. In the event of failure of the test engine, electrical power for the operation of the accessories could be supplied by the left engine and in the proposed flight tests level flight could be maintained with one engine up to an altitude of about 25,000 feet.

The induction system (fig. 1) of each engine installation consists of an external air-intake scoop, an exhaust-driven turbosupercharger, a core-type intercooler, an injection-type carburetor, an engine-stage supercharger, and interconnecting ducting. Charge air coming through the external scoop as ram air can be taken directly into the turbosupercharger or diverted by means of a selective control into the wheel-well space where it passes through an air filter and then into the turbosupercharger. The turbosuperchargers are mounted on the tops of the tail booms. Control of the turbines is achieved by a linkage that connects the turbine waste gate to the carburetor throttle. This linkage is so adjusted that, when the carburetor throttles are set to approximately the two-thirds open position, the turbine waste gate starts to close. The carburetor throttle angle and the turbine waste-gate angle of the test engine were indicated in the cockpit by means of position indicators installed for the tests.

The simulation of rain was accomplished by injecting water from sprays at the air-scoop entrance and at the intercooler cooling-air-duct entrance. Water-flow rates were measured by means of an orifice plate in the water line to the air scoop and one in the water line to the cooling-air duct of the intercooler. The differential pressures across the orifices were applied to pressure transmitters, which indicated the flow on calibrated gages that had been installed in the cockpit. The temperature of the water was measured at the storage tank and at both spray bars.

Sensitive indicating instruments were installed in the cockpit in order that symptoms of icing could be observed during the ground tests and later during the flight tests. Sensitive manifold-pressure gages were installed on both engines and differential-pressure gages indicated the charge-air pressure drop across the intercoolers. Instrumentation was provided for the measurement and automatic recording of charge-air temperature, pressure, and humidity at significant points in the induction system. The stations (fig. 1) at which the measurements were made were the air-scoop entrance (station 1), the turbosupercharger entrance (station 2), the intercooler entrance (station 3), and the carburetor deck (station 4). In addition, the static pressure was measured immediately below the carburetor and in the engine manifold. Fuel-air mixture temperatures were measured both at the supercharger inlet elbow and in the manifold downstream of the engine supercharger. Other temperatures that were recorded include intercooler cooling-air temperature, fuel temperature, accessory-compartment air temperature, and alternate air temperature measured at the filter inlet. Iron-constantan thermocouples were used to measure all temperatures.

Humidity was determined by conducting samples of charge air to a dew-point meter. The entrances of the sampling tubes were shielded to prevent water droplets from being taken in with the air and the water vapor. Free-air humidity was taken to be the same as that of the air entering the scoop upstream of the point of water injection. The automatic instruments installed in the airplane satisfactorily recorded the test data and were considered suitable for future flight tests as well as for ground tests.

Observations of the free water in the ducting were made through transparent sections in the ducts and through a window in the outboard side of the right engine nacelle (figs. 1 and 2). The rain-separation effectiveness of the induction system was studied by putting drains at the lowest point of the plenum chamber at the bottom of the intercooler, which is the lowest point in the induction system.

The cooling of the engine and the accessories was produced by the propeller slipstream at low powers and supplemented by a cooling-air blower at high powers. (See fig. 2.)

The fuel used throughout the test program conformed to specification AN-F-28, Amendment-2.

METHOD AND TESTS

In order to make the test conditions as uniform as possible, tests were run on days when the outside-air temperature was close to 32° F. The air temperatures actually varied between 23° and 37° F.

The simulated-rain water-spray rates used in these tests were calculated by assuming that the rate of water ingestion in flight was directly proportional to the airspeed of the airplane, the projected frontal area of the scoop entrance, and the rain density. These assumptions are valid with rain drops larger than 400 microns. Drops of this size are frequently prevalent in rains of the intensities simulated in these tests. Water-ingestion rates were calculated for a flight condition in which the true airspeed was 350 miles per hour and the rain densities were 0.5, 1.0, and 2.0 grams per cubic meter. These rain densities correspond approximately to moderate, heavy, and excessive rain, respectively. (See reference 2.) The scoop water-injection rates were 0.275, 0.550, and 1.10 pounds per minute for rain densities of 0.5, 1.0, and 2.0 grams per cubic meter, respectively. The area of the intercooler cooling-air duct entrance was approximately twice that of the scoop and therefore the water-injection rates were doubled for the intercooler duct.

The values of engine speed and manifold pressure prescribed in the pilot's operating instructions were used for take-off, normal rated, and high and low cruise power conditions. At the lowest powers, the manifold pressure was set and the speed used was the lowest that would give smooth operation. The engine speeds corresponding to the manifold pressures selected are listed in the following table:

Manifold pressure (in. Hg absolute)	Engine speed (rpm)	Engine power
20	(a)	
25	(a)	
30	2200	Low cruise
35	2300	High cruise
40	2600	
43.5	2600	Normal rated
50	2800	
54	3000	Take-off

[a] Engine speed governed by necessity of smooth operation.

Ground tests were run to determine the effect of the various simulated-rain ingestion rates on the charge-air conditions throughout the induction system. Four series of tests represent conditions of no rain (series A), moderate rain (series B), heavy rain (series C), and excessive rain (series D); each series comprised eight runs at the power conditions previously specified (table I). In order to impose the most severe icing conditions possible at the carburetor, the intercooler flap was left in the full-open position in the four series of tests.

The test runs were continued as long as possible to insure stabilization of the charge-air conditions. When no free water was introduced, 3 minutes was sufficient but 6 minutes was the length of run used when water was injected and the engine was operated above high cruise power. At low powers, when the vibration of the grounded airplane was slight, the tests were continued for 10 minutes.

The effect of the intercooler flap opening on charge-air cooling was studied in ground test series E (table I). This series consisted of nine runs with 1.10 pounds of water per minute injected into the air scoop during all runs. At a manifold pressure of 20 inches of mercury, one run was made with the intercooler flap open and no water injected into the intercooler cooling air, another run with no water injected into cooling air but with the flap closed, and a third run with the flap closed and 2.20 pounds per minute of water sprayed into the intercooler cooling duct. These tests were repeated at manifold pressures of 35 and 50 inches of mercury. The passage of water through the ducts was observed through the observation ports. At the end of each run the water that collected in the intercooler plenum chamber was measured.

RESULTS AND DISCUSSION

The results of these ground tests are presented in table I and in figures 3 to 10.

Disposition of water. - Observations made during the tests and an analysis of the test data established the disposition of the free water in the induction system. The water was observed to follow three courses:

1. A portion of the water that was sprayed into the scoop leaked out into the wheel well through the alternate air valve (fig. 1). This leakage was greatest during operation at low engine power when the induction-system air velocities were lowest.

2. Some of the water was swept along the walls of the intercooler duct and was collected in the plenum chamber at the bottom of the intercooler. The volume of the plenum chamber was calculated to be 360 cubic inches and the greatest volume of water collected after 10 minutes of operation was 43.8 cubic inches. In some cases water was blown out of the intercooler toward the carburetor, although the intercooler plenum chamber was far from filled. At high engine powers the resulting high air velocities in the intake ducting caused this blowing over of water.

3. Part of the water injected into the air scoop evaporated and was carried through the induction system as vapor.

Moisture content at the carburetor was computed on the basis of vapor content alone for all runs; therefore, the values do not represent the total amount of moisture if water was present.

The approximate free-water disposition in the induction system is shown in figure 3 for the three simulated-rain intensities of these tests. The results indicate that at low manifold pressure (at low charge-air flow rates) practically all of the free water leaks out of the induction system before it reaches the intercooler and very little is vaporized into the charge air. For this reason, large percentages of the water injected cannot be accounted for. The maximum amount of free water in the intercooler plenum chamber never exceeded 16 percent of the initial amount injected.

At high manifold pressures with simulated excessive rain, the charge air at the carburetor deck was saturated and some free water was observed passing from the intercooler to the carburetor deck. At a manifold pressure of 40 inches of mercury and above with simulated heavy and moderate rain, however, the entire amount of injected water was evaporated. The value of manifold pressure at which all the free water was evaporated increased with the amount of injected water, as would be expected.

During these ground tests the turbosupercharger began effective operation at a manifold pressure of about 50 inches of mercury. Because the manifold pressure at which turbosupercharging starts reduces as altitude increases, the enthalpy of the charge air at the carburetor deck is probably greater at altitude than at sea level for a given manifold pressure and charge-air inlet temperature. This enthalpy increase represents an increase in the capacity of the charge air for evaporating water. It is therefore reasonable to expect that the charge-air flow rate or manifold pressure at which all the ingested rain water becomes evaporated would be lower at altitude than at sea level for a given rain intensity.

<u>Heat rise available</u>. - The turbosupercharger put an appreciable amount of heat into the charge-air stream even when the turbine was idling. At the pressure altitudes of these tests (150 to 1025 ft), as previously mentioned, the waste gate did not start to close until the manifold pressure reached approximately 50 inches of mercury; at higher altitudes, the wider throttle openings necessary to obtain the desired manifold pressures would cause the turbine waste gate to start closing at a lower manifold pressure and thereby increase the heat rise from the turbosupercharger.

Under the ground-test conditions, the heat input by the turbosupercharger remained practically constant at a value of approximately 4.5 Btu per pound of charge air up to a manifold pressure of 40 inches of mercury. Above 40 inches of mercury, the heat input increased to approximately 11.0 Btu per pound of charge air at a manifold pressure of 54 inches of mercury. These heat increments occurred regardless of the rate of water injection as shown in figure 4.

Although cooling is the function of the intercooler, it is desirable under icing conditions to retain enough of the heat added by the turbosupercharger to prevent icing. As the air passed through the intercooler, much of the heat input was removed except in the cases in which the intercooler flap was in the closed position at low powers. (See fig. 5(a).)

At each of the three power conditions in figure 5, results are shown of a run in which no rain simulation was used and the intercooler flap was full open, of another run in which an excessive rain was simulated with full-open intercooler flap, and of a third run in which the excessive rain was simulated with intercooler flap closed. With the intercooler flap closed, only approximately 85 percent of the heat supplied by the turbosupercharger was retained after passing the intercooler at the high power runs in which the cooling blower was used.

During the tests at manifold pressures of 20 and 35 inches of mercury (figs. 5(a) and 5(b)), the cooling-air flow to the intercooler was maintained only by the propeller slipstream; whereas, at the high powers (manifold pressure, 40 in. Hg absolute and above) the cooling-air flow was increased as a result of the operation of the cooling blower. It is expected that the air flow through the intercooler was lower in all these ground tests than would be obtained in flight and that the charge-air enthalpy reduction in the intercooler would be greater in flight than was obtained in the ground tests.

Results of icing tests. - Ground-test results of carburetor icing are classified as no icing, visible icing, and serious icing. Visible icing could not be detected by observation because the carburetor and engine supercharger were not accessible for visual inspection but manifold-pressure and air-flow loss indicated this type of icing. It is therefore possible that small ice formations were present in some runs classified as no icing, which fell into the visible-icing region as determined from laboratory icing tests. The criterion for serious icing in the ground tests was similar to that used in the laboratory tests of reference 1, that is, a 2-percent reduction of initial air flow within the period of the test. Although the test period of the ground tests was only 10 minutes, the ground tests were comparable with the laboratory tests because the air-flow reduction (if any) usually occurred within the first 10 minutes of operation in the laboratory tests.

The limiting-icing-condition curves of carburetor-air temperature and moisture content as determined in the laboratory (reference 1) for the low cruise, high cruise, and rated power conditions of engine operation are reproduced in figures 6, 7, and 8, respectively. The conditions at the carburetor deck produced by the operation of the engine during the ground tests are presented on these limiting-condition curves for the corresponding engine powers.

The temperatures and moisture contents of the charge air at the scoop entrance during all the tests with simulated-rain injection were such that severe icing would have occurred at or downstream of the carburetor had the air stream passed directly to the carburetor. The removal of water by the induction system and the heat input by the turbosupercharger produced less severe conditions at the carburetor and only at low cruise power were the conditions at the carburetor deck in the serious-icing region. As indicated in figure 6, the ground-test runs that produced carburetor-deck conditions within the laboratory-determined serious-icing range resulted in serious carburetor icing. Time histories of the low-cruise-power runs in which there were indications of icing are shown in figure 9. Ground tests at low cruise power that showed either indications of slight icing (fig. 9(b)) or no indications of icing fell in the laboratory-determined visible-icing region (fig. 6).

Data from ground tests at high cruise power when plotted on the corresponding laboratory-determined limiting-conditions curves (fig. 7) also show that the runs that indicated slight icing (figs. 10(a) and 10(b)) fall in the visible-icing region and that one run, which showed no indication of icing, fell into the no-visible-icing region. No high-cruise-power runs produced carburetor-deck conditions conducive to serious icing and none of the runs displayed symptoms of serious icing.

The runs at normal rated power that showed no indication of icing fell in the region of visible icing, as shown in figure 8. The one run made with simulated excessive-rain rate, however, did show symptoms of serious icing (fig. 10(c)) but this indication of serious icing may have been caused by an unstable engine condition or it may be a borderline serious-icing condition because it is very close to the serious-icing region (fig. 8).

The test results indicate that there is a close correlation between the laboratory-determined limiting conditions and the carburetor-deck conditions, which produce the different classes of icing in the airplane-engine induction system during ground operation. If the effect of the different components of the induction system on the temperature and humidity of the air stream is known, the susceptibility of the induction system to icing can be predicted.

Icing other than the previously mentioned carburetor icing occurred in the induction system during the ground tests. Small formations of impact icing occurred at the bend in the air-scoop intake and around the alternate air valve leading into the wheel well and some formations occurred in the intercooler cooling-air duct. The formations of ice were small, but difficulty in opening the alternate air valve was encountered in those runs in which ice had formed around the valve.

SUMMARY OF RESULTS

The following results were obtained from ground tests made on a twin-engine fighter airplane under artificial conditions representing only an approximate simulation of flight:

1. The induction system of the airplane removed the free water from the charge-air stream before it reached the carburetor deck except when excessive rain equivalent to 2.0 grams per cubic meter was encountered when the engine was operated at manifold pressures of 40 inches of mercury or higher.

2. Approximately 85 percent of the heat added to the charge air by the turbosupercharger was available for ice prevention or de-icing at the carburetor when the intercooler flap was closed.

3. The results of the ground tests were in agreement with the limiting-icing curves determined in the laboratory.

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Cleveland, Ohio.

REFERENCES

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2. Humphreys, W. J.: Physics of the Air. McGraw-Hill Book Co., Inc., 3d ed., 1940, p. 280.

TABLE I - RESULTS OF GROUND TESTS OF AIRPLANE INDUCTION SYSTEM

Run	Duration (min)	Pressure altitude (ft)	True free-air temperature (°F)	Air density (slugs/cu ft)	Density ratio	Simulated rain	Engine speed (rpm)	Manifold pressure (in. Hg absolute)	Mixture setting	Charge-air flow (lb/hr)	Fuel flow (lb/hr)	Fuel-air ratio	Throttle opening (deg)	Waste-gate opening (deg)	Intercooler-flap position	Temperature, °F							Water drained from intercooler (lb/min)	Free water observed flowing to intercooler	Free water observed flowing to carburetor	Manifold pressure drop (in. Hg absolute)	Loss in charge-air flow (percent)
																Fuel at injection nozzle	Supercharger inlet mixture	Center manifold mixture	Cooling air	Alternate air	Accessory compartment	Spray water					
Series A																											
1	3	600	37	0.00243	1.022	None	1800	20.2	AR[a]	1957	160	0.082	10	Open	Open	72	24	91	37	50	113	58	-----	-----	-----	-----	-----
2	3	600	36	.00244	1.024	--do--	2240	25.4	AR	3642	248	.068	18	-do-	-do-	73	26	111	37	51	119	63	-----	-----	-----	-----	-----
3	3	600	36	.00244	1.024	--do--	2200	30.0	AR	4463	300	.067	24	-do-	-do-	80	33	106	37	55	154	66	-----	-----	-----	-----	-----
4	3	600	36	.00244	1.024	--do--	2280	35.0	AR	5718	380	.067	33	-do-	-do-	78	37	111	37	56	166	64	-----	-----	-----	-----	-----
5	3	600	36	.00244	1.024	--do--	2600	39.7	AR	7228	610	.084	45	-do-	-do-	77	36	116	39	56	138	64	-----	-----	-----	-----	-----
6	3	600	36	.00244	1.024	--do--	2600	43.2	AR	8128	710	.087	76	69	-do-	70	41	115	43	61	117	78	-----	-----	-----	-----	-----
7	3	600	35	.00244	1.024	--do--	2800	49.9	AR	9780	870	.089	Open	60	-do-	69	41	132	43	62	116	79	-----	-----	-----	-----	-----
8	3	600	37	.00243	1.022	--do--	2960	53.9	AR	10650	935	.088	-do-	58	-do-	71	44	151	42	64	122	76	-----	-----	-----	-----	-----
Series B																											
1	10	200	24	0.00253	1.065	Moderate	1780	20.1	AR	1873	150	0.080	10	Open	Open	65	24	84	26	39	161	70	0.006	No	No	0	0.2
2	10	200	24	.00253	1.066	--do--	2200	25.0	AR	3412	240	.070	17	-do-	-do-	67	27	101	31	40	179	75	.001	No	No	.0	.3
3	10	200	25	.00253	1.064	--do--	2180	29.7	AR	4374	300	.069	24	-do-	-do-	70	34	98	32	42	207	76	.023	Yes	No	1.1	3.4
4	10	205	24	.00253	1.064	--do--	2280	34.6	AR	5624	379	.067	32	-do-	-do-	74	40	102	31	42	210	77	.045	Yes	No	.5	1.7
5	5	505	36	.00245	1.028	--do--	2580	39.9	AR	7435	630	.085	43	-do-	-do-	59	36	107	42	59	141	99	0	No	No	0	0
6	5	515	35	.00245	1.028	--do--	2600	43.6	AR	8117	715	.088	76	-do-	-do-	63	46	117	41	62	145	104	0	No	No	0	0
7	5	515	36	.00244	1.028	--do--	2760	49.6	AR	9668	860	.089	Open	65	-do-	62	49	126	41	63	151	101	0	No	No	0	0
8	5	505	36	.00244	1.027	--do--	2920	54.3	AR	10803	950	.088	-do-	59	-do-	62	47	139	42	63	158	96	0	No	No	0	0
Series C																											
1	10	180	24	0.00254	1.066	Heavy	1760	19.8	AR	1760	151	0.086	10	Open	Open	75	30	92	32	34	165	68	0.003	No	No	0	0
2	10	170	23	.00254	1.069	--do--	2160	24.9	AR	3344	235	.070	17	-do-	-do-	76	33	105	32	33	184	68	.002	No	No	0	.2
3	10	170	24	.00254	1.066	--do--	2160	29.9	AR	4454	300	.067	24	-do-	-do-	75	37	99	31	36	208	71	.008	No	No	.1	.7
4	10	170	25	.00253	1.065	--do--	2240	34.9	AR	5667	386	.068	32	-do-	-do-	78	41	101	32	38	203	70	.007	Yes	No	.4	0
5	5	520	34	.00245	1.031	--do--	2560	39.9	AR	7342	621	.085	43	-do-	-do-	63	36	105	40	61	139	76	-----	-----	No	0	0
6	5	530	33	.00246	1.033	--do--	2560	43.5	AR	8201	727	.089	76	-do-	-do-	63	42	105	38	58	138	75	.003	Yes	No	0	.2
7	5	520	34	.00245	1.031	--do--	2760	49.8	AR	9846	869	.088	Open	63	-do-	61	43	121	38	61	150	71	0	Yes	No	.3	.2
8	5	500	37	.00244	1.026	--do--	2920	53.7	AR	10434	---	-----	-do-	61	-do-	68	48	139	41	64	157	75	0	No	No	.9	0
Series D																											
1	10	150	25	0.00253	1.065	Excess	1800	19.7	AR	1928	155	0.080	10	Open	Open	68	24	83	26	37	148	64	0.007	No	No	0.1	0
2	10	150	25	.00253	1.064	--do--	2240	25.0	AR	3495	245	.070	17	-do-	-do-	72	32	109	32	36	174	69	.001	No	No	0	.3
3	10	525	34	.00245	1.031	--do--	2200	29.8	AR	4429	298	.067	25	-do-	-do-	79	34	101	32	53	167	72	.031	Yes	No	.4	3.0
4	10	525	36	.00244	1.027	--do--	2280	34.4	AR	5518	368	.067	33	-do-	-do-	83	42	106	32	52	188	73	.076	Yes	No	.6	1.4
5	5	1025	29	.00243	1.023	--do--	2520	40.0	AR	7414	620	.084	48	-do-	-do-	58	35	102	33	48	131	58	.159	Yes	Yes	.4	3.4
6	5	1025	28	.00244	1.025	--do--	2520	43.2	AR	8019	690	.086	76	67	-do-	58	42	98	32	47	132	58	.133	Yes	Yes	0	2.6
7	5	1025	29	.00244	1.024	--do--	2720	49.7	AR	9711	850	.088	Open	59	-do-	56	43	114	32	51	140	58	.093	Yes	Yes	.2	2.6
8	5	1025	31	.00243	1.020	--do--	2880	53.8	AR	10772	945	.088	-do-	61	-do-	67	45	133	32	53	149	59	.052	Yes	Yes	.4	.7
Series E																											
1[b]	10	825	31	0.00244	1.026	Excess	1852	20.4	AR	1935	160	0.083	10	Open	Open	70	24	90	31	47	118	63	-----	No	No	-----	-----
2[b]	10	825	30	.00245	1.028	--do--	1848	20.4	AR	1923	160	.083	10	-do-	Closed	71	29	95	31	41	138	63	-----	No	No	-----	-----
3	10	870	30	.00244	1.026	--do--	1852	20.3	AR	1923	160	.083	10	-do-	-do-	73	29	94	31	39	137	61	-----	No	No	-----	-----
4[b]	10	860	30	.00244	1.026	--do--	2260	35.0	AR	5672	380	.067	34	-do-	Open	78	35	101	31	48	159	64	-----	Yes	Yes	-----	-----
5[b]	10	860	30	.00244	1.026	--do--	2280	35.0	AR	5690	380	.067	34	-do-	Closed	83	39	104	31	41	179	62	-----	Yes	Yes	-----	-----
6	10	860	31	.00244	1.024	--do--	2260	35.2	AR	5718	385	.067	34	-do-	-do-	84	42	108	32	43	181	63	-----	Yes	Yes	-----	-----
7[b]	5	860	30	.00244	1.026	--do--	2740	49.8	AR	9815	870	.089	Open	60	Open	59	43	122	34	53	140	59	-----	Yes	Yes	-----	-----
8[b]	5	860	30	.00244	1.026	--do--	2760	49.8	AR	9718	865	.089	-do-	60	Closed	62	47	127	36	41	152	60	-----	Yes	Yes	-----	-----
9	5	860	30	.00244	1.026	--do--	2740	50.0	AR	9743	865	.089	-do-	60	-do-	63	47	124	34	41	152	56	-----	Yes	Yes	-----	-----

[a]Automatic rich.
[b]No water sprayed into intercooler duct.

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TABLE I - Concluded

RESULTS OF GROUND TESTS OF AIRPLANE INDUCTION SYSTEM - Concluded

Run	Station 1									Station 2			Station 3									Station 4								
	Dew-point temperature (°F)	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)	Relative humidity (percent)	Static pressure (in. Hg absolute)	Air density (lb/cu ft)	Vapor content (lb/lb dry air)	Enthalpy (Btu/lb dry air)	Air velocity (ft/sec)	Dry-bulb temperature (°F)	Static pressure (in. Hg absolute)	Air density (lb/cu ft)	Dew-point temperature (°F)	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)	Relative humidity (percent)	Static pressure (in. Hg absolute)	Air density (lb/cu ft)	Vapor content (lb/lb dry air)	Enthalpy (Btu/lb dry air)	Air velocity (ft/sec)	Dew-point temperature (°F)	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)	Relative humidity (percent)	Static pressure (in. Hg absolute)	Air density (lb/cu ft)	Vapor content (lb/lb dry air)	Enthalpy (Btu/lb dry air)	Air velocity (ft/sec)
Series A																														
1	32	38	35	75	29.2	0.07791	0.00378	13.2	26	39	29.5	0.07837	32	54	44	43	29.4	0.07580	0.00373	17.1	36	32	50	42	50	29.3	0.07621	0.00378	16.2	32
2	32	40	36	68	29.2	.07760	.00378	13.6	49	40	29.5	.07821	32	53	43	42	29.1	.07527	.00380	16.9	68	31	50	42	50	28.9	.07507	.00370	16.1	60
3	33	41	37	69	29.2	.07744	.00392	14.1	60	41	29.4	.07784	32	56	45	40	28.6	.07347	.00385	17.8	86	31	51	42	45	28.2	.07315	.00373	16.5	76
4	33	41	37	69	29.2	.07744	.00392	14.1	77	41	29.3	.07763	32	56	45	40	28.2	.07255	.00388	17.8	111	31	53	43	44	27.5	.07124	.00380	17.0	100
5	31	41	37	69	29.2	.07744	.00364	13.8	97	41	29.3	.07758	29	58	44	31	27.0	.06917	.00355	17.9	147	28	52	41	40	25.9	.06700	.00353	16.4	134
6	31	43	38	63	29.2	.07714	.00364	14.2	110	43	29.4	.07761	29	65	48	27	27.7	.06991	.00360	19.7	164	27	53	41	34	26.3	.06793	.00340	16.7	148
7	33	43	38	63	29.2	.07714	.00392	14.6	132	43	29.3	.07719	33	80	56	18	29.8	.07333	.00390	23.6	188	31	57	44	33	28.0	.07182	.00375	17.8	169
8	32	44	39	64	29.2	.07699	.00378	14.7	144	44	29.0	.07643	33	89	60	14	30.9	.07474	.00373	26.0	201	31	59	46	34	28.7	.07325	.00375	18.5	180
Series B																														
1	21	26	24	75	29.7	0.08112	0.00229	8.7	24	25	30.0	0.08200	22	46	37	39	29.8	0.07818	0.00239	13.8	34	22	43	35	42	29.7	0.07843	0.00240	13.1	30
2	20	27	25	76	29.7	.08103	.00218	8.8	44	26	30.0	.08185	22	43	35	43	29.4	.07761	.00239	12.9	62	24	42	35	48	29.2	.07712	.00261	12.9	55
3	20	28	25	65	29.8	.08089	.00214	9.0	56	31	29.9	.08067	28	41	35	54	28.8	.07618	.00319	13.3	81	33	44	39	64	28.4	.07468	.00404	15.0	73
4	20	27	25	76	29.8	.08105	.00214	8.8	72	29	29.6	.08027	26	42	35	48	28.4	.07505	.00292	13.3	106	29	44	37	52	27.7	.07300	.00351	14.2	96
5	24	41	34	47	29.3	.07771	.00268	12.7	101	35	29.7	.07955	30	56	45	42	27.4	.07052	.00369	17.9	149	34	48	42	62	26.3	.06855	.00462	16.7	135
6	24	41	34	47	29.3	.07763	.00268	12.7	109	37	29.5	.07886	32	60	47	37	27.4	.06979	.00412	19.1	164	34	50	42	52	26.0	.06757	.00468	17.1	149
7	24	41	34	47	29.3	.07766	.00268	12.7	130	35	29.4	.07884	30	72	52	22	29.4	.07336	.00355	21.4	186	33	52	43	48	27.5	.07130	.00422	17.1	168
8	27	42	36	55	29.3	.07750	.00269	13.3	145	35	29.3	.07844	33	81	57	19	31.2	.07658	.00380	23.8	199	36	56	47	50	29.0	.07454	.00458	18.6	180
Series C																														
1	22	25	24	87	29.8	0.08159	0.00240	8.6	22	25	29.7	0.08121	23	48	38	35	29.7	0.07763	0.00252	14.4	32	24	51	40	34	29.7	0.07698	0.00264	15.3	28
2	23	25	24	87	29.8	.08159	.00252	8.7	43	24	29.7	.08137	23	44	36	44	29.4	.07738	.00255	13.3	61	24	46	37	40	29.2	.07654	.00264	13.9	54
3	19	26	24	75	29.8	.08142	.00202	8.4	57	26	29.7	.08098	22	44	35	37	28.9	.07599	.00240	13.2	83	25	46	37	40	28.5	.07471	.00279	14.1	74
4	16	27	24	64	29.8	.08125	.00174	8.3	73	27	29.6	.08076	21	42	34	41	28.0	.07404	.00240	12.7	108	25	45	36	41	27.4	.07195	.00294	14.0	98
5	27	39	34	60	29.3	.07802	.00308	12.7	98	37	29.7	.07927	37	51	44	58	27.5	.07139	.00500	17.7	145	36	47	42	67	26.4	.06898	.00502	16.6	132
6	27	38	34	67	29.3	.07818	.00310	12.4	109	34	29.6	.07954	38	49	43	63	27.4	.07136	.00520	17.5	162	36	45	41	72	26.0	.06815	.00525	16.4	149
7	27	39	34	60	29.3	.07789	.00310	12.8	132	35	29.4	.07890	41	64	52	43	29.8	.07536	.00542	21.4	184	39	48	44	74	27.8	.07269	.00545	17.4	168
8	24	42	35	48	29.3	.07777	.00269	12.9	140	36	29.3	.07831	39	74	55	26	30.5	.07579	.00482	23.2	194	42	53	47	64	28.2	.07301	.00588	19.1	177
Series D																														
1	21	25	24	88	29.9	0.08181	0.00218	8.3	25	25	29.9	0.08173	23	43	35	42	29.6	0.07819	0.00252	13.2	35	24	43	35	42	29.6	0.07801	0.00259	13.3	31
2	20	27	25	78	29.9	.08150	.00206	8.7	45	31	29.9	.08089	26	43	36	49	29.4	.07751	.00292	13.5	64	26	46	38	46	29.1	.07642	.00288	14.2	57
3	25	37	32	59	29.4	.07853	.00278	11.9	59	36	29.6	.07911	35	48	42	60	28.7	.07489	.00446	16.4	83	39	47	43	73	28.3	.07407	.00525	17.0	74
4	25	39	34	59	29.5	.07853	.00278	12.4	73	36	29.6	.07919	48	47	47	100	28.2	.07378	.00750	19.0	106	41	48	45	80	27.6	.07202	.00590	18.0	95
5	29	33	31	82	29.8	.07752	.00335	11.5	100	33	29.0	.07811	45	42	42	100	27.0	.07127	.00710	16.8	147	44	40	40	100	25.5	.06773	.00610	16.3	136
6	29	32	31	92	29.8	.07773	.00335	11.3	107	33	29.0	.07806	46	46	46	100	27.9	.07322	.00710	18.7	154	45	40	40	100	26.2	.06961	.00690	16.0	143
7	32	34	33	90	29.8	.07742	.00385	12.2	130	33	28.8	.07760	49	54	51	82	30.4	.07835	.00710	20.6	175	47	43	43	100	28.2	.07437	.00620	17.0	162
8	33	35	34	90	29.8	.07729	.00402	12.7	145	34	28.8	.07726	48	61	54	63	30.9	.07880	.00680	22.3	193	47	47	47	100	28.5	.07454	.00710	19.0	179
Series E																														
1	31	31	31	100	28.7	0.07748	0.00376	11.5	26	33	28.8	0.07763	33	51	43	51	29.1	0.07547	0.00400	16.7	36	33	47	41	60	29.0	0.07585	0.00400	15.7	32
2	31	30	30	100	28.7	.07778	.00376	11.2	26	32	28.9	.07789	33	50	42	50	29.1	.07561	.00400	16.4	36	33	53	44	47	29.0	.07496	.00400	17.2	32
3	32	30	30	100	28.8	.07791	.00393	11.4	26	31	28.9	.07819	35	49	42	55	29.1	.07576	.00435	16.4	36	34	53	44	47	29.0	.07496	.00420	17.3	32
4	30	33	32	90	28.8	.07744	.00350	11.3	76	33	28.8	.07763	36	44	41	78	28.1	.07395	.00475	15.8	108	38	45	42	79	27.4	.07195	.00530	16.7	98
5	31	32	32	100	28.8	.07760	.00376	11.6	76	32	28.8	.07778	36	43	40	78	28.1	.07410	.00475	15.6	108	38	47	43	74	27.4	.07166	.00530	17.1	99
6	31	33	32	90	28.8	.07744	.00376	11.7	77	33	28.8	.07763	36	46	42	72	28.1	.07366	.00475	16.3	110	38	49	44	69	27.4	.07138	.00530	17.6	99
7	30	35	33	82	28.9	.07734	.00357	11.8	132	35	28.9	.07747	41	57	49	55	29.9	.07669	.00548	19.6	181	40	47	43	74	27.8	.07281	.00550	17.2	167
8	30	34	33	90	28.9	.07750	.00357	11.7	130	34	28.9	.07763	44	55	49	65	29.8	.07689	.00615	20.0	178	42	53	47	65	27.8	.07196	.00595	19.1	168
9	30	35	33	82	28.9	.07734	.00357	11.8	131	33	28.9	.07779	46	56	51	71	29.9	.07700	.00660	20.8	178	44	51	48	82	27.9	.07250	.00650	19.5	167

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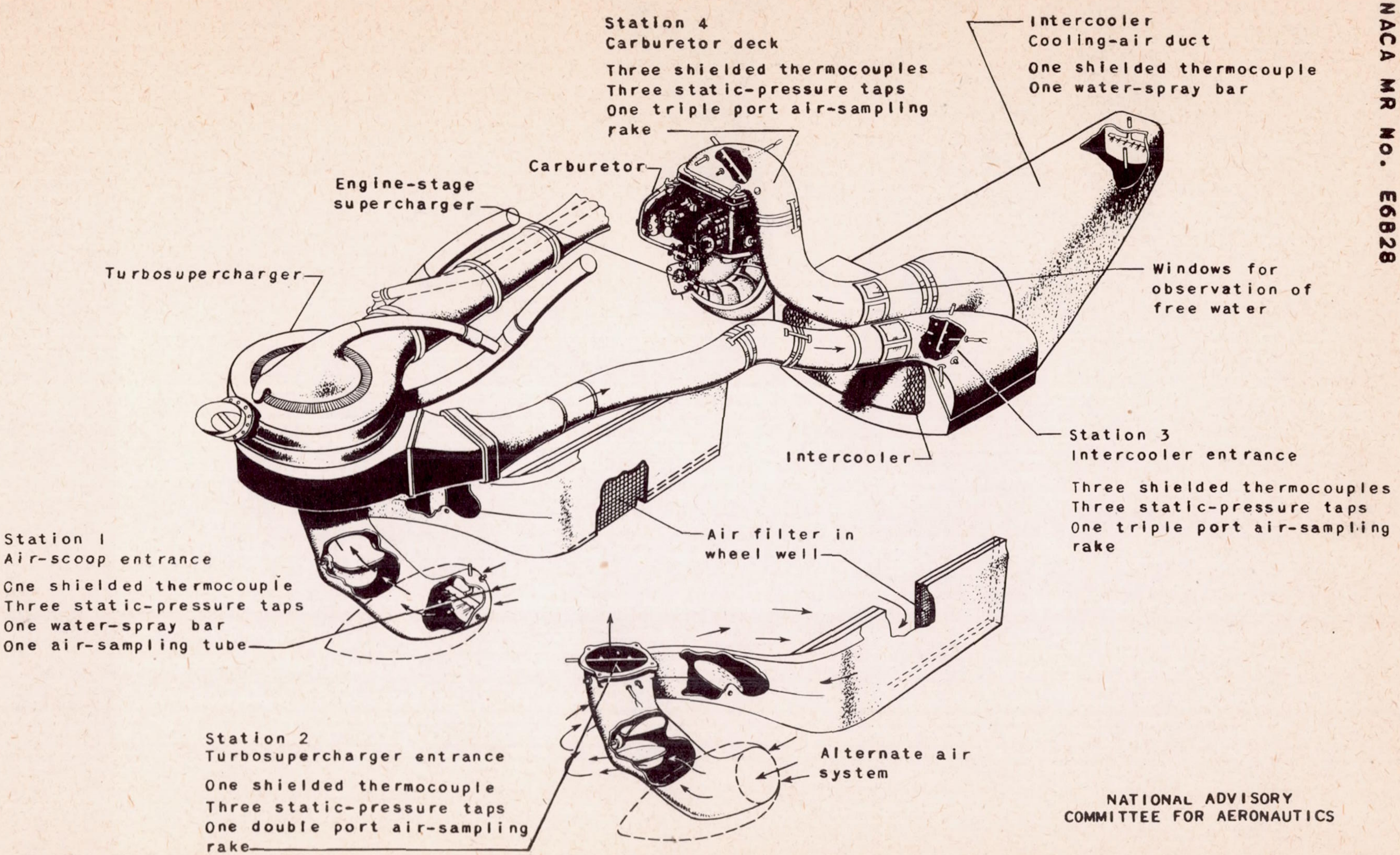

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Figure 1. - Right-engine induction system of a twin-engine fighter airplane instrumented for ground icing tests.

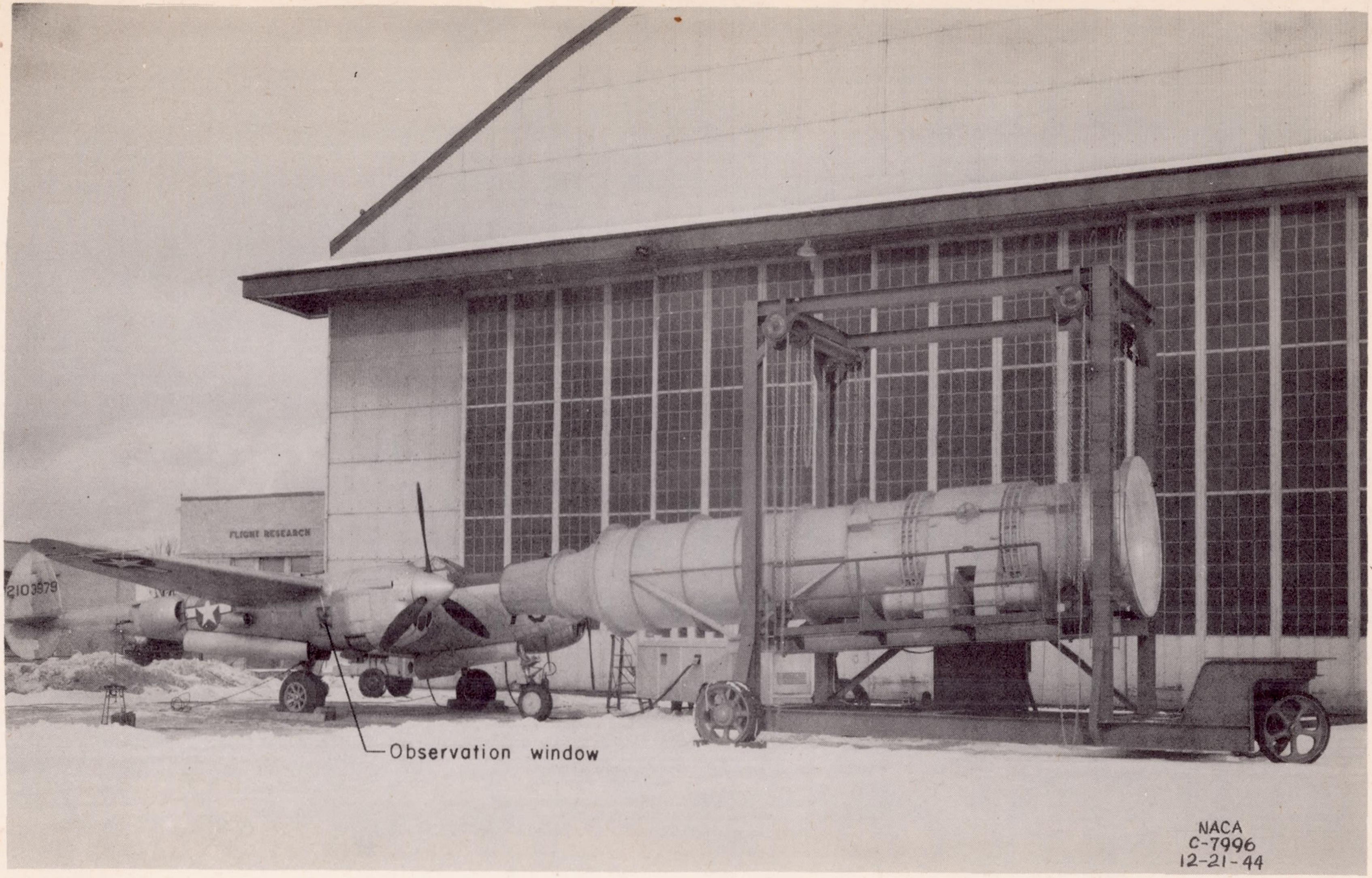
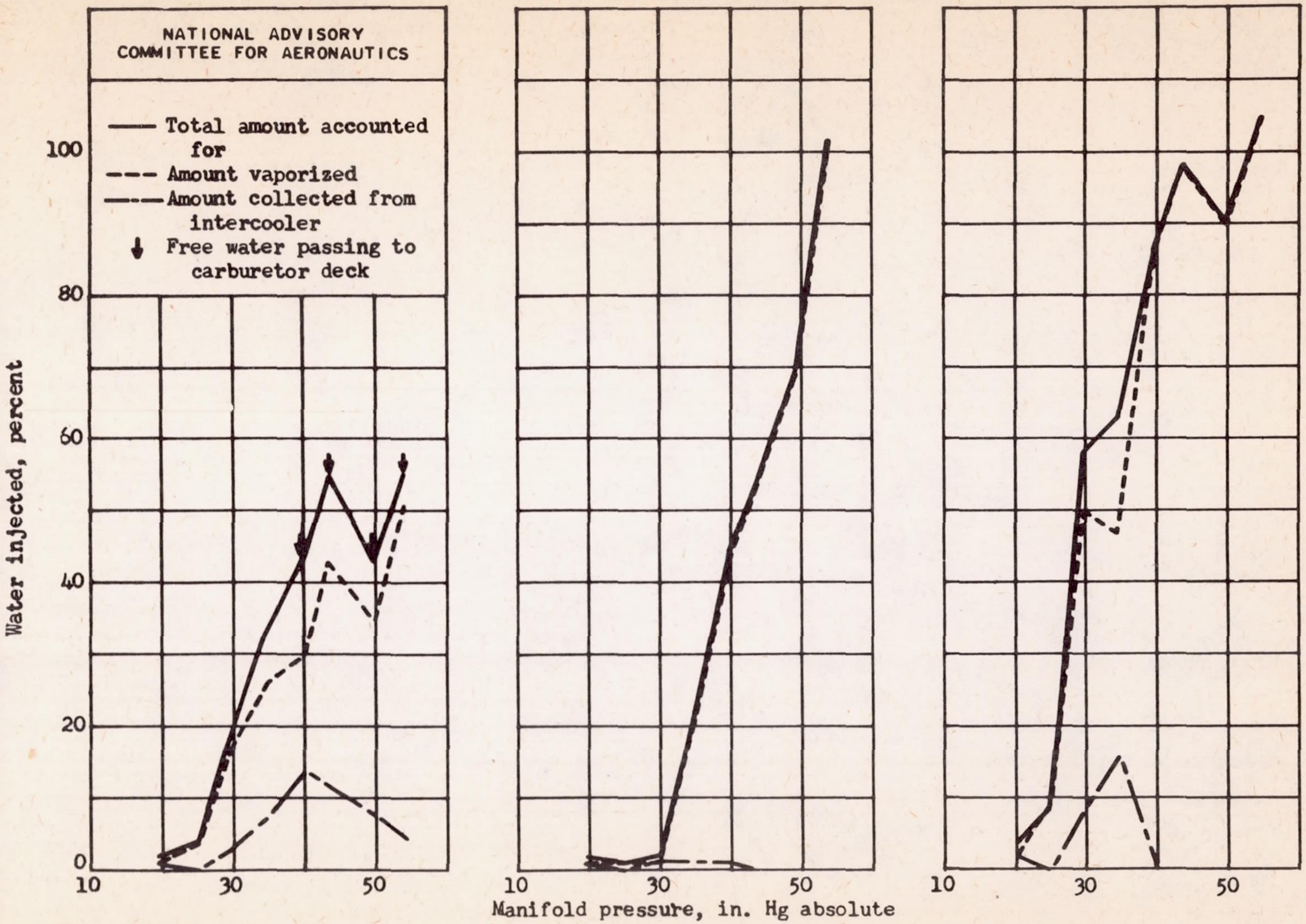


Figure 2. - Setup for ground tests of induction-system icing.



(a) Simulated excessive rain. (b) Simulated heavy rain. (c) Simulated moderate rain.

Figure 3. - Disposition of ingested rain in the induction system.

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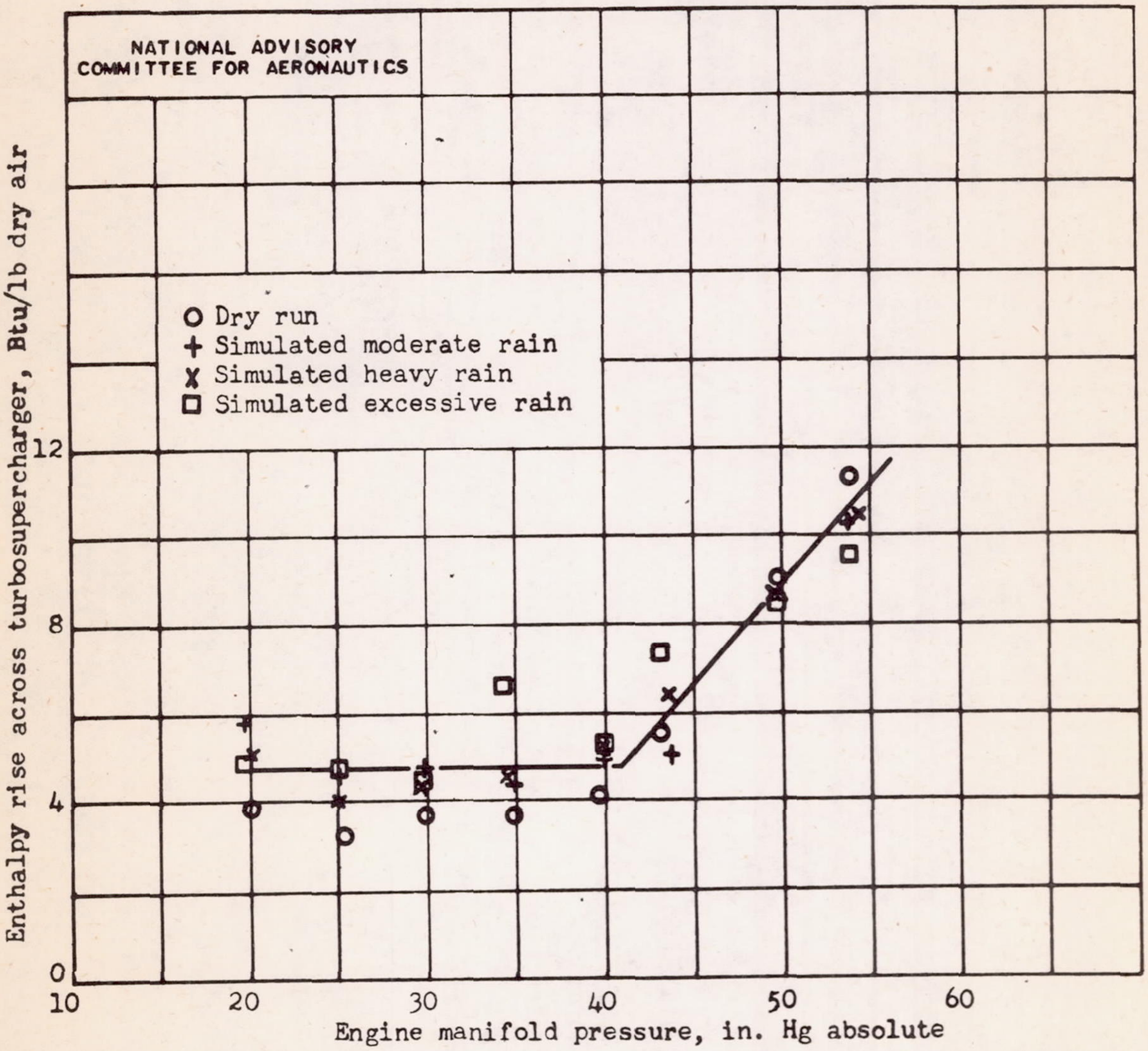

Figure 4. - Enthalpy increase across turbosupercharger in ground icing tests.

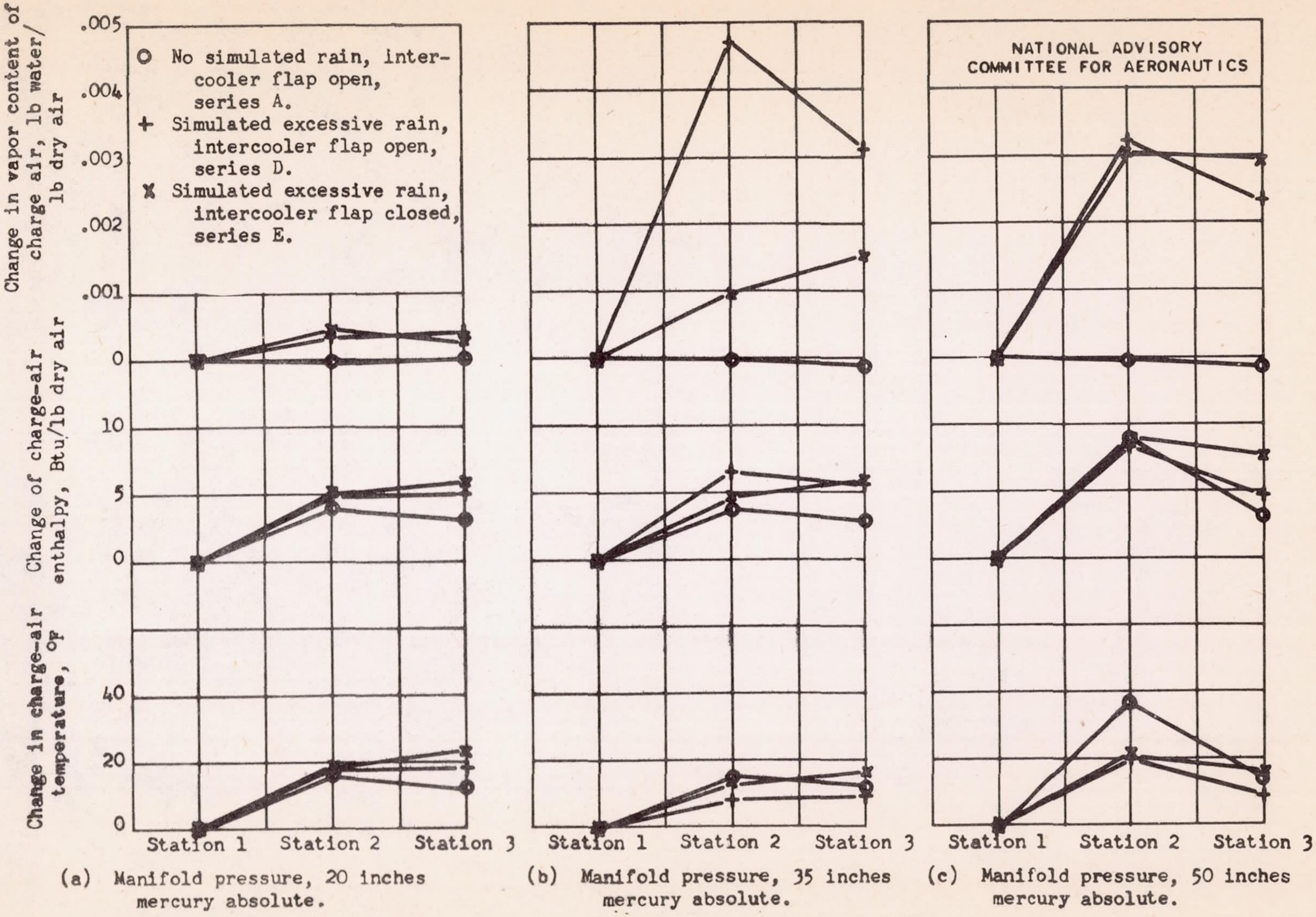

Figure 5. - Effect of induction system on charge air with varying simulated-rain intensities and engine power settings.

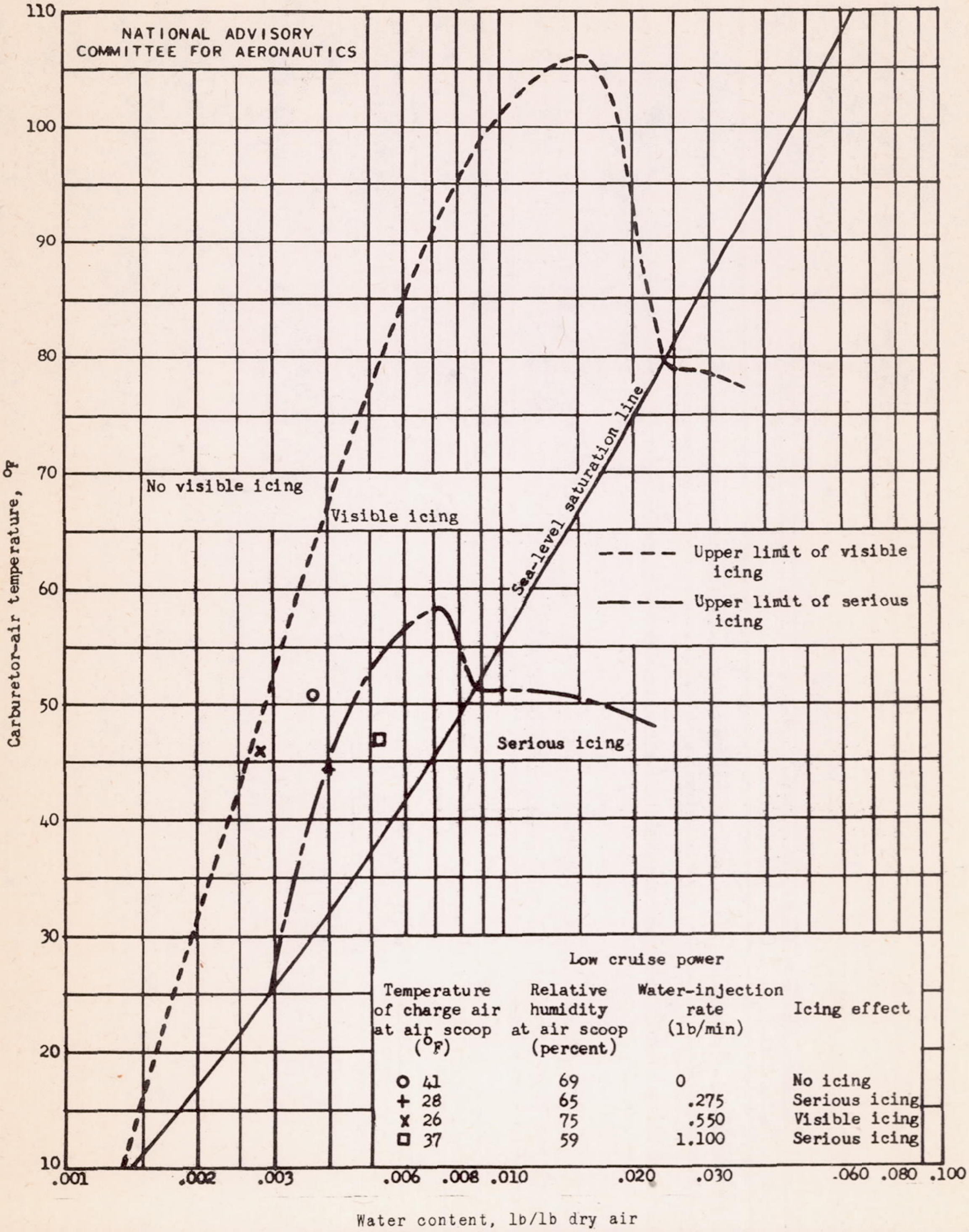

Figure 6. - Comparison of laboratory and ground icing tests at low cruise power. (Curves from laboratory tests of reference 1.)

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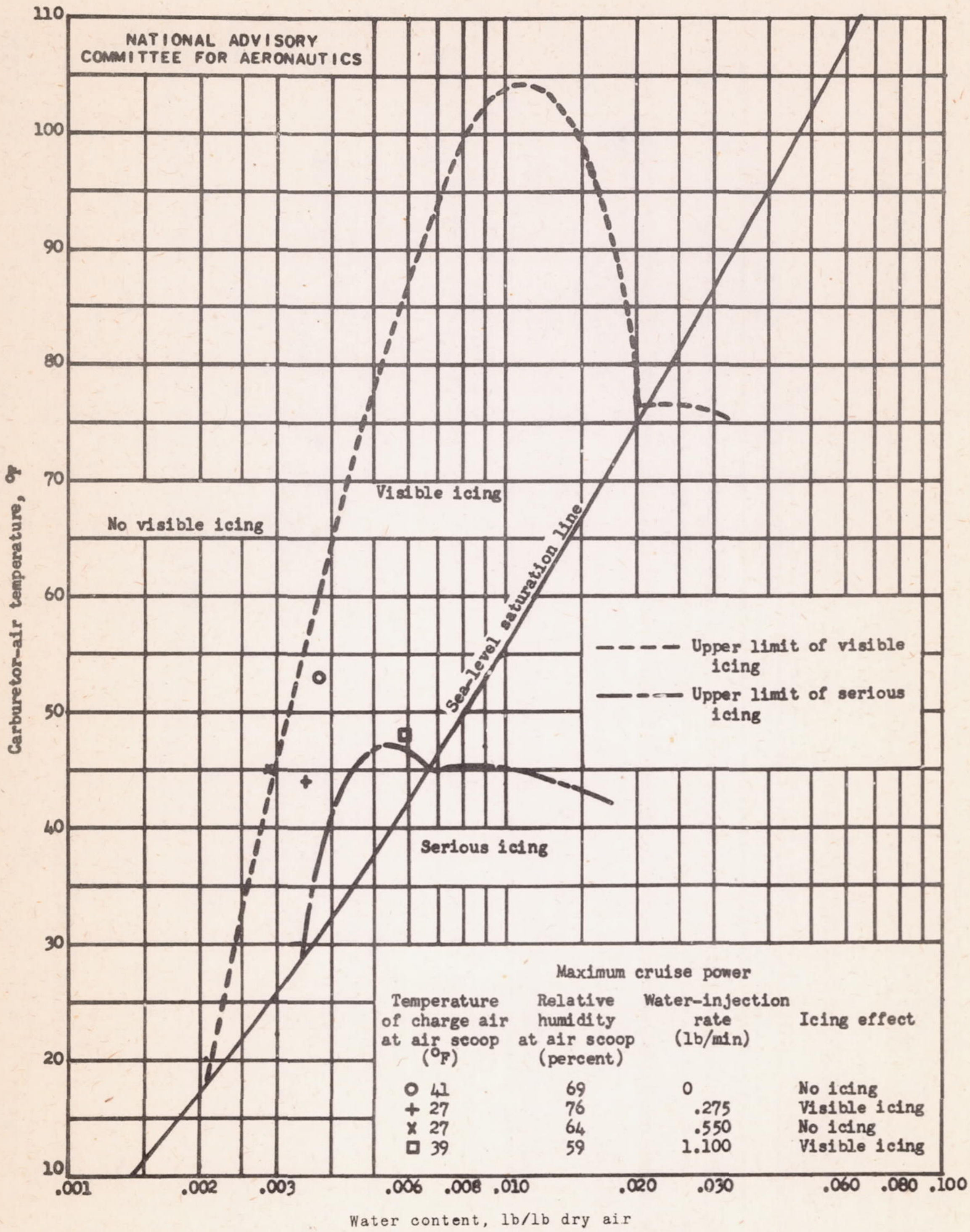


Figure 7. - Comparison of laboratory and ground icing tests at high cruise power. (Curves from laboratory tests of reference 1.)

E-176

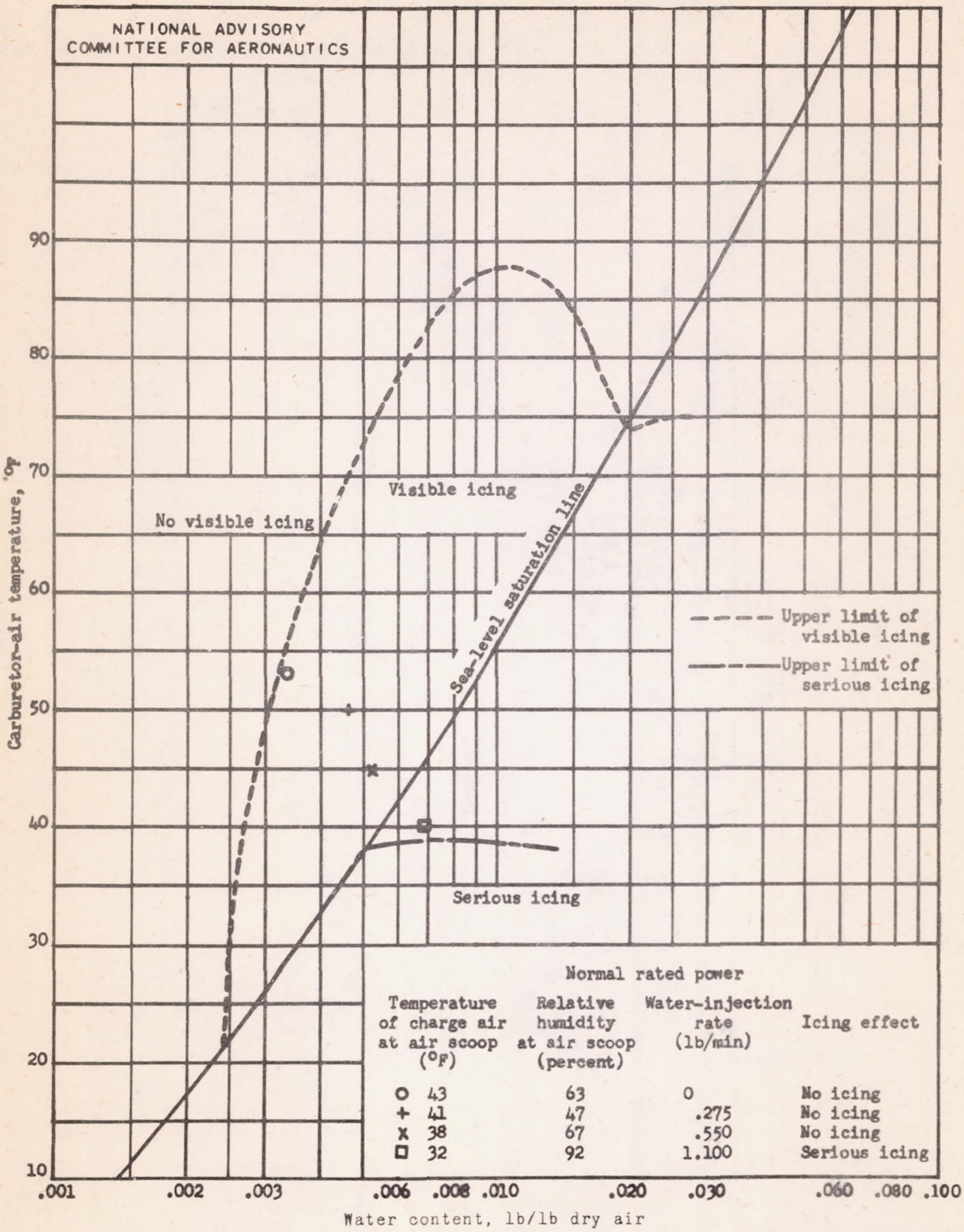
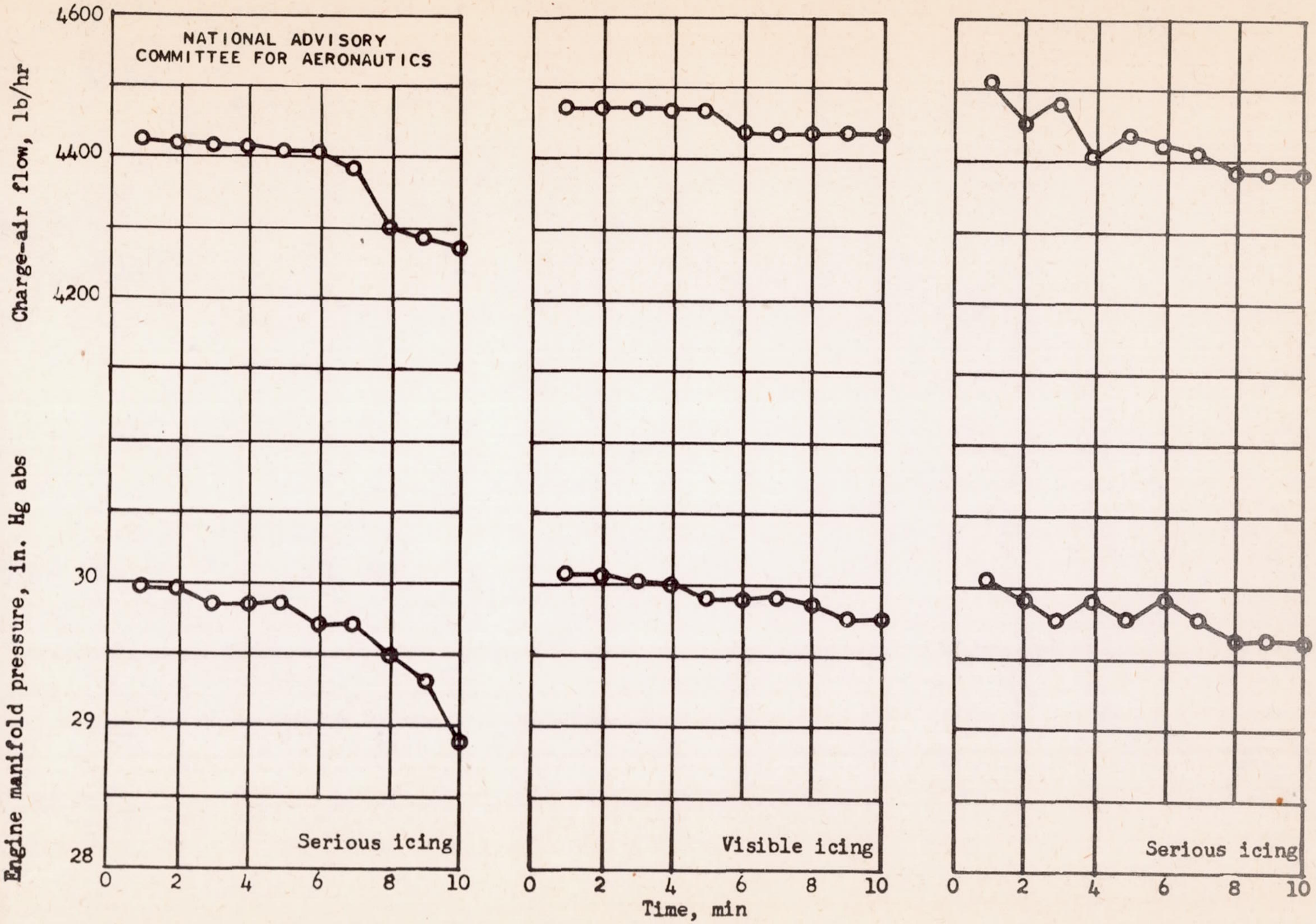
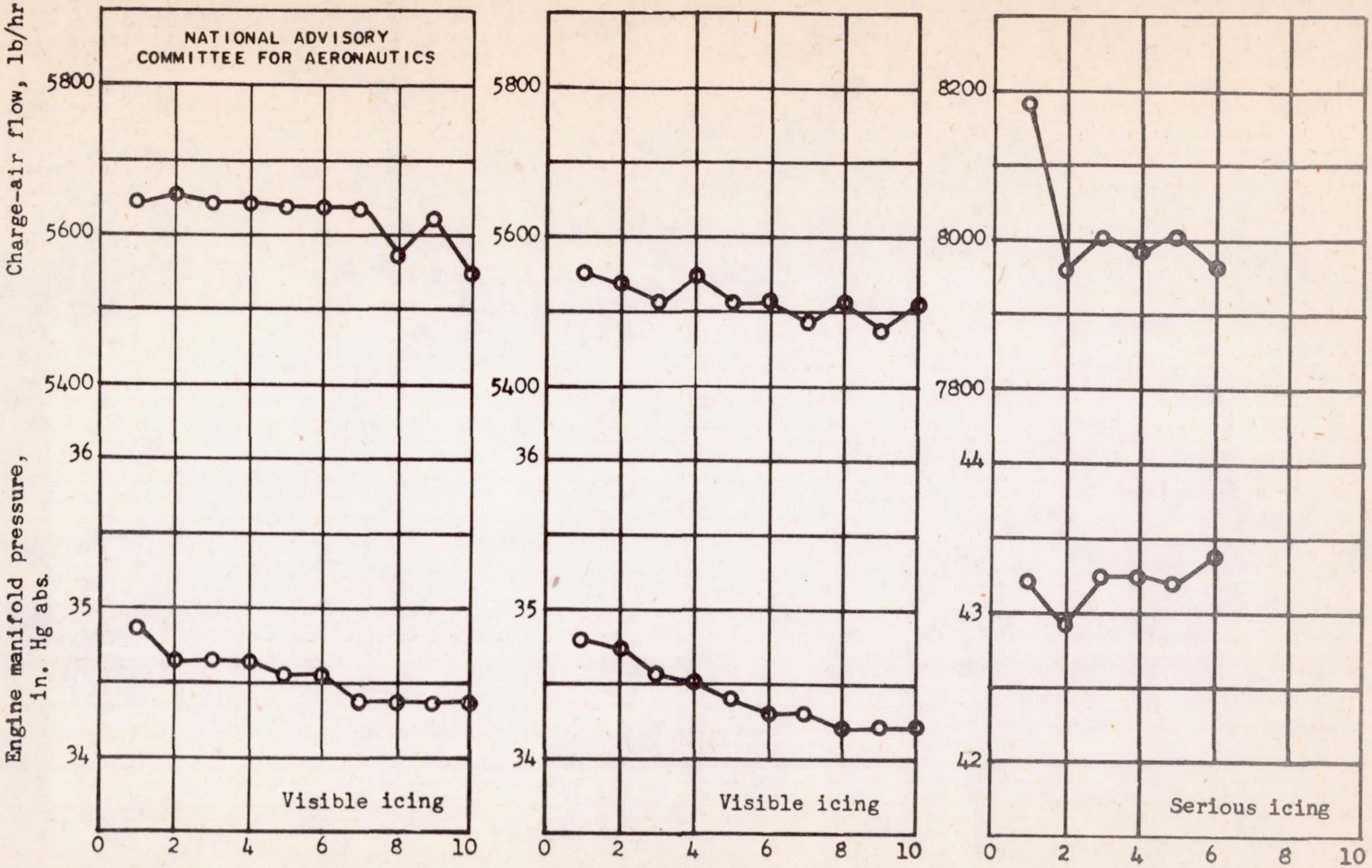


Figure 8. - Comparison of laboratory and ground icing tests at normal rated power. (Curves from laboratory tests of reference 1.)



(a) Simulated moderate rain. (b) Simulated heavy rain. (c) Simulated excessive rain.

Figure 9. - Induction-system icing at low cruise power.



(a) Simulated moderate rain; high cruise power setting.

(b) Simulated heavy rain; high cruise power setting.

(c) Simulated excessive rain; normal rated power setting.

Figure 10. - Induction-system icing at high cruise and normal rated conditions of engine power.