RM No.SE7A20a

NACA

RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

FLIGHT INVESTIGATION OF THE EFFECTS OF ICE

ON AN I-16 JET-PROPULSION ENGINE

By Philip C. Pragliola and Milton Werner

Aircraft Engine Research Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

JANUARY 31, 1947

CLASSIFICATION CANCELLED

RESTRICTED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

FLIGHT INVESTIGATION OF THE EFFECTS OF ICE

ON AN I-16 JET-PROPULSION ENGINE

By Philip C. Pragliola and Milton Werner

SUMMARY

A flight investigation of an I-16 jet-propulsion engine installed
in the waist compartment of a B-24M airplane was made to determine the
effect of induction-system icing on the performance of the engine.
Flights were made at inlet-air temperatures of 15°, 20°, and 25° F, an
indicated airspeed of 180 miles per hour, jet-engine speeds of 13,000
and 15,000 rpm, liquid-water contents of approximately 0.3 to 0.5 gram
per cubic meter, and an average water droplet size of approximately
50 microns.

Under the most severe icing conditions obtained, ice formed on
the screen over the front inlet to the compressor and obstructed about
70 percent of the front-inlet area. The thrust was thereby reduced
13.5 percent, the specific fuel consumption increased 17 percent, and
the tail-pipe temperature increased 82° F. No icing of the rear-
compressor-inlet screen was encountered.

INTRODUCTION

A flight investigation has been conducted at the NACA Cleveland
laboratory to determine the effect of induction-system icing on the
performance of an I-16 jet-propulsion engine. The engine alone was
investigated and no attempt was made to determine the effect of icing
of the inlet duct to the engine. The engine was located in the waist
compartment of a B-24M airplane.

Data are presented to show the effect of icing of the induction
system on jet thrust, engine speed, tail-pipe temperature, and

CLASSIFICATION CANCELLED

RESTRICTED

specific fuel consumption. These data are compared with results of
flights made when the front inlet of the engine was obstructed by
aluminum bands.

INSTALLATION

The I-16 jet-propulsion engine has a twin-inlet centrifugal
compressor and is rated at 1600 pounds of thrust at an engine speed
of 16,500 rpm. The engine was installed in the waist compartment of
the B-24M airplane, as shown in figures 1 and 2. In order to facili-
tate the investigation, all turrets were removed from the airplane
and replaced by suitable fairing. The leading edges of the wing
(except inboard) and tail surfaces were thermally de-iced by four
exhaust-heat exchangers. An induction-air inlet was installed on top
of the airplane to provide induction air to the engine (fig. 2).
Windows were installed in this duct in order to observe the forma-
tion of ice on the front and rear air inlets to the compressor and
in the inlet duct. Exhaust gas was expelled through a long tail
pipe that was provided with external cooling by air supplied from
two scoops, one located in each waist gunner's window. Air at a
pressure of 100 pounds per square inch and water at a pressure of
10 pounds per square inch were externally mixed by the use of nozzles
that were installed 9 feet in front of the induction-air inlet. This
water-air spray, which was directed towards the inlet, was used to
simulate icing conditions and also to raise the liquid-water content
of the air at the engine inlet during natural icing conditions.

INSTRUMENTATION

The engine was instrumented as shown in figure 3. In addition
to standard measurements of engine speed, burner-fuel pressure, oil
pressure, tail-pipe temperature, and bearing temperatures, the
following measurements were obtained.

(1) Surveys of the inlet air were made by iron-constantan
thermocouples unshielded from ice and total-pressure tubes located
in both front and rear inlets to the compressor. The pressure tubes
in the compressor inlets were heated to prevent icing.

(2) Free-stream static pressure was measured by flush orifices
located on the sides of the airplane.

(3) Static pressure at the inlet to the compressor was measured
by a flush orifice located in the duct over the front compressor
inlet.

(4) Chromel-alumel thermocouples were spot-welded to the out-side of all the burner-outlet elbows to indicate burner combustion.

(5) A calibrated survey ring was installed in the tail pipe to measure tail-pipe temperatures and pressures for the determination of jet thrust. These thermocouples also were of the chromel-alumel type.

(6) Ice formation on the front inlet to the compressor was photographed by a 35-millimeter moving-picture camera mounted next to the jet engine.

The liquid-water content of the air entering the engine was determined by means of a rotating cylinder, one-eighth inch in diameter (fig. 4) located just ahead of the front compressor inlet (fig. 3). This cylinder was inserted about once every 8 minutes during icing runs for a 5-minute period. From the weight of ice collected, the average diameters were determined. The liquid-water content of the air was then directly determined from the volume of air intercepted and the weight of ice collected, inasmuch as the collection efficiency of small-diameter cylinders (one-eighth in.) approaches 100 percent (reference 1).

Water-droplet size for simulated icing runs was determined by means of a droplet sampler, as shown in figure 5. Use of this droplet sampler and method of analyzing the slides is given in detail in reference 1. By use of a sooted slide, a droplet sample could be taken in flight and analyzed later. The slide is exposed for 0.01 second and droplets collect on the sooted surface. As each droplet hits the sooted surface, it flattens because of impact pressure. The slide is treated with a nonwetting agent before it is sooted; thus, when the droplet returns to a partial sphere after the force of impact is lost, the soot clings to the water rather than to the slide. After the water evaporates, a black spot equal to the diameter of this partial sphere is left on the slide. This diameter is divided by a factor of 1.25 to determine the true droplet diameter.

Iron-constantan thermocouples were accurate to $\pm 2^{\circ}$ F and chromel-alumel thermocouples to $\pm 7^{\circ}$ F. Calibration data of gages used for measuring tail-pipe pressures deviated from the average curve by a maximum of 0.1 inch of mercury. The measurements of liquid-water content and droplet size were made as accurately as current instruments permit; however, the state of this method does not permit a definite statement of accuracy.

CONDITIONS AND PROCEDURE

Flights were made at three altitudes in order to obtain front inlet-air temperatures of 15°, 20°, and 25°; at each altitude an indicated airspeed of 180 miles per hour was maintained. All performance data presented, however, are reduced to standard sea-level conditions to eliminate variations due to different air densities. The engine was operated at speeds of 13,000 and 15,000 rpm corresponding to low and high normal-cruise conditions.

Simulated icing conditions and a combination of natural and simulated engine operating conditions were used. Only light natural-icing conditions were encountered, but it was possible to augment the natural icing with water sprays that produced liquid water at the rate of approximately 0.3 to 0.5 gram per cubic meter with an average droplet size of 50 microns at the front inlet to the compressor. The most severe icing conditions were obtained in flight 3. Greater water contents similar to severe natural-icing conditions were desirable but were unobtainable with the equipment installed in the airplane. Additional runs were made with the front inlet to the compressor obstructed by aluminum bands.

SYMBOLS

The following symbols are used in this report:

A tail-pipe exit area, 0.818 (sq ft)

A_r tail-pipe area at survey ring, 1.108 (sq ft)

C_1, C_2 constants

F_j jet thrust, (lb)

F_n net thrust, (lb)

f specific fuel consumption, (lb fuel/hr/lb thrust)

g acceleration of gravity, 32.2 (ft/sec^2)

H total pressure, (lb/sq ft absolute)

k calibration factor

N engine speed, (rpm)

p   static pressure, (lb/sq ft absolute)

R   gas constant $((\text{ft-lb})/(\text{slug})(^\circ F))$

T   temperature, $(^\circ R)$

V   true airspeed, (ft/sec)

W_a air flow, (lb/sec)

W_f fuel flow, (lb/hr)

W_g gas flow, (lb/sec or lb/hr)

γ ratio of specific heats, 1.33

Subscripts:

corr   corrected to standard sea-level conditions

r   tail-pipe survey ring

0   ambient free stream

METHOD OF CALCULATION

The thrust was calculated from temperatures and pressures obtained with the survey ring located in the tail pipe.

The jet thrust F_j was obtained from

$$F_j = C_1 p_0 \left[\left(\frac{H_r}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

where

$$C_1 = \frac{2\gamma}{\gamma-1} Ak^2$$

The net thrust F_n was found by subtracting the initial momentum of the inlet air from the jet thrust.

$$F_n = F_j - \frac{W_a V_0}{g}$$

The gas flow W_g was obtained from the equation

$$W_g = C_2 p_r \sqrt{\frac{\left[\left(\frac{H_r}{p_r}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + 0.6\left[\left(\frac{H_r}{p_r}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]^2}{T_r}}$$

where

$$C_2 = kA_r \sqrt{\frac{2\gamma g}{(\gamma-1)R}}$$

The air flow is then found by subtracting the fuel flow from gas flow

$$W_a = W_g - W_f$$

The net specific fuel consumption is given as W_f/F_n.

All performance data were corrected to standard sea-level conditions at the compressor inlet by the following correction factors:

δ $\dfrac{\text{compressor-inlet total pressure} \quad H, \quad (\text{lb/sq ft absolute})}{\text{standard sea-level pressure (2117 lb/sq ft absolute)}}$

θ $\dfrac{\text{compressor-inlet temperature} \quad T, \quad (^\circ R)}{\text{standard sea-level temperature (518}^\circ \text{ R)}}$

The following equations show the method of correcting the various performance variables:

$$F_{n,corr} = \frac{F_n}{\delta}$$

$$N_{corr} = \frac{N}{\sqrt{\theta}}$$

$$W_{g,corr} = \frac{W_g \sqrt{\theta}}{\delta}$$

$$W_{a,corr} = \frac{W_a \sqrt{\theta}}{\delta}$$

$$W_{f,corr} = \frac{W_f \sqrt{\theta}}{\delta}$$

$$T_{r,corr} = \frac{T_r}{\theta}$$

$$f_{corr} = \frac{f}{\sqrt{\theta}}$$

RESULTS AND DISCUSSION

Data taken during three flights (1,2, and 3) in which natural- and simulated-icing conditions were combined are shown graphically in figure 6. The conditions and results are presented in table I. From this table it can be seen that the loss in thrust varied from 5.5 to 13.5 percent, the tail-pipe temperature increased from 27° to 90° F, the specific fuel consumption increased from 6.5 to 17.0 percent, and the percent obstruction varied from 32 to 75 percent. Natural-icing conditions encountered during all three flights resulted in a band of ice approximately 6 inches wide and about 1/2 inch thick on the leading edge of the unprotected inboard section of the wing.

Ice formations on the screen over the front inlet to the compressor during the three flights are shown in figure 7. These photographs were taken when the maximum change in performance was noted.

During flight 2, the nozzles froze after 27 minutes (fig. 6) and the ice on the inlet sublimated. Some ice collected in the bends of the duct and at the duct inlet but it is believed that the effect of this ice on the performance of the jet engine has no significance on the results reported.

The air that entered the rear inlet was required to pass the compressor-outlet ducts (fig. 3), which heated the inlet air sufficiently to maintain above freezing temperatures at the rear screen during all three icing flights and therefore prevented ice formation on the rear screen. At lower ambient-air temperatures, the temperature of the rear screen might be below the freezing level. In this case, if very small droplets would reach the screen without separating from the air stream at sharp bends, ice would result.

Aluminum bands were placed over the front inlet to the compressor (fig. 8) to determine the change in performance with 25, 50, and 75 percent of the front-inlet area obstructed. The bands were located to the rear of the inlet to represent the ice formed in the previous flights. The rear inlet was left unrestricted because no ice formed in this inlet. Results of flights with the restriction bands are shown in figure 9. From these data, it is possible to determine the change in performance when a certain percentage of the front inlet is obstructed. The maximum loss in net thrust with 75 percent of the front inlet obstructed was about 13.5 percent at 13,000 rpm and 31 percent at 16,500 rpm. The increase in tail-pipe temperatures at these speeds and 74-percent obstruction of the front compressor inlet was 82° F at 13,000 rpm and 166° F at 16,500 rpm. Specific fuel consumption increased 24 percent at 13,000 rpm and 35 percent at 16,500 rpm.

The tailed points on figure 9 are the maximum changes in performance of flights 1, 2, and 3 taken from figure 6. An approximation of the amount of blocking of the front inlet from the ice when the average droplet size was 50 microns can be made from these points. In the case of flight 3, with a water content of 0.4 to 0.5 gram per cubic meter and a front inlet-air temperature of 25° F, the inlet to the compressor was obstructed about 70 percent. With a water content of 0.3 to 0.4 gram per cubic meter and a front inlet-air temperature of 15° F the obstruction for flight 2 was about 60 percent. For flight 1 with an inlet-air temperature of 20° F, the inlet area was reduced somewhere from 30 to 50 percent. These approximations of the obstruction of the front inlet based on changes of engine performance satisfactorily agree with comparison of photographs of the ice in figure 7 and the artificially obstructed inlet shown in figure 8.

Attempts in clear air to simulate natural-icing conditions and to cause blocking of the compressor inlet were unsuccessful because of the large size of water droplets and unsaturated atmospheric air. Best results were obtained when water sprays were used in conjunction with natural ice.

After 54 hours of running time, the I-16 engine still operated satisfactorily. During about 20 percent of this time, the front inlet was partly blocked by either ice or by the obstructing bands. These conditions had no noticeable permanent effect on the rotor bearings or on the engine itself. During runs when the inlet was blocked, there were no indications of poor combustion or rough engine operation.

SUMMARY OF RESULTS

The following results were obtained from the icing investigation of the I-16 jet-propulsion engine installed in the waist compartment of a B-24M airplane:

1. With an average liquid-water content of 0.4 to 0.5 gram per cubic meter, an average droplet size of 50 microns, and a front inlet-air temperature of 25° F, ice formed on the screen over the front inlet to the compressor and blocked the front inlet approximately 70 percent. The obstruction of the front inlet to the compressor produced by the ice formation reduced the thrust 13.5 percent, increased the specific fuel consumption 17 percent, and increased the tail-pipe temperature 82° F.

2. No icing of the rear inlet screen occurred because the inlet-air temperature of the rear inlet to the compressor was above freezing in all cases. With lower temperatures and small water droplets it is possible that some ice would build up on this screen.

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

<div style="text-align: right">

Philip C. Pragliola,
Aeronautical Engineer.

Milton Werner
Milton Werner,
Mechanical Engineer.

</div>

Approved:
        Lewis A. Rodert,
      Aeronautical Engineer.

        Abe Silverstein
        Abe Silverstein,
      Aeronautical Engineer.

jh

REFERENCE

1. Vonnegut, B., Cunningham, R. M., and Katz, R. E.: Instruments
   for Measuring Atmospheric Factors Related to Ice Formation on
   Airplanes. Dept. Meteorology, De-Icing Res. Lab., M.I.T.,
   April 1946.

TABLE I - CONDITIONS AND RESULTS OF ICING FLIGHTS

Flight ⟶	1	2	3
CONDITIONS			
Pressure altitude, ft	17,000	19,500	5000

Inlet-air temperature, °F
    Front
    Rear
	20
	36
		15
		33
			25
			35

Indicated airspeed, mph	180	180	180
Jet-engine speed, rpm	15,000	15,000	13,000

Liquid-water content at
    front compressor inlet,
    gram/cu meter
	(a)	0.3 to
		0.4
			0.4 to
			0.5

Average droplet size, microns	50	50	50
Length of time in icing conditions, min	30	27	37
RESULTS			

Loss in thrust[b]
    percent
    pounds
    percent obstruction[c]
	5.5
	50
	49
		10
		100
		61
			13.5
			80
			75

Increase in tail-pipe
    temperature, °F[b]
    percent obstruction[c]
	27
	32
		90
		60
			82
			74

Increase in specific fuel
    consumption[b]
        percent
        lb/(hr)(lb thrust)
        percent obstruction[c]
	6.5
	0.11
	47
		9
		0.15
		53
			17
			0.36
			68

[a]Not determined.
[b]Corrected to standard sea-level conditions.
[c]Taken from figure 9.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
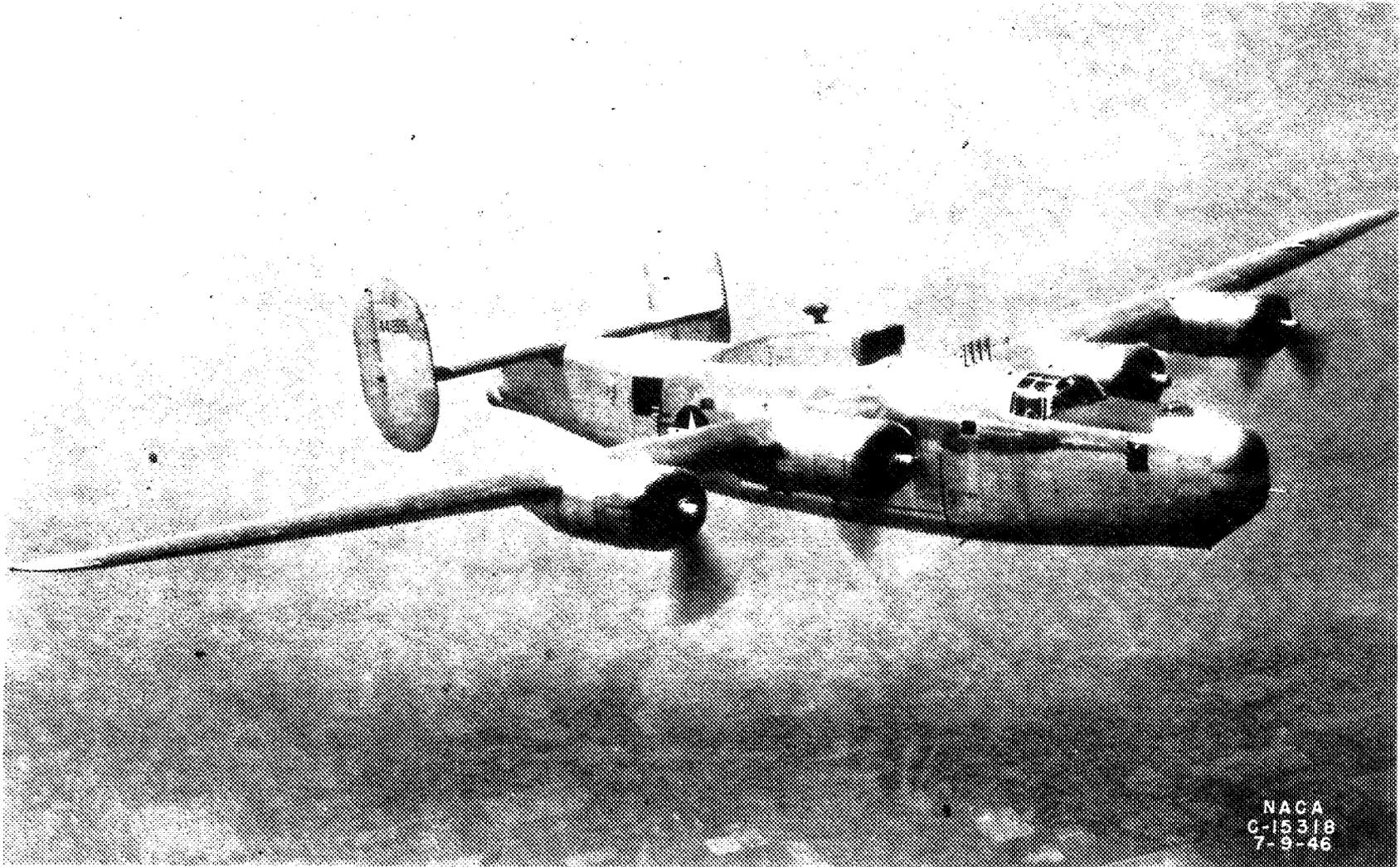
Figure 1. — B-24M airplane with I-16 jet-propulsion engine installed in waist compartment.

Fig. 1

Survey ring

Front inlet
to com-
pressor

Spray nozzles

Induction-air
inlet

Tail-pipe cooling-
air inlet scoop

I-16 jet-propulsion
engine
35-mm camera

Recording instruments

Copilot's
controls and
instruments

Engineer's instrument panel

Engineer's jet-engine controls

Total-head tube
for airspeed

Fig. 2
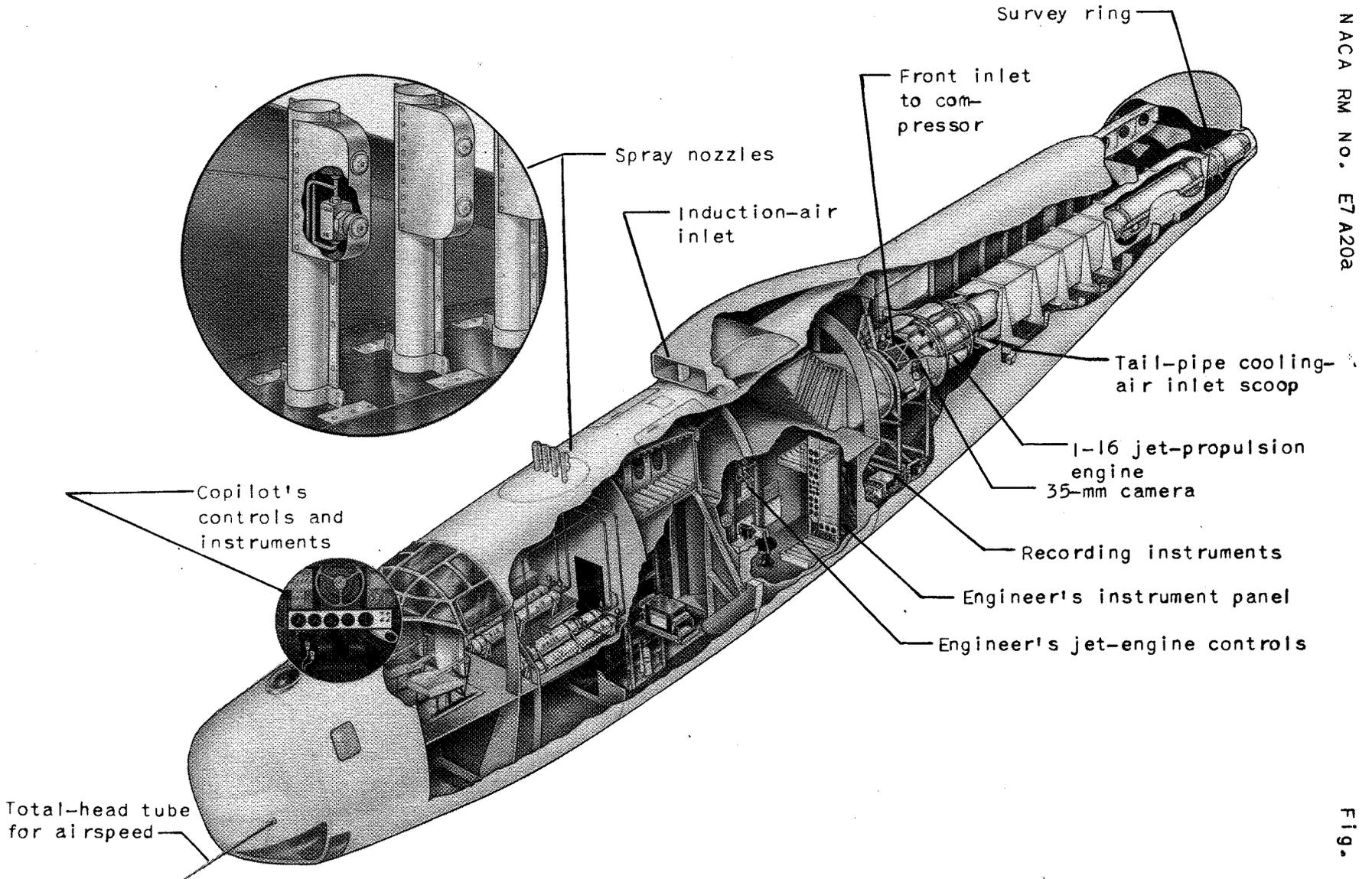
Figure 2. - B-24 fuselage showing location of jet engine and equipment for tests.

Droplet sampler

Rotating cylinder

Compressor-outlet duct

Burner-outlet thermocouple

Static-pressure tube

Tail-pipe thermocouple

Total-pressure tubes

Calibrated survey ring

Rear inlet-air total-pressure tube

Rear inlet-screen thermocouple

Rear inlet-air thermocouple

Front inlet total-pressure tube

Front inlet-screen thermocouple

Front inlet-air thermocouple
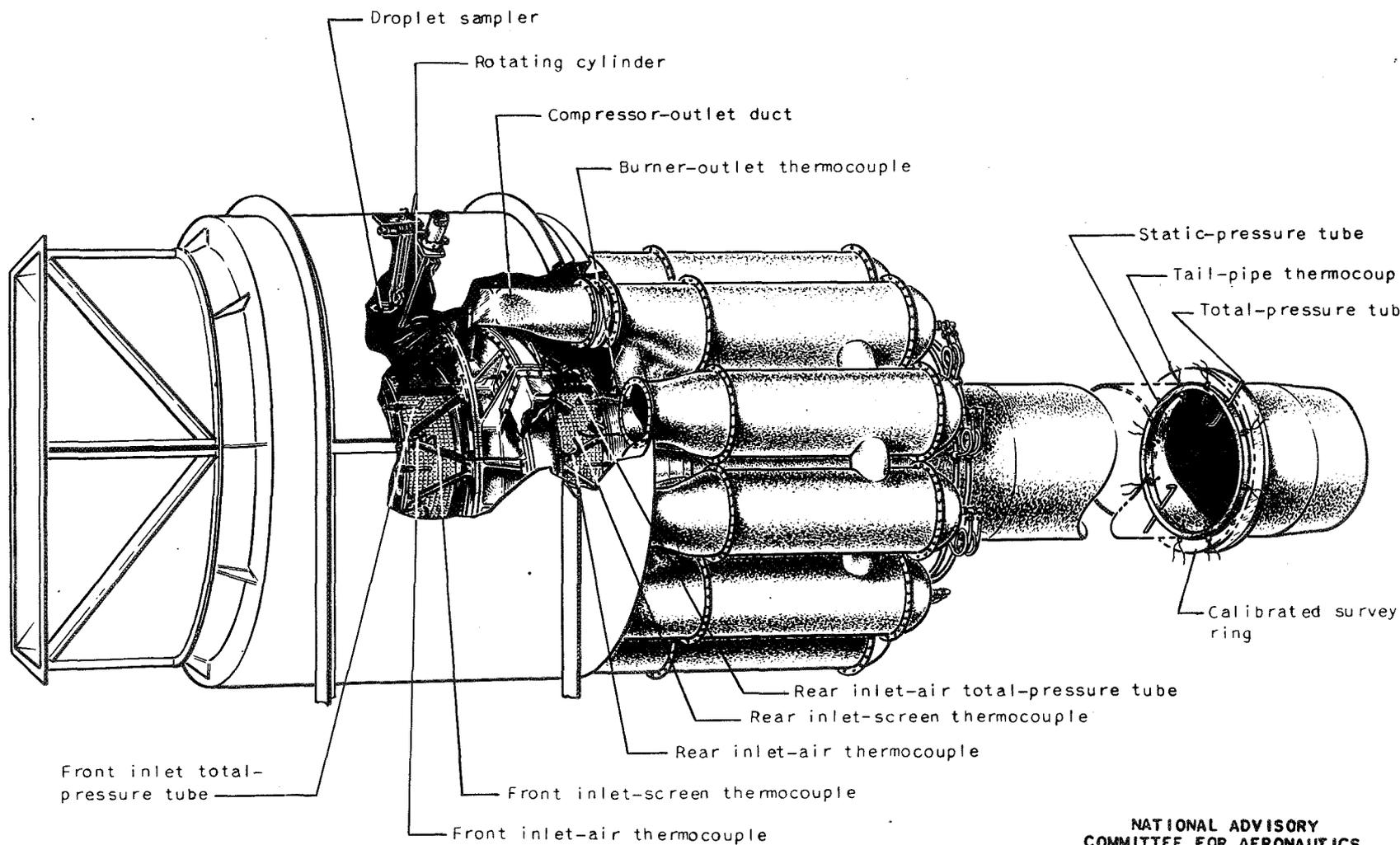
NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

Figure 3. — Location of temperature, pressure, and meteorological measuring instruments on I-16 engine.

Fig. 3
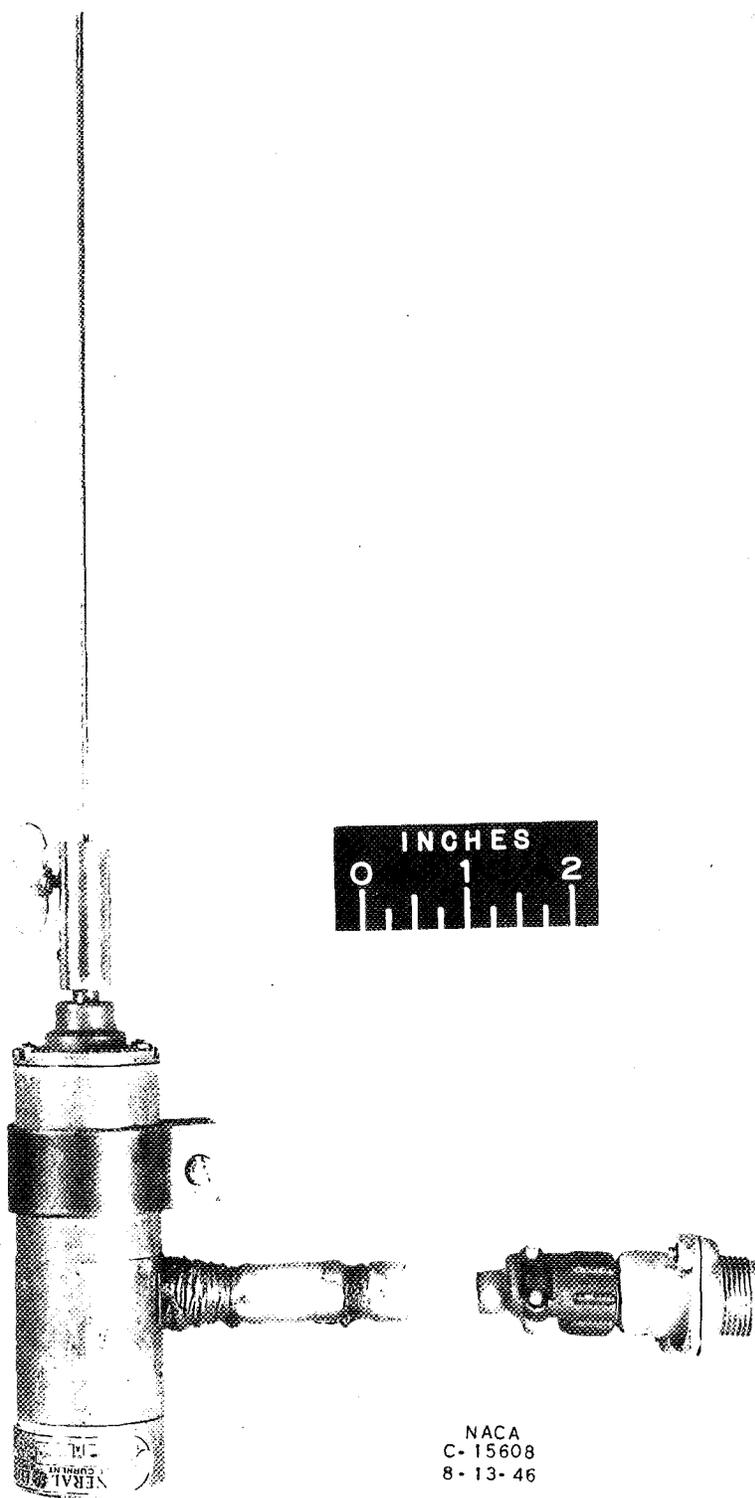
Figure 4. – Rotating cylinder used for determination of
water content.
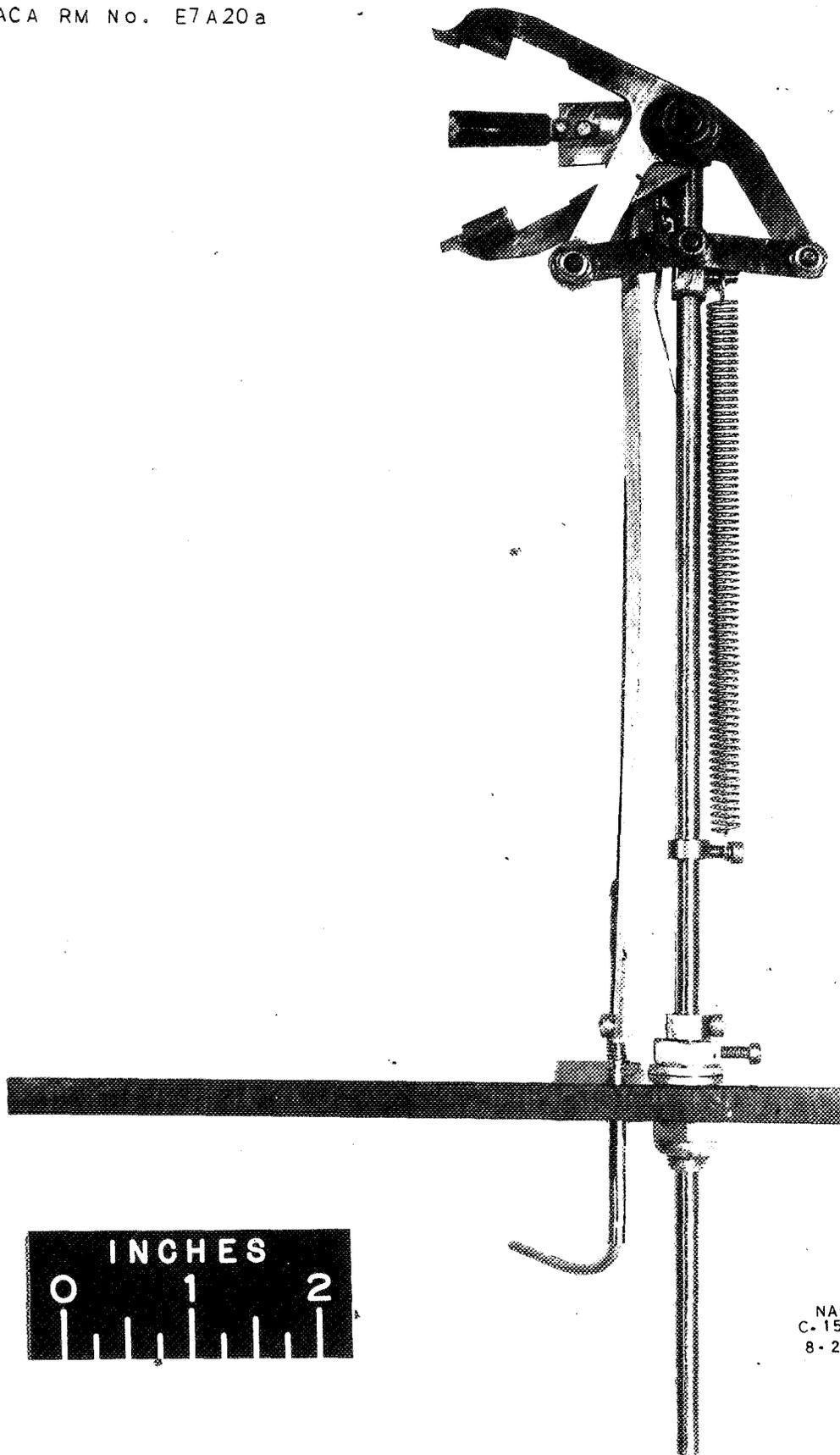
Figure 5. – Droplet sampler used for determination of water–droplet size.
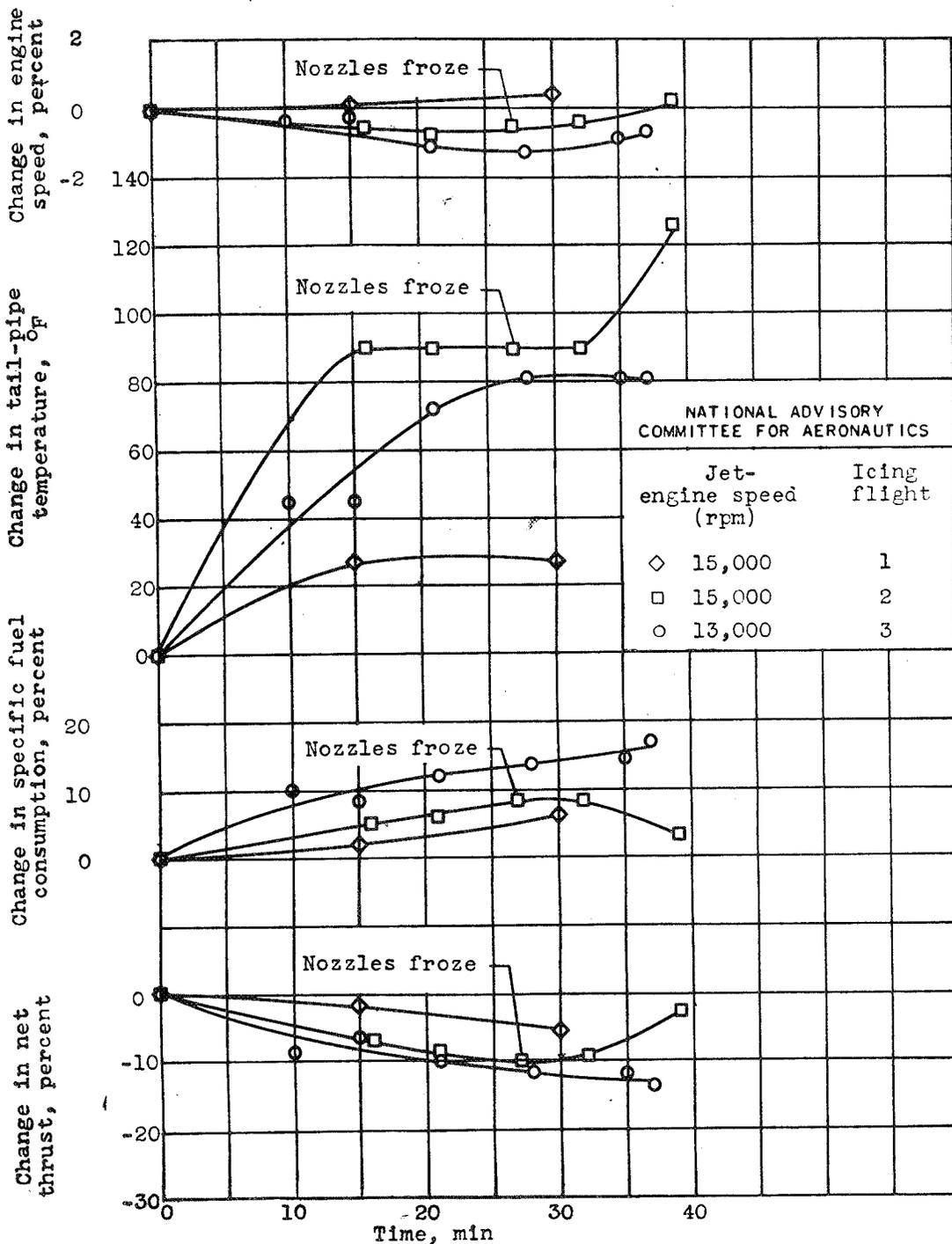
Figure 6. - Engine performance during icing runs of flights 1, 2, and 3. All values corrected to standard sea-level conditions.
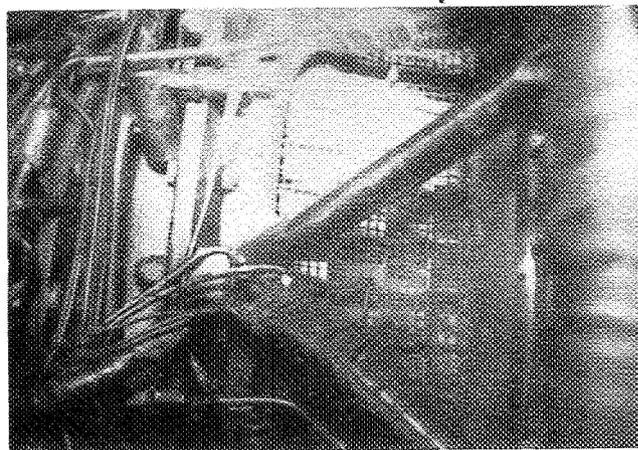
(a) No ice.
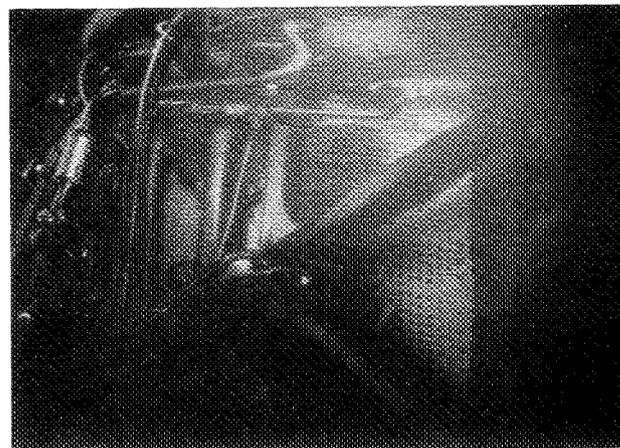
(b) Flight 1.
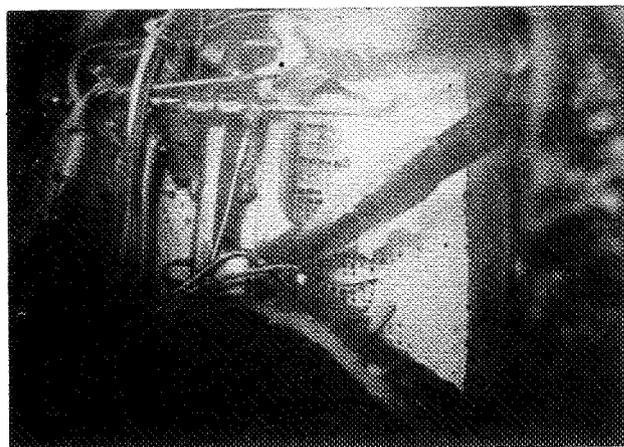
NACA
C- 17457
12-31-46
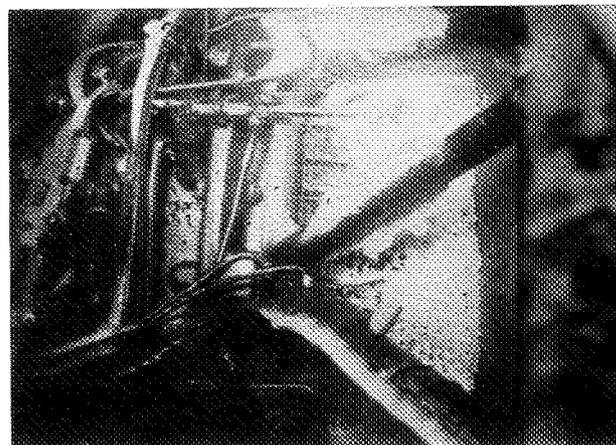
(c) Flight 2.

(d) Flight 3.

Figure 7. — Front compressor—inlet screen without and with ice during flights 1, 2, and 3.

Fig. 7
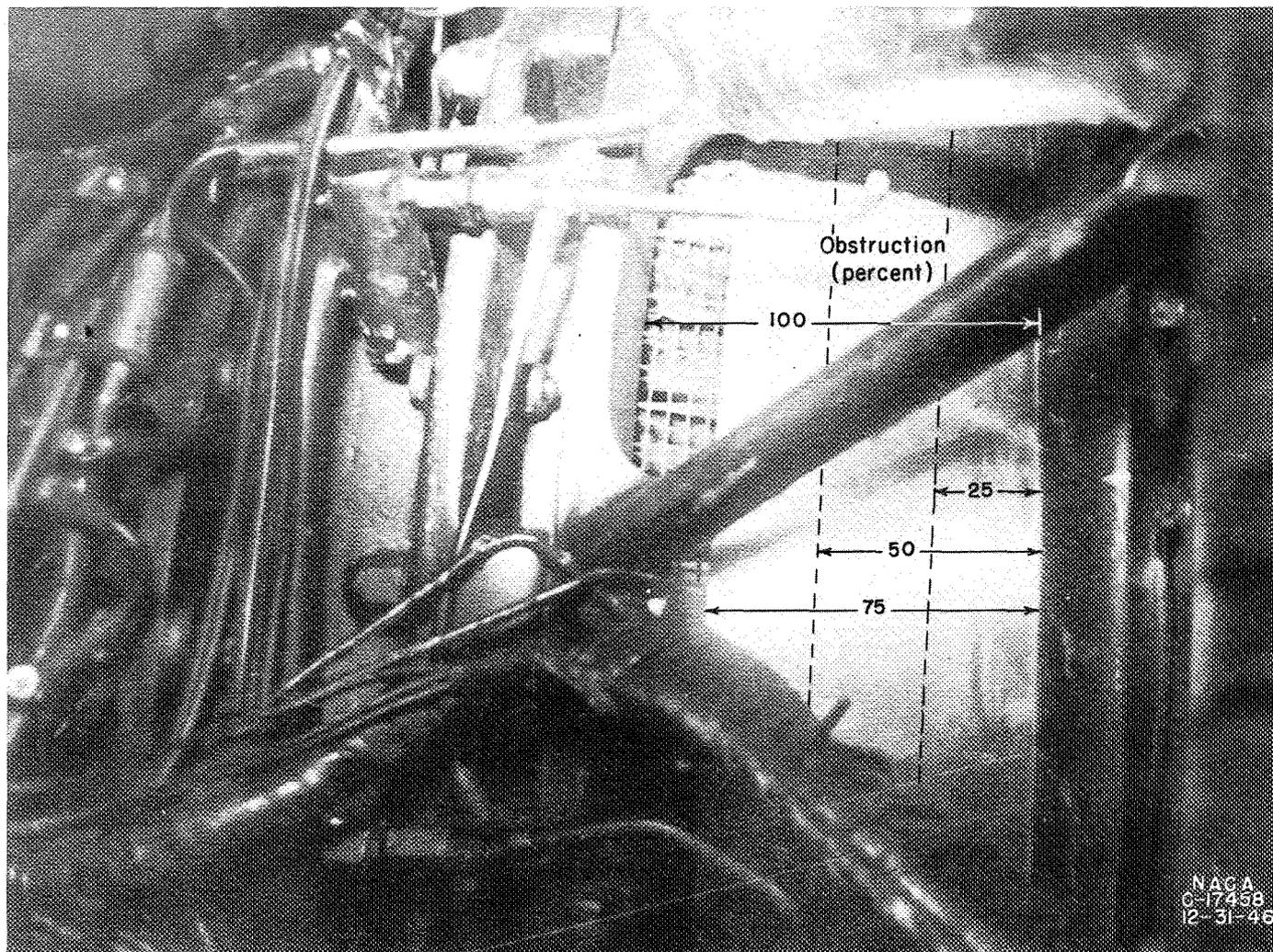
Figure 8. — Location of aluminum bands used to block front compressor inlet.

Fig. 8
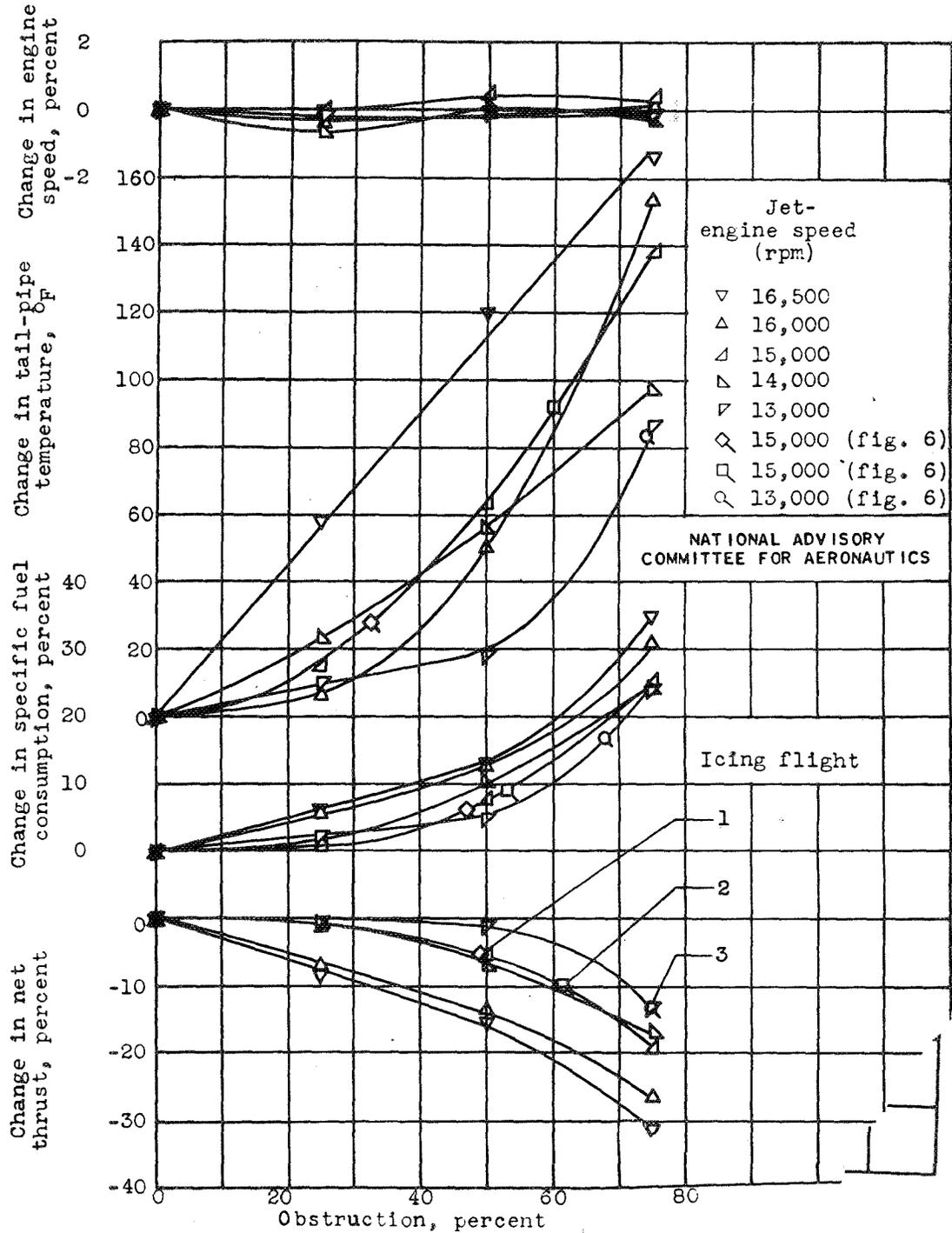
Figure 9. - Engine performance during flights with aluminum restriction bands on front compressor inlet and comparison of these data with data from icing flights. All values corrected to standard sea-level conditions.