An experimental jet engine ejector tunnel

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AN EXPERIMENTAL JET ENGINE EJECTOR TUNNEL

REPORT NO. ME-167

BY

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DIVISION OF MECHANICAL ENGINEERING

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Subject: AN EXPERIMENTAL JET ENGINE EJECTOR TUNNEL

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SUMMARY

This report describes the construction and testing of a jet engine ejector tunnel erected in the Engine Laboratory of the National Research Council in Ottawa.

The tunnel was built for the purpose of simulating flight conditions around the nose of a Jumo 004 jet engine to be used in connection with icing experiments.

Velocity traverses near the nose of the engine indicated that speeds up to about 230 feet per second could be attained, and that a ratio of secondary to primary air flow of about 5.5:1 was reached.

A brief investigation of the flow pattern around the nose of the engine has shown that at the speed attained, the air stream accelerates considerably before reaching the engine intake and that the flow breaks away rather badly from the outer skin of the cowling.

ACKNOWLEDGEMENT

The author desires to acknowledge the very considerable assistance given to him by Mr. F. W. Pruden of the Aerodynamics Section of the Division of Mechanical Engineering, National Research Council, Ottawa.

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2. MODEL TESTS

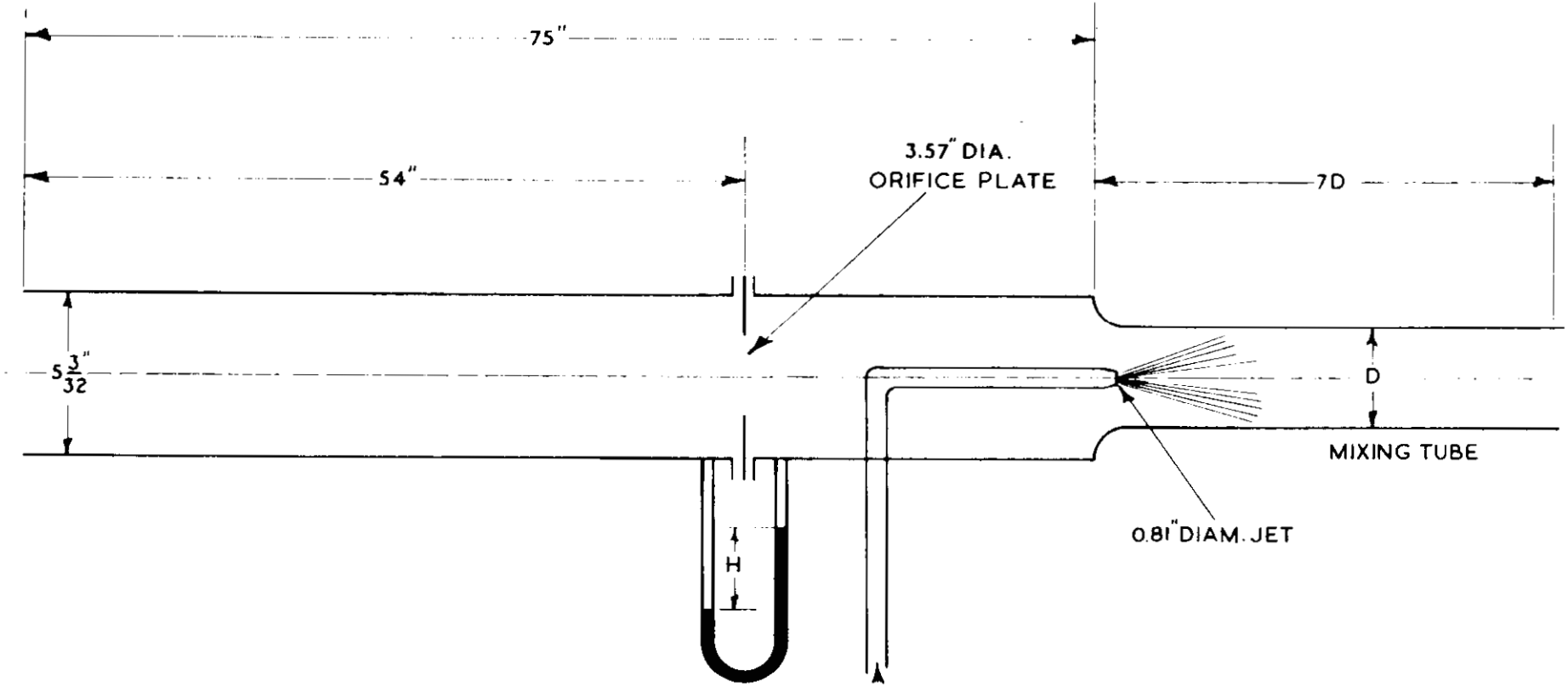
As a preliminary step in the design of the full size tunnel, tests were made on a simplified model as shown in Figure 1. The model tunnel consisted of a 75 in. length of moderately smooth bore pipe 5-3/32 in. inside diameter. At a point 54 inches from the entrance to the pipe was located a standard sharp-edged orifice plate of 3.57 in. diameter across which a water manometer was connected. Secondary air flow rate could therefore be calculated from the pressure drop across this manometer. At the exit end of the pipe arrangements were made to attach various sizes of mixing tube, these being faired into the main tube by suitable plasticene throats. The mixing tubes were such that their lengths were seven times their respective diameters.

The jet engine was represented by a short length of 0.81 in. inside diameter pipe, turned down at the exit end to simulate the tail pipe of the Jumo engine. This nozzle projected into the plasticene throat and freely discharged cold air. The nozzle was supplied by a 3-1/4 in. inside diameter air main, the pressure as measured in this main at a point about 25 feet back from the nozzle being 30 lb. per sq. in. Air flow as measured by a Fischer and Porter flowmeter was 0.32 lb. per second approximately. It was estimated that this arrangement gave approximately the same jet velocity as that of the Jumo 004 engine.

Tests were carried out to determine the secondary air flow using a range of mixing tubes from 1-3/8 in. inside diameter to 5-5/32 in. inside diameter, the throat position being adjusted in each instance to obtain the maximum secondary flow.

In Figure 2, the calculated secondary air flow rate and the calculated secondary air flow velocity at the orifice have been plotted against the mixing tube diameter. This shows that the optimum mixing tube diameter for maximum secondary flow is about 5 inches. Below 3 in. mixing tube diameter, choking in the mixing tube causes considerable reduction in the secondary flow. It was evident that if choking was to be avoided in the full sized tunnel it was important to avoid reducing the mixing tube diameter too far.

The value of the ratio of the secondary air flow to the primary air flow for the 3-7/8 in. diameter mixing tube was calculated to be approximately 3:1.



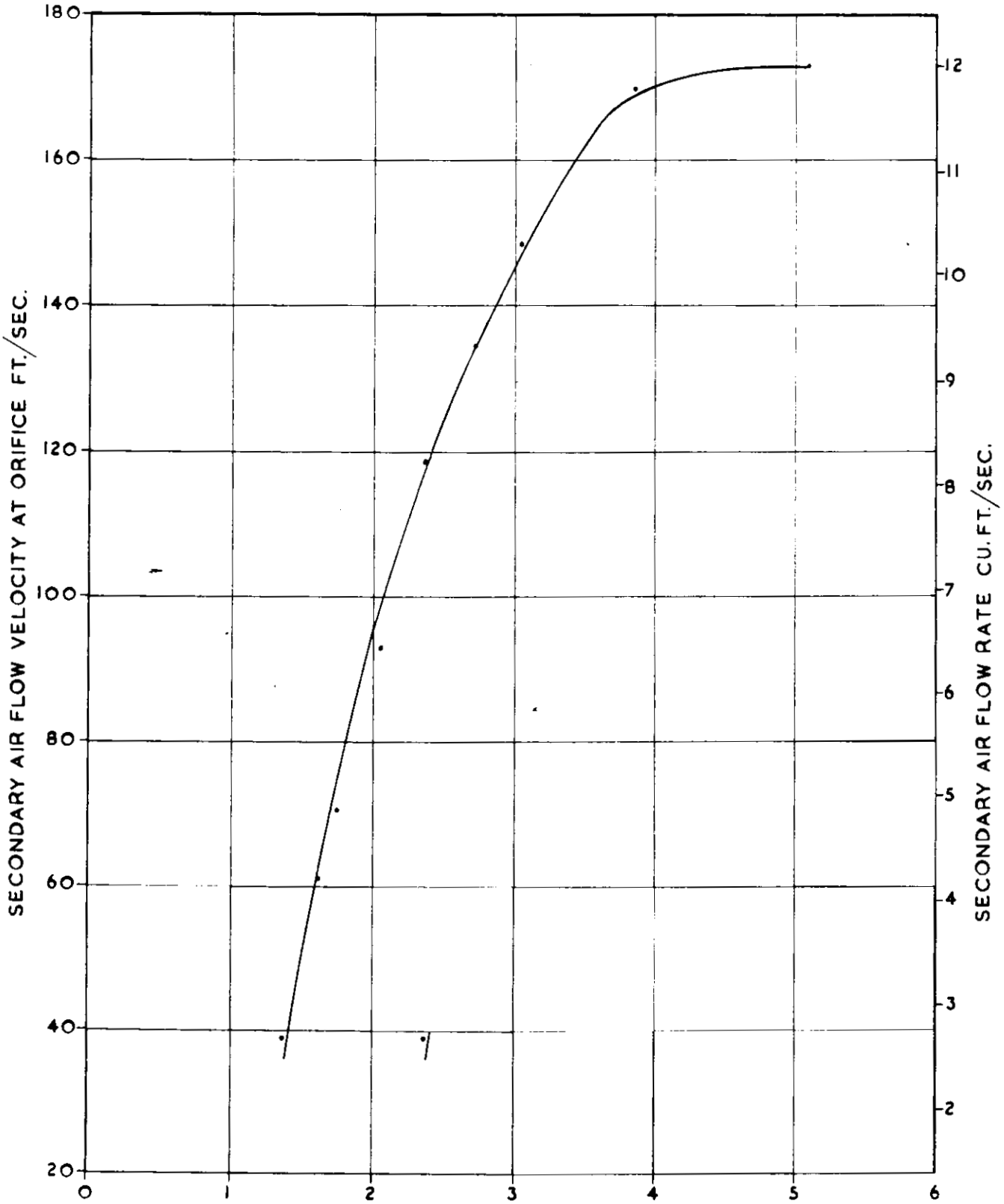
DIAGRAMMATIC ARRANGEMENT OF MODEL

FIG. 1
ME-167

FIG. 2
ME - 167

TEST ON MODEL JET EJECTOR

MODEL JET DIA. 0.81" READINGS TAKEN WITH MIXING TUBE IN OPTIMUM POSITION. ALL MIXING TUBES 7 DIA. LONG. READINGS NOT CORRECTED. 3.57" ORIFICE DIA.



Considering now a full sized tunnel of approximately the same geometry as that of the model, then the following differences between the two might be expected:

(1) Separation from the orifice plate in the model would give higher losses, but would tend to shield the air supply pipe line which has a higher drag than the full scale arrangement.

(2) The model jet is cold whereas the full scale jet operates at approximately 600°C. Hence the model jet has a much higher density.

(3) The scale and temperature effects will be such as to allow of much better mixing of the primary and secondary gas streams in the full scale tunnel than in the model.

It was considered that (1) and (3) would outweigh (2) so that deductions from the model tests would be on the pessimistic side.

The design proceeded therefore on the basis that model speeds could at least be attained. Basic dimensions in the design of the tunnel were the fixed diameters of 18 in. for the Jumo 004 jet pipe and 63 in. for the existing air intake duct.

3. CONSTRUCTION OF THE TUNNEL

Figure 3 shows the layout of the tunnel, while Figures 4, 5, 6 and 7 show views of the assembly. Air enters the tunnel through the large wooden bellmouth whence it passes through 20 feet of 63 in. diameter intake duct to the working section. This is, in effect, a large cylindrical box 108 in. in diameter and 48 in. long. Air enters one side of this box through the intake duct and leaves at the opposite side through a small entry flare into the parallel throat section housing the Jumo engine. This parallel section is 75 in. in diameter and 12 feet long and is attached directly to the small end of the diffuser. The diffuser, or more truly, the diffuser-mixing tube tapers from 75 inches in diameter to approximately 106 inches in diameter in a distance of 37-1/2 feet, having an included angle of taper of 4 degrees. This gives a diffuser expansion area ratio of almost exactly 2:1.

The working section serves to produce an open jet around the nose of the engine which protrudes some 24 inches into it. This section of the tunnel is provided with a sliding door by means of which access to the interior may be readily gained.

The parallel throat section is divided by longitudinal joints into three segments, the upper two of which may be lifted out to provide access to the engine when any repair work has to be done.

Immediately under the parallel throat section is the test bed on which the engine is mounted. The engine mountings consist of two "N" shaped tubular frames attached to four pick-up points on the engine. These frames pass through sponge rubber-grommetted holes in the lower third segment of the parallel throat, so allowing the engine to move slightly longitudinally, but preventing any large air leakage at this position. The engine test bed is suspended by means of "Emery Pivots" at its four corners, the thrust being measured by a precimeter.

Engine services such as fuel lines, electric power supply, hydraulic throttle controls, gauge connections, etc. are carried down beside one of the legs of the "N" shaped frames.

The diffuser is made up of five sections, each 7-1/2 feet long and supported at the end of each of these sections by suitable frames. Owing to the unsatisfactory standard of the workmanship, the diffuser surface was rather irregular and it became necessary to smooth out this surface by attaching strips of sheet metal at the joints.

With the exception of the working section which is of 1/8 in. thick plate, the sheet metal used throughout the tunnel is 1/16 in. thick mild steel.

4. INSTRUMENTATION

Engine Thrust was measured by means of a precimeter and a 100 in. mercury manometer. Calibration of the precimeter was carried out by means of a flexible steel strap, pulley, scale pan and dead weights.

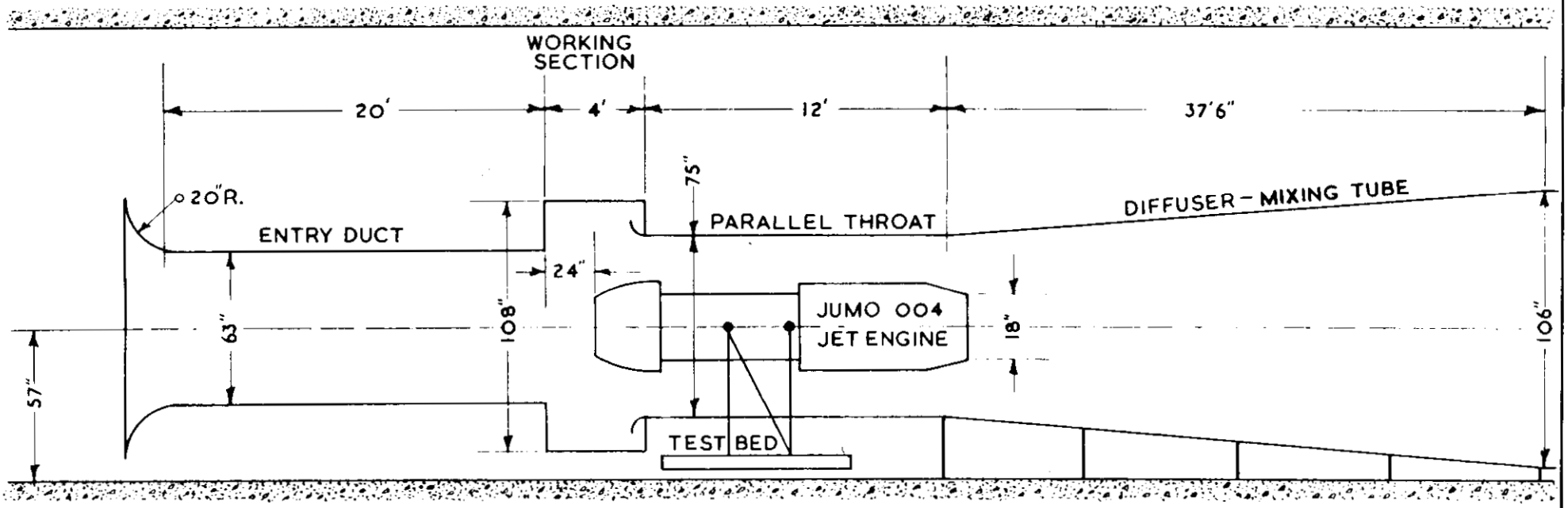
Range	0 - 3,000 lb.
Accuracy	± 10 lb.

Engine Speed was measured by means of a calibrated aircraft tachometer as supplied with the engine.

Range	0 - 9,500 r.p.m.
Accuracy	± 25 r.p.m. (approx.)

Fuel Flow was measured by a calibrated Fischer and Porter flowmeter.

Range	700 - 3,500 lb. per hr.
Accuracy	± 10 lb. per hr. (approx.)

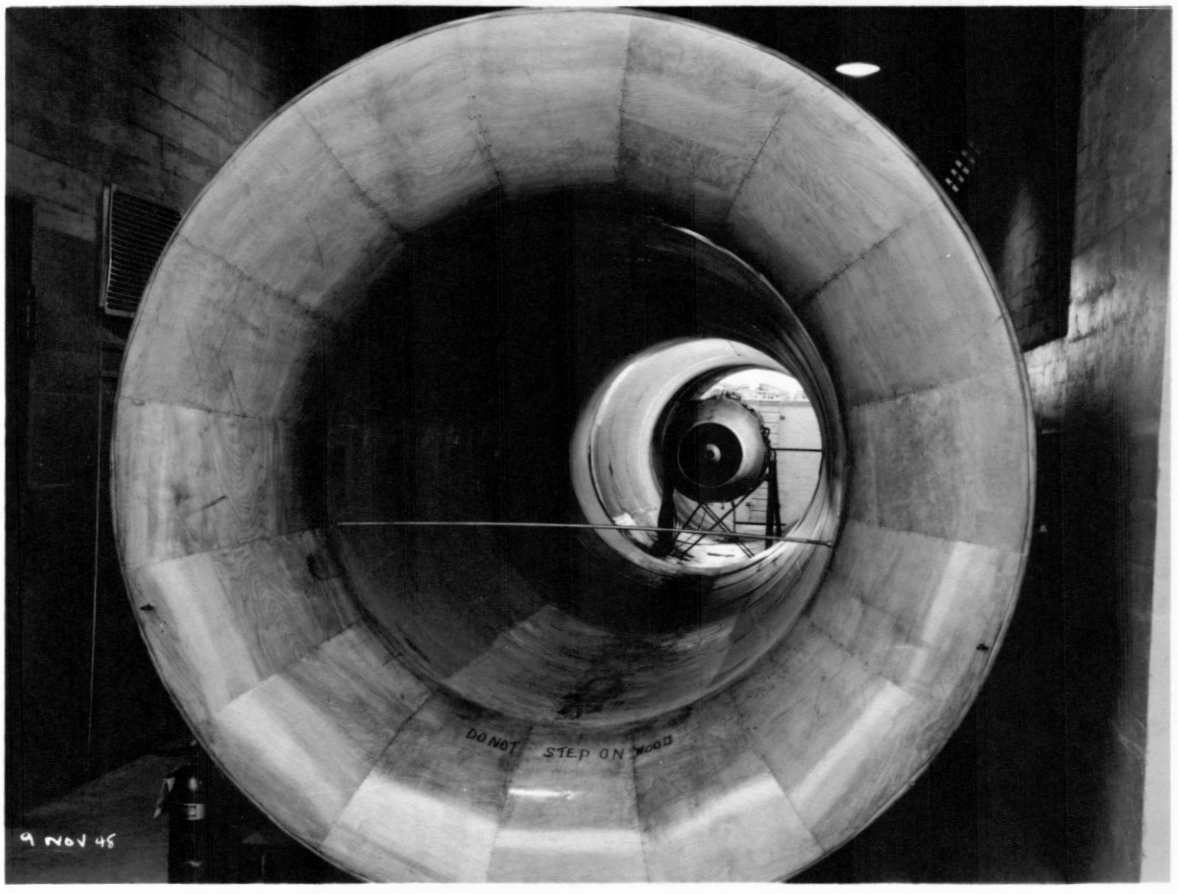


DIAGRAMMATIC LAYOUT OF EJECTOR TUNNEL

NOT TO SCALE

FIG. 3
ME-167

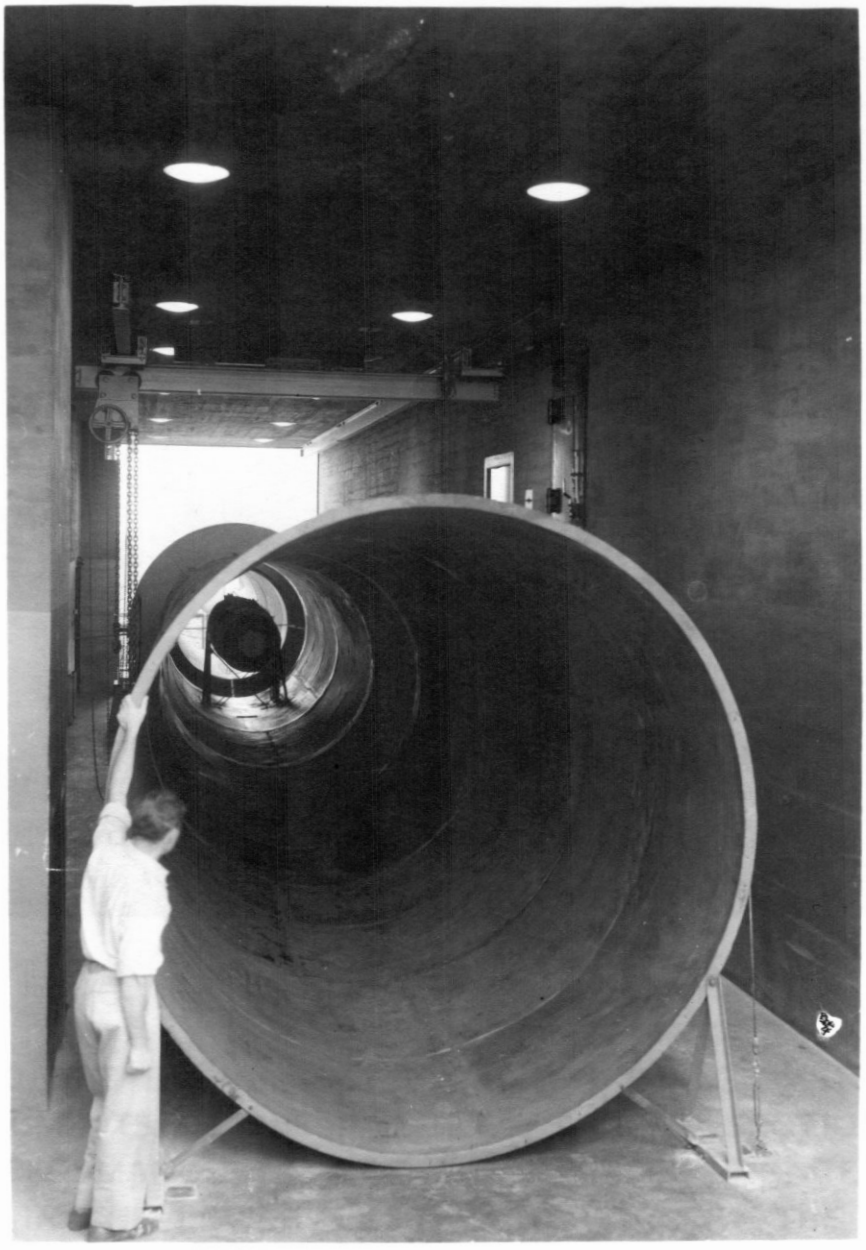
FIG. 4
ME - 167



ENTRY END OF TUNNEL

SHOWING LARGE WOODEN BELLMOUTH AND NOSE OF THE ENGINE. BAR AT THE FRONT IS SAFETY BAR.

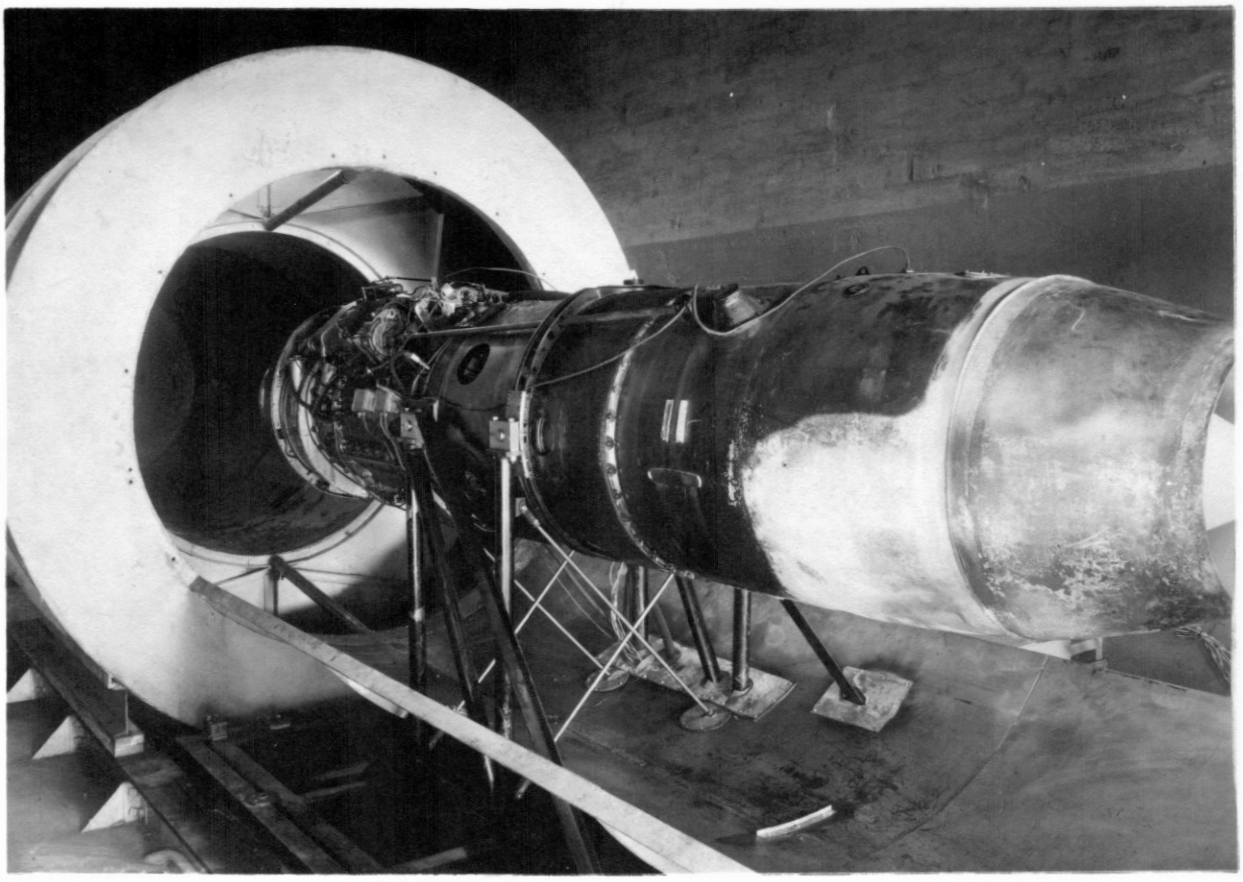
FIG. 5
ME-167



EXIT END OF TUNNEL

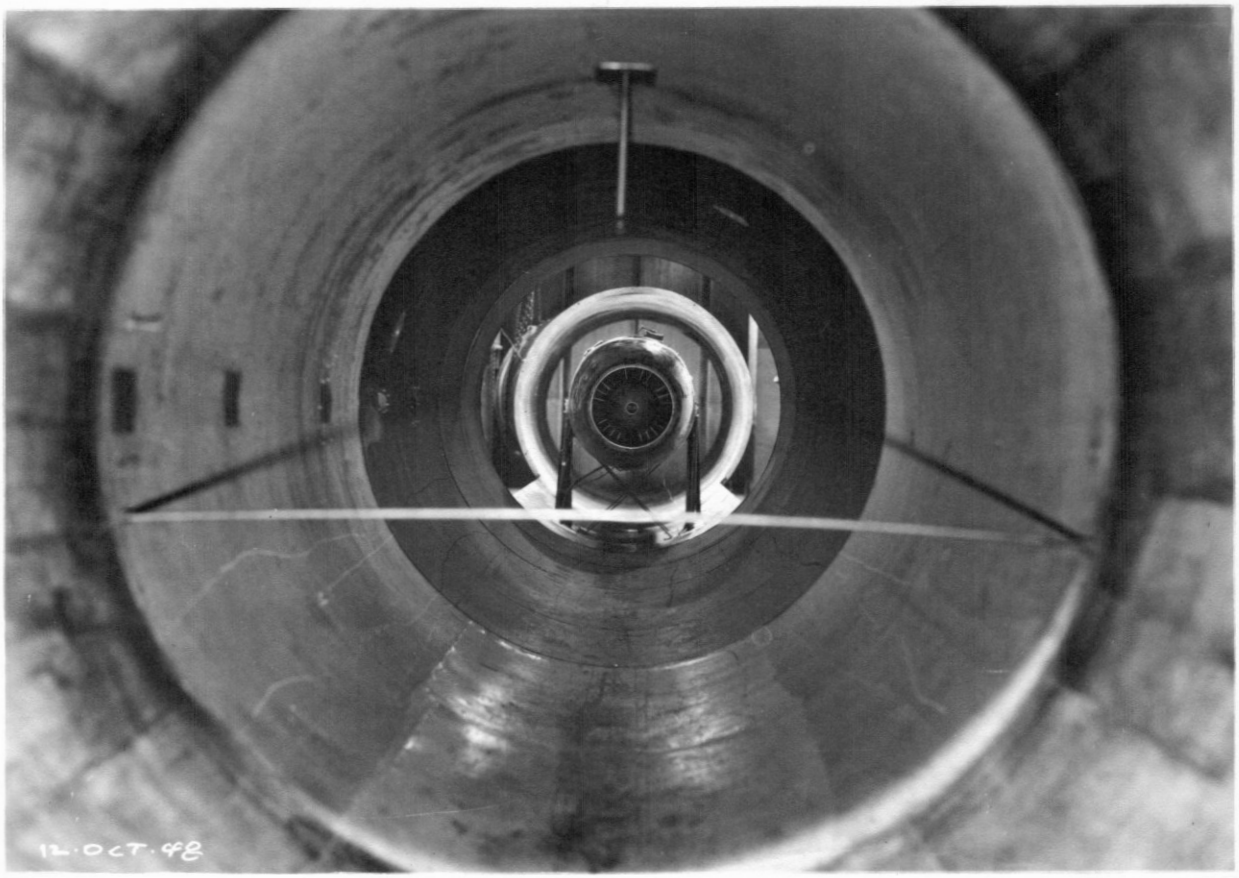
LOOKING BACK THROUGH THE DIFFUSER
TOWARDS THE ENGINE JET PIPE

FIG. 6
ME – 167



SHOWING THE ENGINE SET UP IN THE TUNNEL WITH THE TOP TWO SEGMENTS OF THE PARALLEL THROAT SECTION REMOVED FOR PERFORMANCE TEST OF THE BARE ENGINE. TEST BED IS VISIBLE IN THE LOWER LEFT HAND CORNER. THE WORKING SECTION OF THE TUNNEL ENCLOSES THE NOSE OF THE ENGINE.

FIG. 7
ME-167



FRONT VIEW OF THE TUNNEL PARTLY DISASSEMBLED AS DESCRIBED IN FIGURE 6. THE UPPER SEGMENTS OF THE PARALLEL SECTION ARE REMOVED.

Jet Pipe Temperature was measured by means of a Bristol Pyrometer and the standard chromel-alumel thermocouple supplied with this engine.

Range 0 - 1,200°C.
Accuracy ± 10°C. (Approx.)

Pressures (Jet Pipe Total Head etc.) were measured with mercury manometers.

Range 0 - 20 in., 0 - 40 in.
Accuracy ± 0.1 in.

Velocities (Traverses across open jet and intake duct) were measured with standard pitot heads and water manometers. Velocities were then calculated from the expression $V = 21.3\sqrt{T.h/P}$
Where V - Velocity in feet per second
T - Absolute Temperature °K.
h - Pitot differential in inches of water
P - Absolute pressure in inches of mercury

Range of Manometers 0 - 20 in.
Accuracy of Manometers ± 0.1 in.

5. PERFORMANCE OF THE TUNNEL

Initial tests indicated that there was considerable leakage of air into the tunnel by way of the badly fitting joints and holes which had originally been cut in the entry duct for lights and other equipment. Time spent in plugging up these leaks was well rewarded by the improvement in the general performance.

These tests also indicated that, owing to the high velocity of the air at the tunnel intake, it was necessary to take safety precautions to keep personnel away from this part of the apparatus during running.

It was expected that most of the diffuser would be fairly hot in operation, and arrangements were made to allow for its expansion under these conditions. However, it was found that in actual operation, only the last few feet of the diffuser were warm, and even then, temperatures did not exceed about 50°C. This seems to indicate that the diffuser proportions were not far from the desired values. A temperature traverse at the diffuser exit showed that the temperatures in the gas-stream there were of the order of 80 ± 5°C. and that there was relatively little variation in the

temperature across the section.

Pitot tube traverses were made across the intake duct at a position 52 inches upstream from the working section, and across the open jet in the working section at a position 10.8 inches upstream from the nose of the Jumo engine. These traverses were made during successive runs using the same pitot tube. From these results, air velocities were calculated and are plotted in Figures 8 and 9. It will be seen that the velocity distribution across the intake duct is fairly uniform except along the walls, as might be expected. Figure 9 shows that, in the open jet, there is a moderate increase in the air velocity in the area just ahead of the engine intake and at the outer periphery of the jet stream. This is accompanied by a reduction of the air velocity in the area just outside that encompassed by the engine nose cowling. Velocities close to the engine nose appeared to be nearly identical with those in the intake duct.

The diffuser exit velocity was measured and found to be about half the intake duct velocity. Considerable turbulence at this position made it impossible to get an accurate reading.

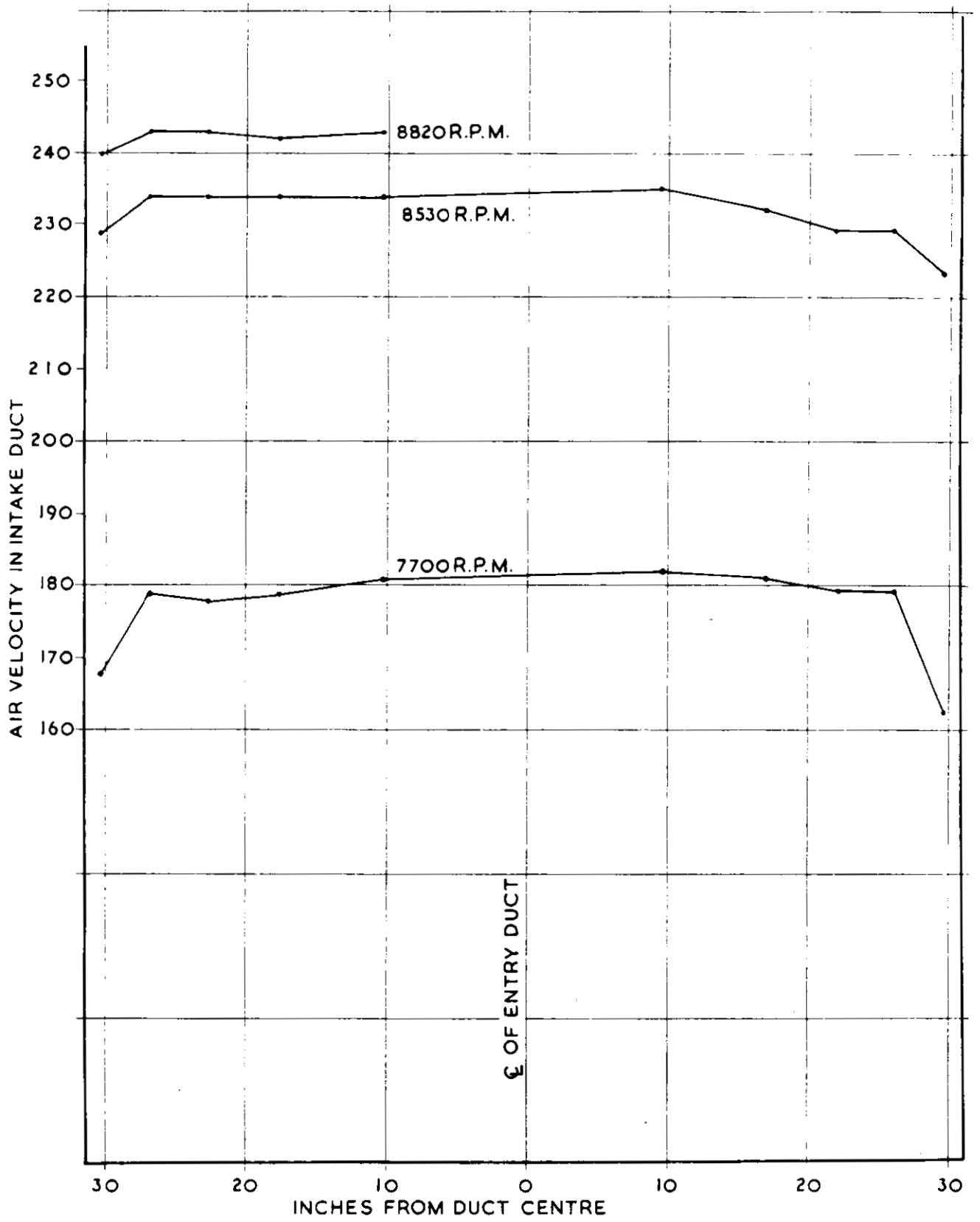
TABLE I.

Pressures in the Tunnel. Inches of Water (-ve)

Position in Tunnel	Corrected Engine R.P.M.		
	7690	8530	8820
7-1/2 ft. from diffuser exit	1.05	1.9	2.1
15 ft. from diffuser exit	2.5	4.2	4.6
22-1/2 ft. from diffuser exit	3.8	6.4	7.2
30 ft. from diffuser exit	5.0	8.9	9.4
At working section	8.3	14.0	15.1

In Table I is shown the depression measured at various parts of the tunnel and for various engine speeds. It will be observed that the pressures in the working section are low enough to require that the working section be designed with adequate strength in compression.

FIG. 8
ME-167

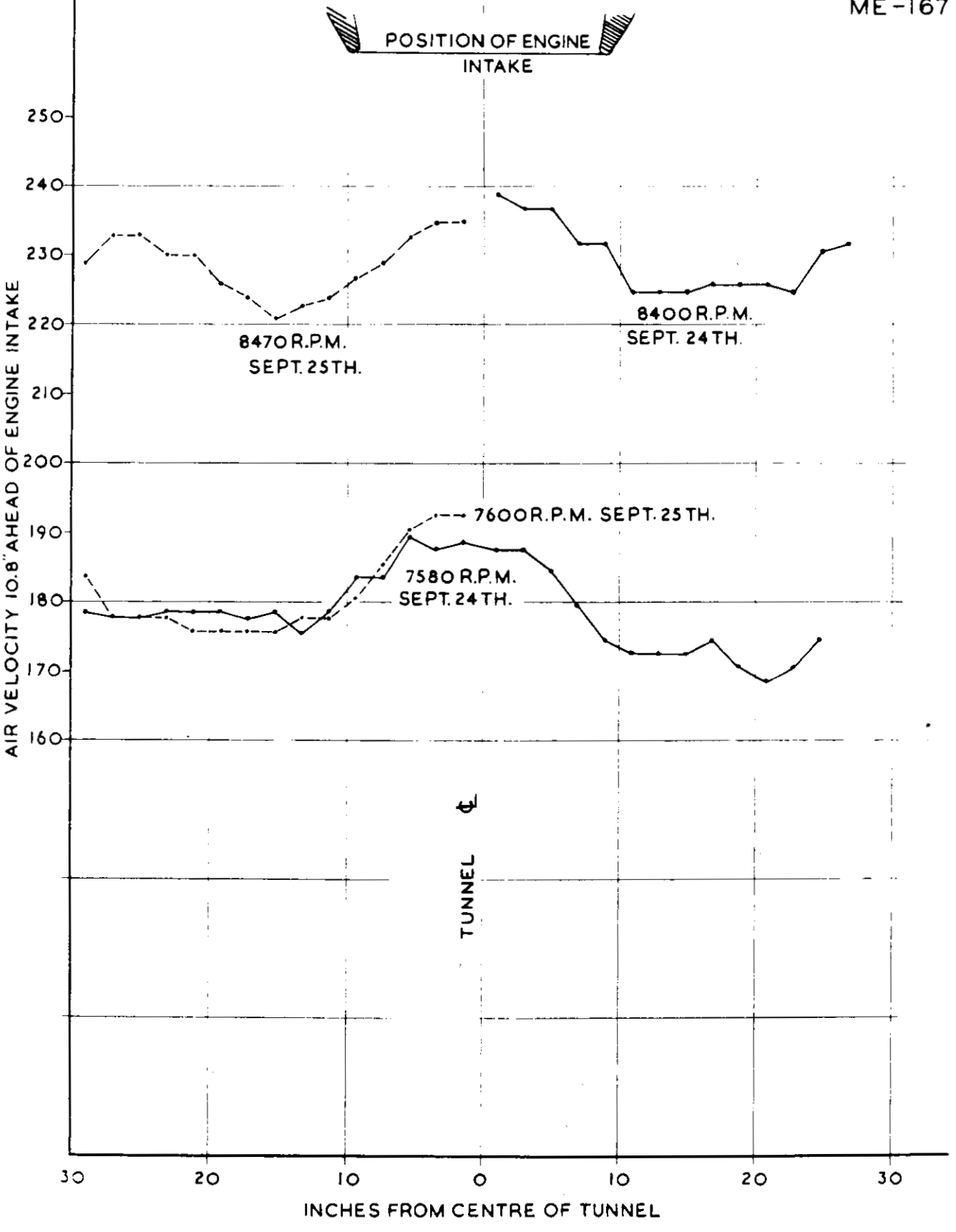


VELOCITY TRAVERSE IN INTAKE DUCT AT VARIOUS ENGINE SPEEDS

MEASURED AT A POSITION 52" UPSTREAM FROM THE WORKING SECTION

(ENGINE SPEEDS CORRECTED FOR TEMPERATURE)

FIG. 9
ME-167



VELOCITY TRAVERSE ACROSS THE OPEN JET 10.8" AHEAD OF THE ENGINE INTAKE

(ENGINE SPEEDS CORRECTED FOR TEMPERATURE)

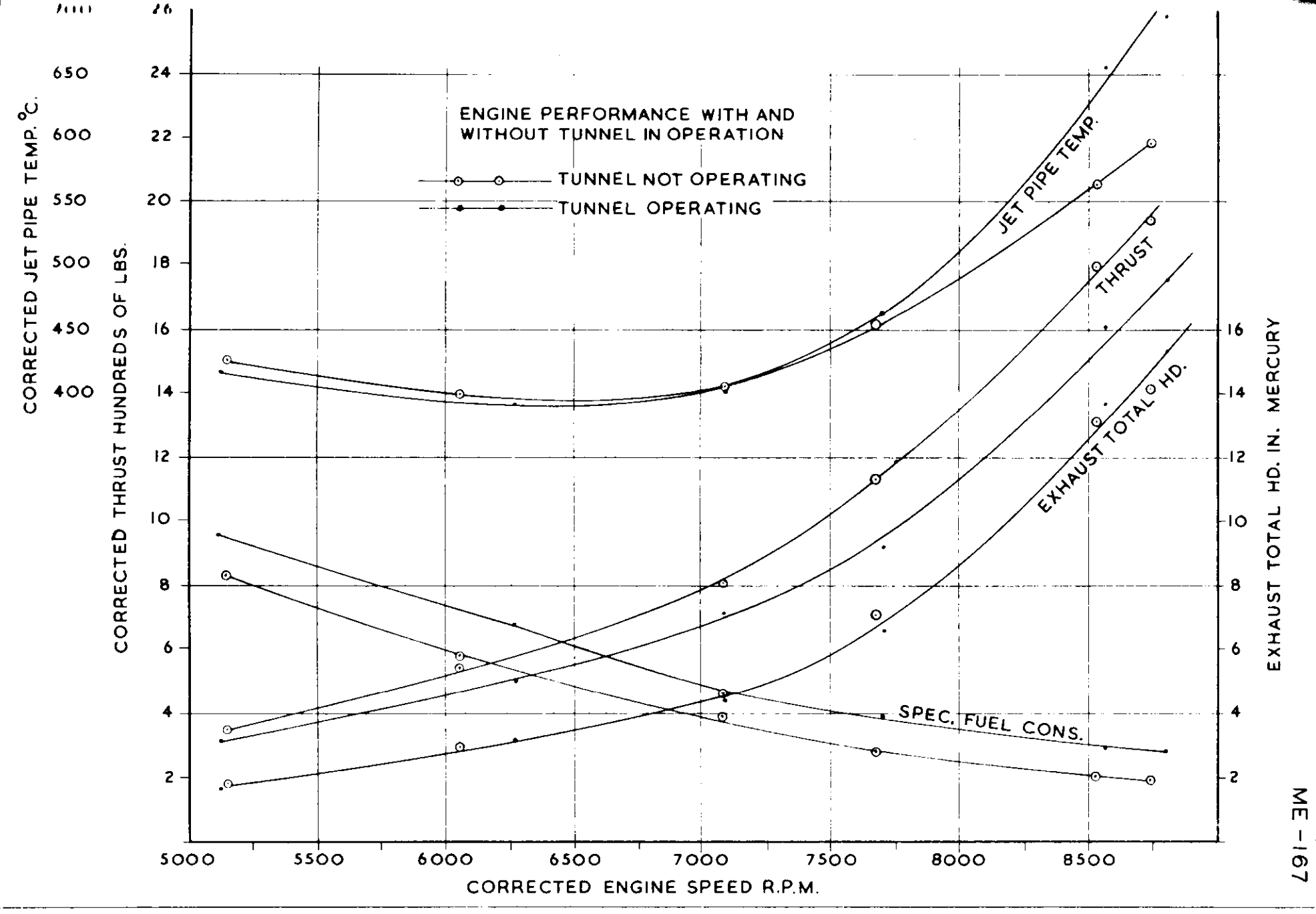

ENGINE PERFORMANCE WITH AND
WITHOUT TUNNEL IN OPERATION
TUNNEL NOT OPERATING
TUNNEL OPERATING
JET PIPE TEMP.
THRUST
EXHAUST TOTAL HD.
SPEC. FUEL CONS.
CORRECTED JET PIPE TEMP. °C.
650
600
550
500
450
400
CORRECTED THRUST HUNDREDS OF LBS.
26
24
22
20
18
16
14
12
10
8
6
4
2
EXHAUST TOTAL HD. IN. MERCURY
16
14
12
10
8
6
4
2
5000
5500
6000
6500
7000
7500
8000
8500
CORRECTED ENGINE SPEED R.P.M.

FIG. 10
ME-167

In order to evaluate the drag of the engine, the engine was given a calibration run first in the complete tunnel and then in the partly disassembled tunnel, as shown in Figure 6. For this latter run the two upper segments were removed from the parallel throat section of the tunnel, so rendering the front part of the apparatus ineffective and giving engine conditions similar to those obtaining in still air. It must be remembered that the ejector effect of the tunnel reduces the pressure both at the engine intake and at the engine exhaust. Ram pressure at the former position practically compensates for the depression in the working section, but there still remains the depression at the exhaust which will tend to increase the thrust of the engine. However, due to the considerable drag of the engine and support when the tunnel is operating, the net thrust is lower. In addition, the jet pipe temperatures differ greatly under the two operating conditions, being higher when the engine is running in the complete tunnel.

In Figure 10 the performance curves for the engine are plotted for the two conditions. These results have been corrected for barometer and temperature in the normal way. The difference between the two thrust curves gives a rough figure for the drag of the engine and support in the tunnel. Since the thrust has not been corrected for the exhaust depression, this value for the drag will be approximate only. It will be observed that the exhaust total heads in both sets of results are very close, but that the specific fuel consumption is considerably higher when the engine is running in the complete tunnel.

Additional tests were also carried out to determine the flow pattern of the open jet around the nose of the Jumo engine. Figure 11 shows the means initially employed to accomplish this. Three steel piano wires were stretched at right angles to the engine axis so that they were lying in the vertical plane. Cotton tufts were fastened every 2 inches along these wires to indicate the direction of the air flow. While this method served to show that there was considerable turbulence at the outer edge of the open jet, it was found to give an insufficiently detailed picture of the flow.

A second method employed to determine the flow pattern made use of 3/16 in. thick steel plate, painted white and mounted in front of the engine in the vertical plane. This plate was painted with a mixture of lampblack and kerosene of such a consistency as to show up the flow pattern by its smearing and consequent drying. Figure 12 shows the appearance of the plate after the test. It will be observed that the plate has been notched out to fit into the nose of the engine and show up the conditions just inside the intake.

The plate shows that there is considerable breakaway of the air flow from the leading edge of the nose cowling, and it was found possible to trace the stagnation lines. There is considerable acceleration of the airstream just ahead of the engine and also just inside of the engine nose. This latter is illustrated by the fact that at the trailing edge much of the lampblack has been blown right off the plate. While this method does not give a completely true picture of the air flow, due to the "end plate effect", it does at least serve as a guide to conditions in the open jet.

The stagnation lines shown up by this method were used to calculate the approximate values of the engine mass flow and the secondary to primary air mass flow ratio for a given engine speed. It was found to be fairly easy to trace the stagnation lines back from the nose to the points at which they intersected the vertical plane 10.8 inches ahead of the nose. The latter plane was chosen because a horizontal velocity traverse had previously been made there, and for this reason the average velocity was known. For the purposes of the calculation it was assumed that the average velocity across the horizontal axis in this plane equalled that for the vertical axis. Averaging the diameters on both sides of the plate for the air stream contained by the stagnation lines gave a figure of 24-1/2 inches. Knowing the average velocity, the area, the pressure and the temperature of this air stream, the air mass flow of the engine was calculated to be 45.6 lb. per second at 7,580 r.p.m. under standard conditions. Assuming a straight line relationship between mass flow and r.p.m., the mass flow was calculated at 7,700 r.p.m., at which corrected speed a velocity traverse across the intake duct had been made earlier. From these figures the mass air flow for the intake duct was calculated as 297 cu. ft. per second. The ratio of the secondary air flow to the primary air flow is therefore:

$$(297 - 45.6) : 45.6 = 5.46:1$$
(at 7,700 r.p.m. and at standard conditions)

6. CONCLUSIONS

The jet engine ejector tunnel provides a ready means of producing large moderate-velocity air flows cheaply and simply. Such tunnels should be ideal for producing, on the ground, the conditions of low to moderate-speed flight.

No special precautions are necessary to guard against undue heating in any part of the equipment, but on the other hand, some precautions should be taken to safeguard personnel working near the intake.

FIG. 11
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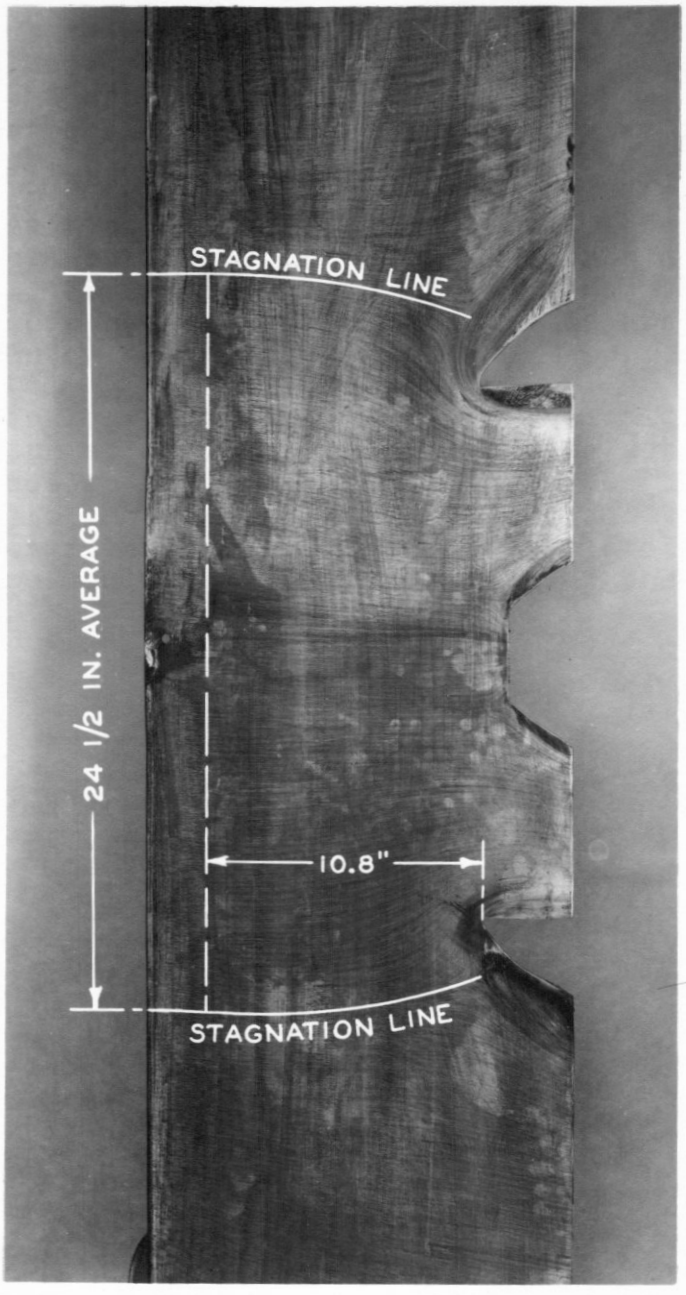
FIRST METHOD USED TO
DETERMINE FLOW PATTERN AT NOSE

FIG. 12
ME-167



FLOW PATTERN NEAR NOSE OF JUMO ENGINE

SECOND METHOD

ENGINE SPEED 7600 R.P.M.
VELOCITY AT POINT 10.8 INCHES AHEAD OF NOSE
185 FT. PER SEC. (APPROX.)
SHOWING METHOD OF USING STAGNATION LINES TO CALCULATE ENGINE MASS FLOW. VERTICAL STREAKS ARE BRUSH MARKS. LIGHT COLOURED AREAS INSIDE INTAKE ARE THOSE WHERE THE HIGHER VELOCITY HAS COMPLETELY REMOVED THE LAMPBLACK.

The noise level is a little higher than that noticed with the bare engine and is likely to be somewhat unpleasant for personnel working in close proximity to the tunnel.

Velocities induced in this tunnel were insufficient to prevent acceleration of the air stream just ahead of the engine intake. It is submitted that, even so, the tunnel should allow more realistic conditions to be attained during icing experiments.

It is suggested that if higher velocities are to be used in a tunnel of this design, adequate attention be given to the design of the working section, to the design of the diffuser, to the cowling of the engine and to the fairing of the engine support. It is probable that a closed jet of smaller section would also assist in raising the velocity.

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