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DESIGN OF AN ICING WIND TUNNEL

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FOREWORD

The work reported here is a part of the icing research program at the University of Michigan; it was performed by the Engineering Research Institute at Willow Run Airport, Ypsilanti, Michigan. This work was accomplished under Air Force Contract No. AF18(600)-51, which was initiated in October, 1951, by the Flight Propulsion Laboratory, Wright Air Development Center, Dayton, Ohio.

ABSTRACT

The design criteria for an icing tunnel which will satisfactorily simulate natural conditions are briefly set forth.

A tunnel was designed to satisfy these criteria. The test section is one by one foot in cross section. Air ejectors drive the tunnel and provide speeds in excess of 300 ft/sec. The purpose of the tunnel is to permit a study of icing simulation.

Preliminary test data are given.

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DESIGN OF AN ICING WIND TUNNEL

INTRODUCTION

The Engineering Research Institute of the University of Michigan has initiated a study of the problem of icing simulation as a part of its work in Icing Research for the United States Air Force. The impetus for this particular study was given by a series of interviews with representatives of various aircraft companies, who stated that the lack of icing facilities wherein meaningful tests could be accomplished was a major handicap in the development of new methods of airplane anti-icing and de-icing.

The report which follows represents a first contribution by the University of Michigan to the solution of this problem. A preliminary search of the literature and discussion of simulation with other groups led to the conclusion that certain key problems would have to be solved before an icing wind tunnel could be built which correctly simulates icing conditions. These problems, which are in addition to those of any wind-tunnel design, may be described as follows:

(a) The introduction of the water droplets should not produce tunnel turbulence.

(b) The water droplets should be produced in the proper size, quantity, and size distribution to correspond to a natural cloud.

(c) The acceleration of the cloud should not produce a centrifuging effect which projects the drops either to the centerline of the tunnel or onto the tunnel walls.

(d) The humidity of the air at the test station should correspond to saturation.

(e) The water drops should supercool without freezing.

The initial installation which is described in this report was designed as a facility in which the problems of icing simulation could be studied at minimum expense. For this reason, the tunnel incorporates no refrigeration equipment and, consequently, summer tests are restricted to those not involving freezing. The tunnel is driven by ejector action and was designed to attain a velocity of 300 ft/sec in a one-foot-square test section.

It is believed that the key problems enumerated above have been solved satisfactorily. The lack of freezing weather has prevented a check on the "freezeout" problem, but a study of the literature has indicated freezeout will not be serious in a naturally refrigerated tunnel.

A number of investigations which are currently directed towards the "freezeout" problem and towards that of spray evaporation will be discussed in subsequent reports.

GENERAL ARRANGEMENT OF THE TUNNEL

Icing wind tunnels commonly utilize a spray rig to project the spray directly into the tunnel stream. In some cases this is done in a closed system and in others at the entrance to the bell-mouth of a nonreturn system. The disadvantages of such a scheme are that the sprays induce turbulence, they impinge on the tunnel walls, and also sampling techniques are both difficult and inconclusive. Accordingly, it was decided that the spray should be injected into a very large settling chamber and the spray rig located an appreciable distance from the bell-mouth to permit the induced turbulence to dampen out. This arrangement also permits an investigator to enter the chamber while the tunnel is in operation and obtain drop samples at any point desired in the settling chamber. Establishment of the drop characteristics at the inlet gives a very good indication of those at the test section, since there is very little time (approximately 0.06 second) for evaporation between the inlet and test section.

An available engine test cell proved to be an excellent solution to the above requirements This cell had a high tower to one end into which outside air could be introduced through louvres at the top. This tower was sealed off from the rest of the test cell with an insulated plywood partition and the tunnel entrance was mounted in the partition. The sprays were located near the top of the tower.

Fig. 1 is a schematic diagram of the system. Fig. 2 is a photograph showing the inlet nozzle mounted in the partition.

Spray Room

The spray room is 10-1/2 feet by 16 feet by 32 feet high with louvres on all four sides at the top. The sprays are located in the tower of this room 18 feet above the centerline of the tunnel and pointed downward. At present the spray system consists of four Devilbiss paint-spraygun nozzles (Devilbiss No. FX). Previous tests in the Chemical Engineering Department[1] have indicated that the DeVilbiss nozzles give a satisfactory spray distribution under the correct water-to-air ratios (volume mean drop size of 35 microns).

A second set of sprays (six solid injection Binks No. FO) are located 4 feet above the DeVilbiss nozzles and are available for experimentation with larger drops. The availability of hot water and compressed air permits experimentation with various types of spraymakers.

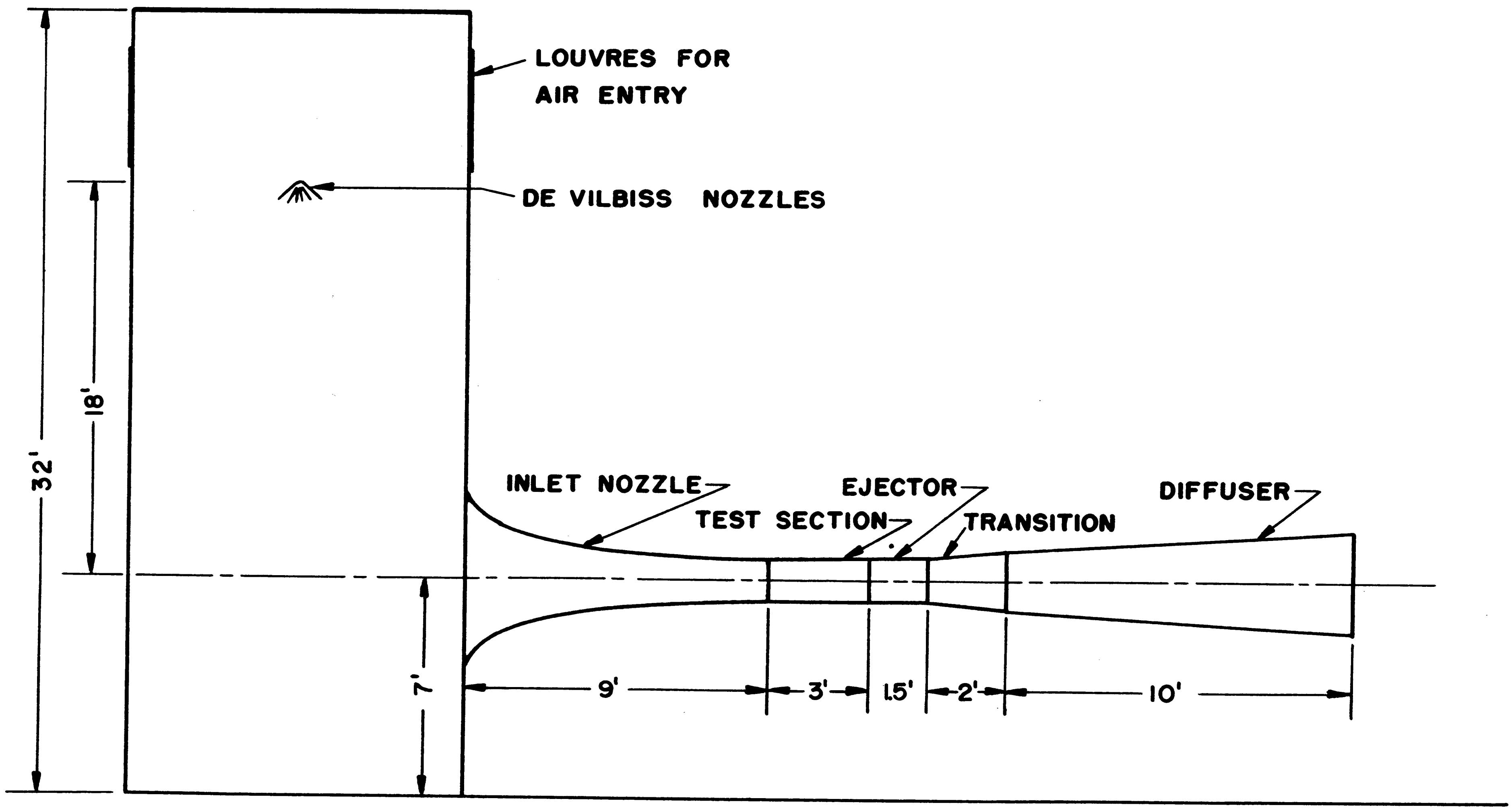

FIG. 1 GENERAL ARRANGEMENT OF ICING TUNNEL

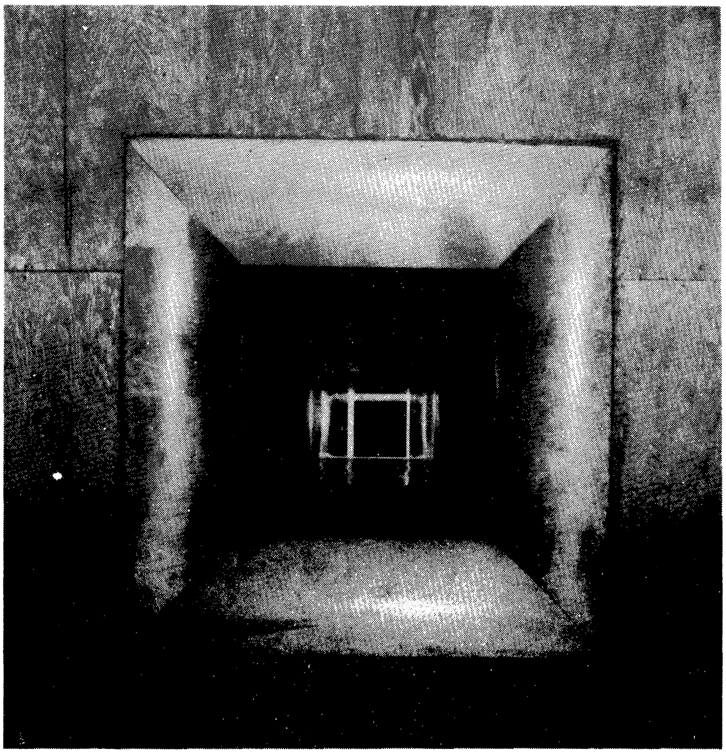

Fig. 2. Inlet Nozzle

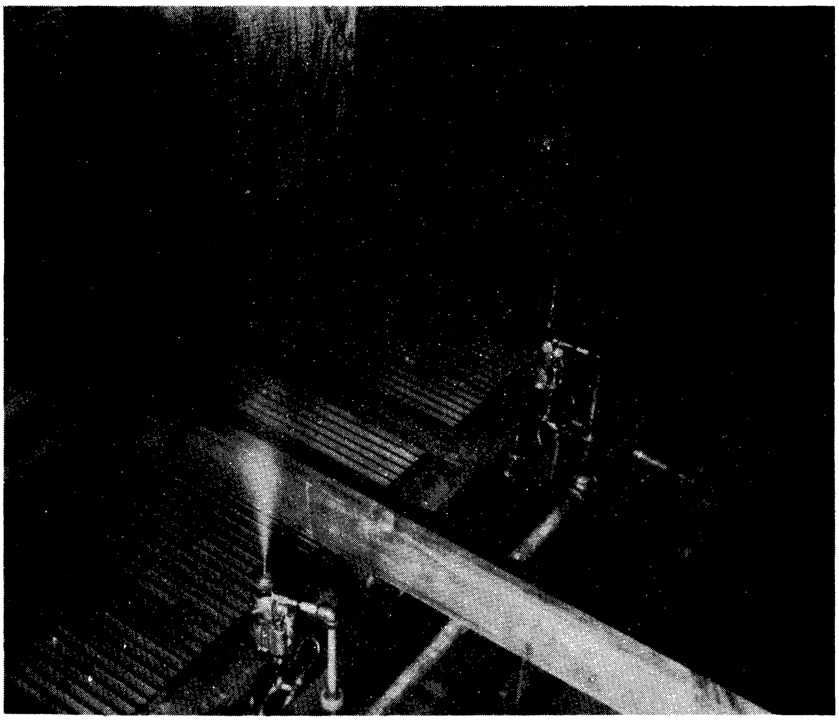

Fig. 3. DeVilbiss Sprays in operation

NOTE: Fig. 3 is upside down.

A ladder and catwalk provide ready access to all spray nozzles. Fig. 3 shows two of the DeVilbiss sprays in operation. The catwalk is seen just above the sprays. The screening shown covers the louvres and serves to keep birds out of the tower. Spray samples can be taken anywhere in the room. The method of sampling used at present is that of trapping the droplets between a layer of castor oil and xylene in a glass petri dish. Bausch and Lomb photomicrographic equipment is then used to study the sample obtained.* Fig. 4 is a picture of the photomicrographic equipment.

A light attenuation measuring system is presently being installed in the spray room which will allow measurement of drop size distribution, or liquid water content when the other is known.**

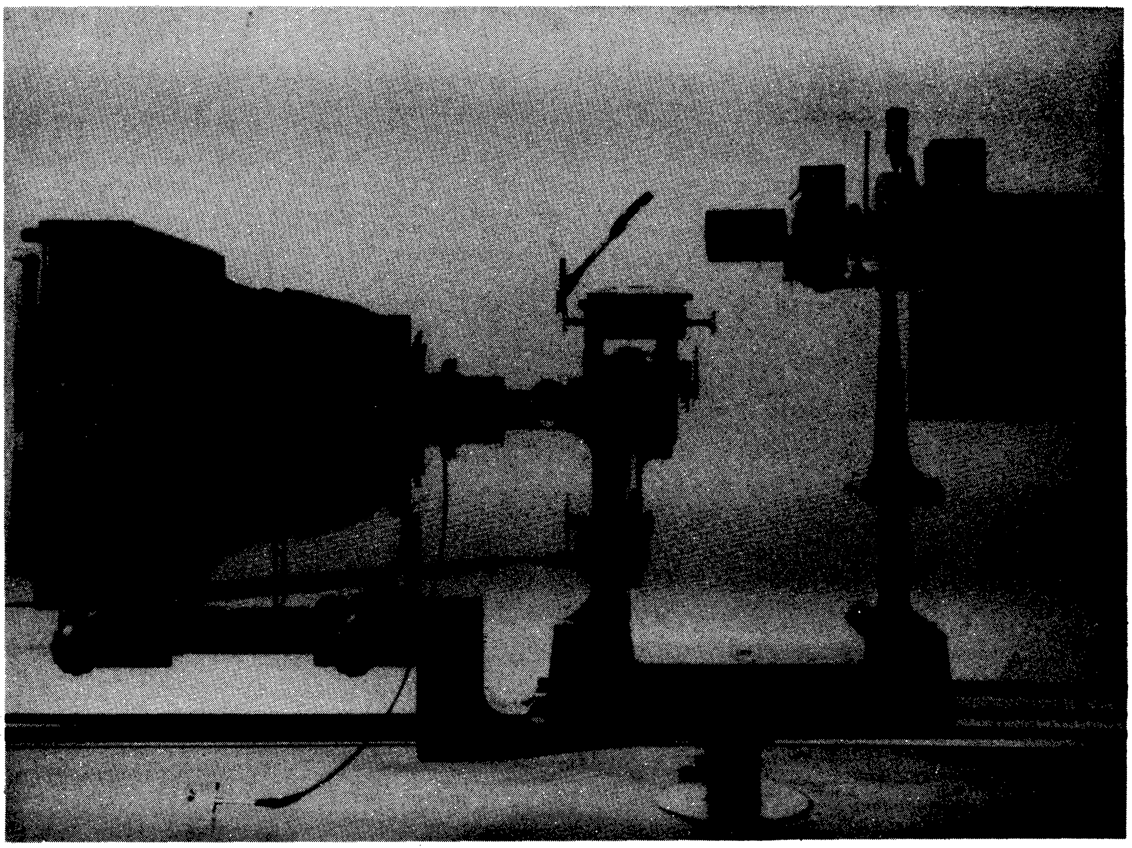

Fig. 4. Photomicrographic apparatus

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*Drop-size measurement has been supervised by Bruce Toms, Research Assistant. A separate report on this work is in preparation.

**Joseph Consiglio, Chemical Engineering Department, has recently prepared a doctoral thesis showing the method of interpreting light-scattering data for a system such as is under construction.

Inlet Nozzle Design

The design of an inlet nozzle in an icing wind tunnel must consider the centrifuging of water droplets towards the center of the tunnel. If the spray distribution at the test section is to be homogeneous, the centrifuging action must be minimized. A number of inlet curves were evaluated in regard to their centrifuging action by comparing the displacement of a drop from its original air streamline as the drop and air are accelerated into the tunnel. In this analysis the drop was assumed to have the same speed as its associated air streamline (the streamline nearest the wall) and to obey Stokes' Law. The calculations of the lateral displacement of such a drop will be on the conservative side, as the radius of curvature of the drop is always greater than that used in the calculations.

Let the curve defining the inlet wall be symmetrical about $y = 0$ and be given $y = y(x)$.

Stokes' Law applied to a spherical drop in a velocity field where the radius of curvature of the streamlines and drop path is R, yields the relation:

$$u = \frac{V^2 d^2 (\rho_d - \rho_a)}{18 R \mu} , \tag{1}$$

where u = displacement velocity of the drop perpendicular to the local streamline, ft/sec;

d = diameter of the drop, ft;

ρ_d = density of the drop, slugs/ft^3;

ρ_a = density of the air, slugs/ft^3;

R = radius of curvature, ft;

μ = viscosity of air, lb-sec/ft^2;

V = local speed (for both drop and air), ft/sec; and

V^2/R = the radical acceleration, ft/sec^2.

For incompressible one-dimensional flow, the continuity equation is:

$$AV = A_1 V_1 = C_1 = \text{constant} , \tag{2}$$

where "1" refers to test section conditions. If the cross section is square,

$$V = \frac{C_1}{A} = \frac{C_1}{(2y)^2} = \frac{C_1}{4y^2} \quad . \tag{3}$$

For the outermost streamline,

$$R = \frac{(1 + y'^2)^{3/2}}{y^4} \quad , \tag{4}$$

where $y' = \frac{dy}{dx}$ and $y'' = \frac{d^2y}{dx^2}$.

Introducing (3) and (4) into (1):

$$u = \frac{C_1^2 d^2 (\rho_d - \rho_a)\, y''}{288\, y^4 \mu\, (1 + y'^2)^{3/2}} \quad . \tag{5}$$

The optimum curve will be that which minimizes the relative displacement, λ,

$$\lambda = \int_{t_o}^{t_L} u\, dt = \frac{C_1{}^2 d^2 (\rho_d - \rho_a)}{288 \mu} = \int_{t_o}^{t_L} \frac{y''\, dt}{y^4 \left[1 + y'^2\right]^{3/2}} \quad , \tag{6}$$

where $t = t_o$ at $x = 0$

$t = t_L$ at $x = L$

L = axial length of inlet nozzle.

Such a curve must be consistent with the boundary conditions. These conditions are determined by the elimination of flow discontinuities at the inlet and test section and are:

$$\frac{dy}{dx} = \infty, \quad \frac{d^2y}{dx^2} = 0 \text{ at } x = 0 \quad \text{(bell-mouth entry)}$$

$$\frac{dy}{dx} = 0, \quad \frac{d^2y}{dx^2} = 0 \text{ at } x = L \quad \text{(straight test section)}$$

An analytical solution of (6) with its imposed boundary conditions is an extremely difficult problem in calculus of variations. For this reason, a few functions were specified and a stepwise integration of equation (6) made. Functions considered were an Archimedes spiral, a cubic in x, and a curve giving constant air acceleration. The latter curve afforded the best solution and has been adopted for the tunnel. For this curve, as well as the others, the centrifugal acceleration was computed for a number of points and its variation with time (Fig. 5) was graphically integrated to yield an average acceleration. Substitution of this average acceleration in Stokes' Law gave an average displacement velocity which, when multiplied by the total time, predicted the total displacement, λ, of the drop from its original streamline. For a 30-micron drop this amounted to 0.08 inch at the design velocity (300 ft/sec). Considering the conservative conditions for the calculation, this displacement was considered to be allowable.

The equation for the constant acceleration curve is derived as follows (assuming one-dimensional flow):

$$a = C_2 = \frac{dV}{dt} = \frac{dV}{dx}\frac{dx}{dt} = V\frac{dV}{dx} \quad , \tag{7}$$

where a = acceleration, ft/sec^2.

Substituting from (3),

$$C_2 = \frac{C_1}{4y^2}\,\frac{d\left(\frac{C_1}{4y^2}\right)}{dx} \quad ,$$

or, by a change of variable

$$Z = \frac{C_1}{4y^2} \quad ;$$

then,

$$Z^2 = 2C_2\,x + C_3$$

or

$$\frac{C_1^{\,2}}{16y^4} = 2C_2\,x + C_3$$

CENTRIFUGAL ACCELERATION OF A DROP VS. TIME
IN TRAVERSING THE INLET NOZZLE

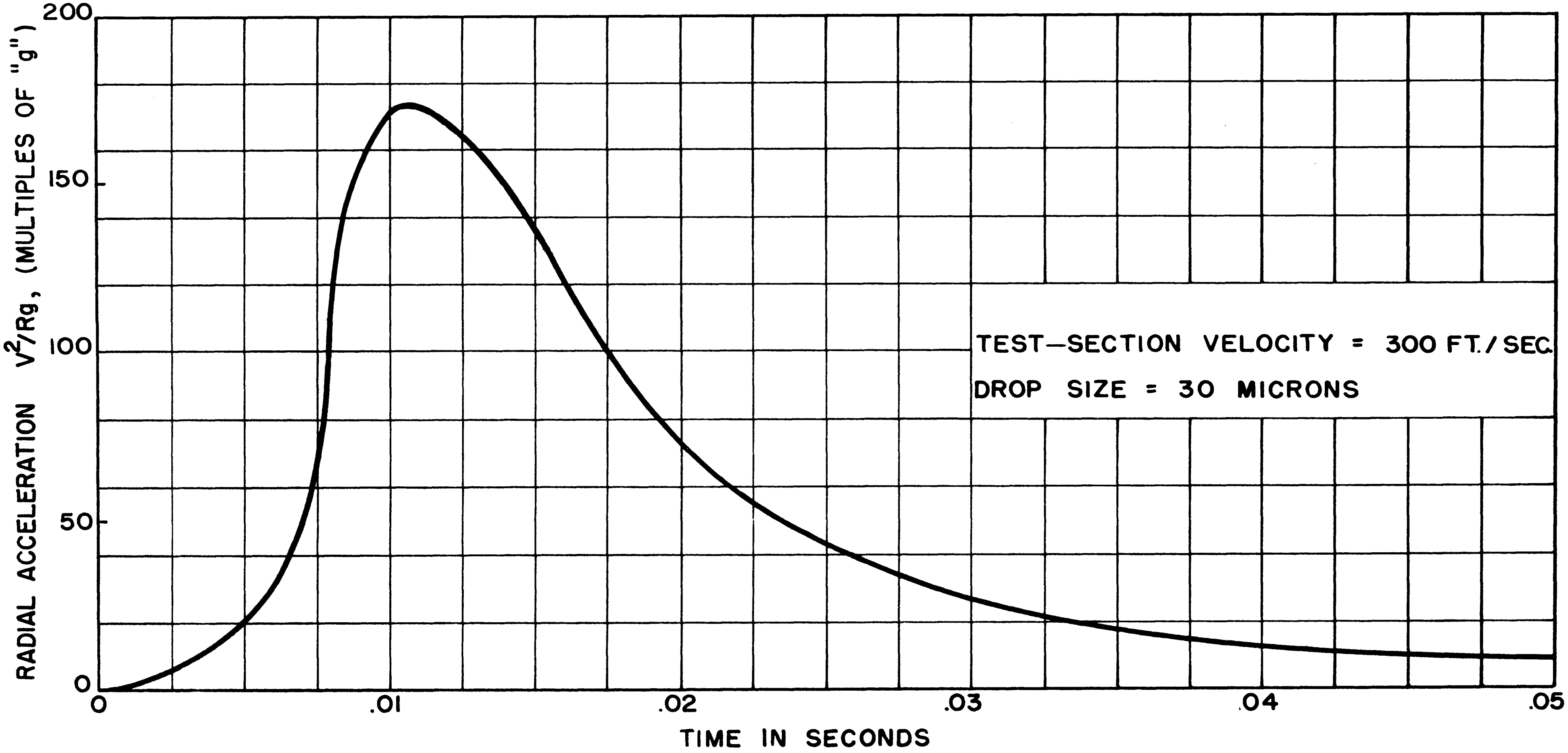

FIG. 5

Boundary conditions prescribe that at $x = 0$, $y = \infty$.

Therefore, $C_3 = 0$ and we have

$$y = \sqrt[4]{\frac{C_1^2}{32\, C_2 x}} \quad . \tag{8}$$

For this particular case the tunnel was designed for 300 ft/sec at the one-foot-square test section. From (2) and (3) we have

$$C_1 = 300 \quad .$$

The constant acceleration was selected as 6000 ft/sec^2, which fixes the inlet length at 7.5 feet. Equation (8) then reduces to

$$x = \frac{0.469}{y^4} \tag{9}$$

The inlet was constructed according to this equation except that the entrance was faired more abruptly so as to give infinite slope at $y = 2$ feet instead of at $y = 0$. Also, the curve was faired gradually to give zero slope at the test section. This lengthened the inlet to 9 feet. The profile and coordinates actually used are shown in Fig. 6 and Table 1, respectively.

Plywood of 1/8-inch thickness with suitable reinforcement was used in the fabrication of the inlet nozzle. The inside surfaces were treated with spar varnish as a protection against moisture. The nozzle was mounted in the plywood partition of the spray room, and gives a very large contraction ratio for the inlet. The inlet is shown to the left of Fig. 7.

Fig. 8 shows streamlines for the tunnel obtained on a fluid mapper.* These figures indicate that the flow near the wall has nearly a constant acceleration, as obtained from the one-dimensional analysis.

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*Courtesy of Professor A. D. Moore, Electrical Engineering Department, University of Michigan[2].

INLET NOZZLE COORDINATES

X-FT.	0	0.25	0.50	0.75	1.00	2.00	3.50	5.50	7.50	9.00
Y-FT	2	1.20	1.00	0.90	0.84	0.70	0.60	0.54	0.51	0.50

TABLE I

INLET NOZZLE PROFILE

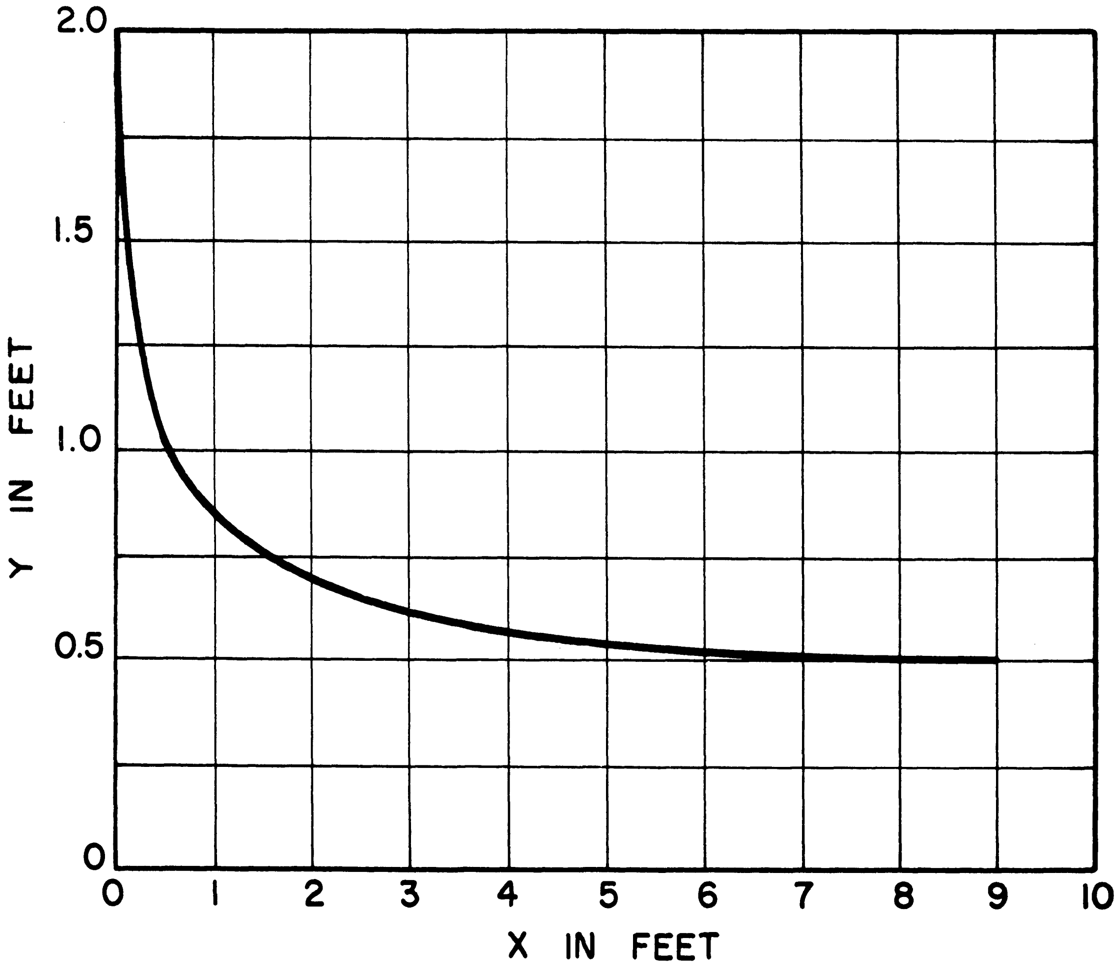

FIG. 6

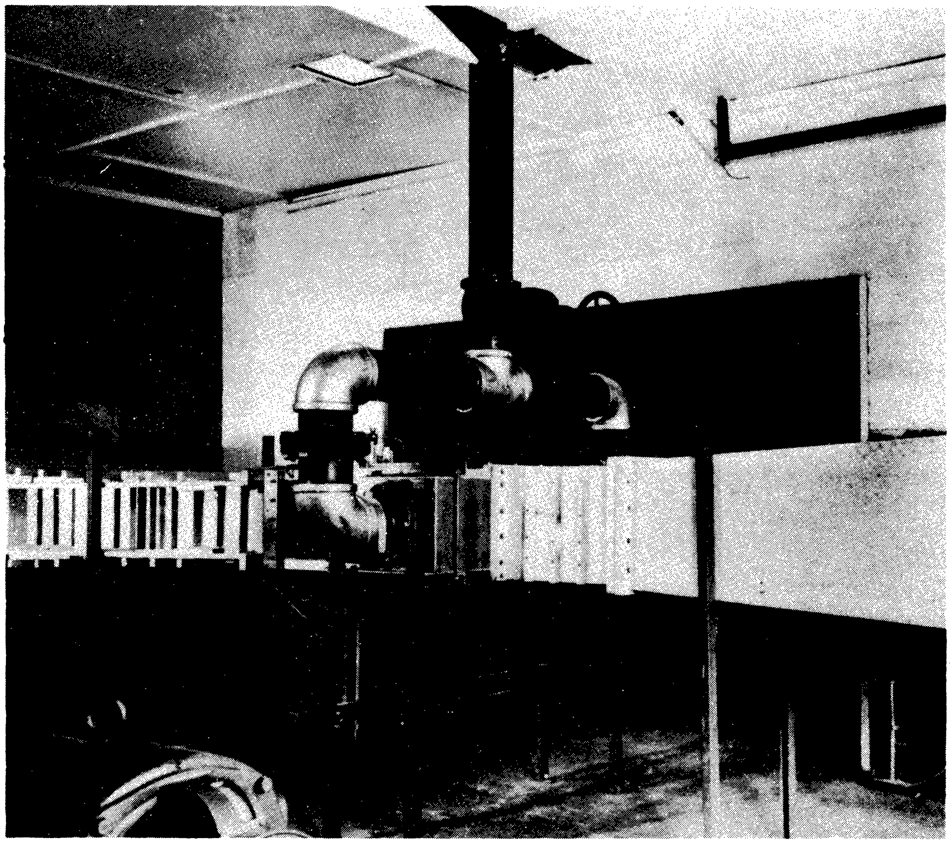

Fig. 7. Wind Tunnel

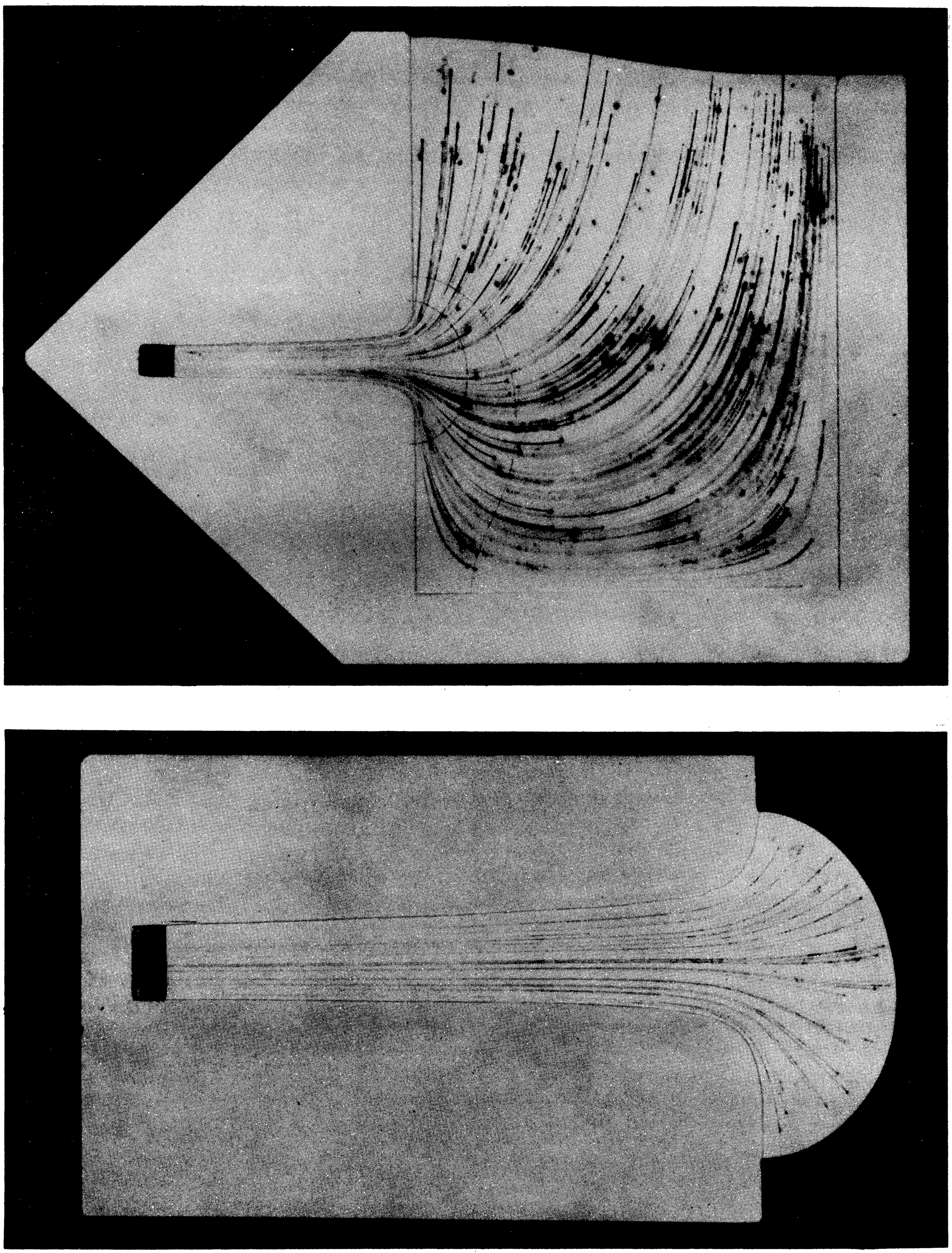

Fig. 8. Two-dimensional air streamlines for tunnel profile of Fig. 6. Streamlines obtained through use of fluid mapper by Professor A. D. Moore, Electrical Engineering Department, University of Michigan. See reference 2.

Test Section

The test section is 1 foot square and 3 feet long. All four sides are of 1/2-inch plexiglas braced by 1-1/2 by 1-1/2 by 1/8-inch aluminum angle iron.

Each of the four sides is provided with a window which serves as a mount for models and provides quick access. The side mounting windows are 7 by 15 inches, while the top and bottom dimensions are 6 by 15 inches.

Design of the Ejector

An ejector system has many advantages in an icing wind tunnel which can overshadow the relatively low efficiencies of such an arrangement. Such a system, with its associated high temperatures of the driving gas, prevents icing of the tunnel walls downstream of the ejector. Also, it eliminates any worries concerning ice particles impinging on fan blades. In our case, the source of driving air was already available and, by a minimum of piping, was readily adaptable to the tunnel.

A Rolls-Royce VI650-7 aircraft engine is used to drive a supercharger, which serves as the compressed air source to drive the ejector.

A simplified ejector analysis proved satisfactory and is as follows:* Writing an equation for conservation of momentum for the mixing process (see Fig. 9):

$$P_iA_i + \rho_iA_iV_i^2 + P_DA_D + \rho_DA_DV_D^2 = P_2A_2 + \rho_2A_2V_2^2 \quad , \qquad (10)$$

where P = static pressure, psia;

A = Area, ft^2;

ρ = density, slugs/ft^3;

V = velocity, ft/sec; and

subscripts

i = induced, D = driving, and 2 = after mixing.

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*A more detailed analysis appears in reference 3.

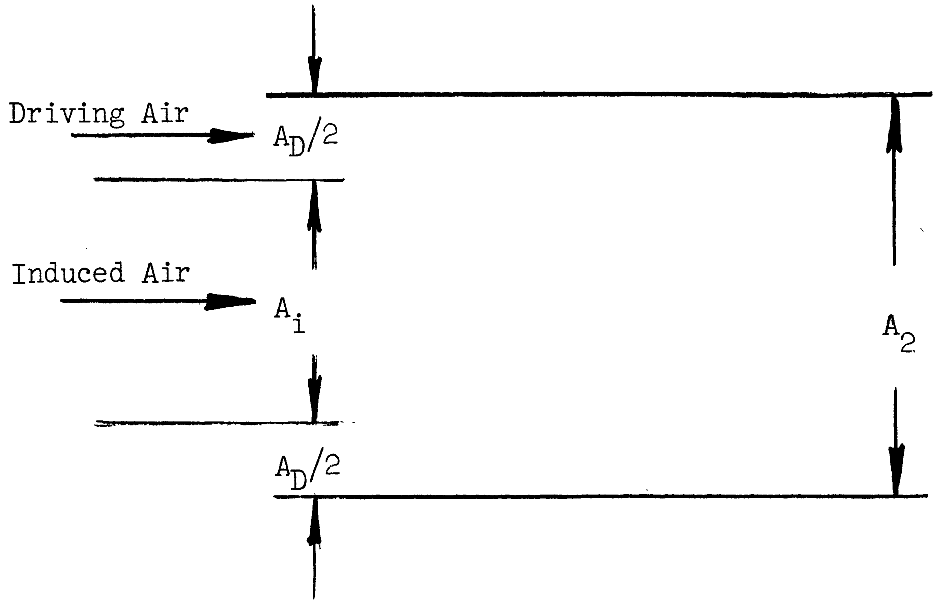


Fig. 9. System Used for Ejector Analysis

Making the following simplifying postulates:

$$\rho = \text{const.}$$

$$P_i = P_D = P_2$$

$$A_2 = A_i + A_D \quad ,$$

equation (10) then reduces to:

$$V_2^2 = \frac{A_i}{A_2} V_i^2 + \frac{A_D}{A_2} V_D^2 \quad . \tag{11}$$

Introducing the losses of the tunnel, we may write the energy equation as:

$$P_i + \frac{\rho}{2} V_i^2 + \Delta P_t = P_2 + \frac{\rho}{2} V_2^2 \quad ,$$

where ΔP_t = losses of the tunnel.

This reduces to the form,

$$\Delta P_t = \frac{\rho}{2} (V_2^2 - V_i^2) \quad . \tag{12}$$

Substitution from equation (11) yields the relation

$$\Delta P_t = \frac{\rho}{2} \frac{A_D}{A_2} (V_D^2 - V_i^2) \quad .$$

In general:

$$V_D^2 >> V_i^2 \quad ,$$

so

$$\Delta P_t \cong \frac{\rho A_D V_D^2}{2A_2} \cong \frac{1}{2} \frac{M_2}{A_2} V_D \quad . \tag{13}$$

Knolwedge of the supercharger capabilities (mass flow vs. delivery pressure) for various operating conditions then permits an evaluation of the ΔP_t that could be obtained, (ρ is taken as constant for these calculations). A curve of allowable tunnel losses is shown in Fig. 10 plotted against flow characteristics with the rpm taken as 2150 (low blower) and the ratio of ejector area to test section area serving as a parameter ($A_2 \cong A_i$). Much higher outputs from the supercharger are available, but the simplified ejector analysis used would be inappropriate when pressure ratios beyond critical are used across the ejector blocks. An estimate of the tunnel losses[4] will then determine the dynamic head at which the tunnel may operate.

It was assumed that the losses would be of the order of 14 inches H_2O when operating at design velocity. This value is rather high for a tunnel, but was utilized because space limitations dictated diffusing to only four times the area of the test section. Also, the ejector involves a relatively great length of minimum area which, of course, yields high frictional losses. The above losses were accepted, since the output of the Rolls-Royce was more than sufficient for the tunnel.

Assuming these losses to be those actually attained and that the losses vary with the square of the velocity, Fig. 10 may be used to predict the tunnel velocity for various driving flows. Such a plot is shown in

CALCULATED EJECTOR CAPABILITIES FOR VARIOUS AREA RATIOS

ENGINE RPM = 2150 (LOW BLOWER)

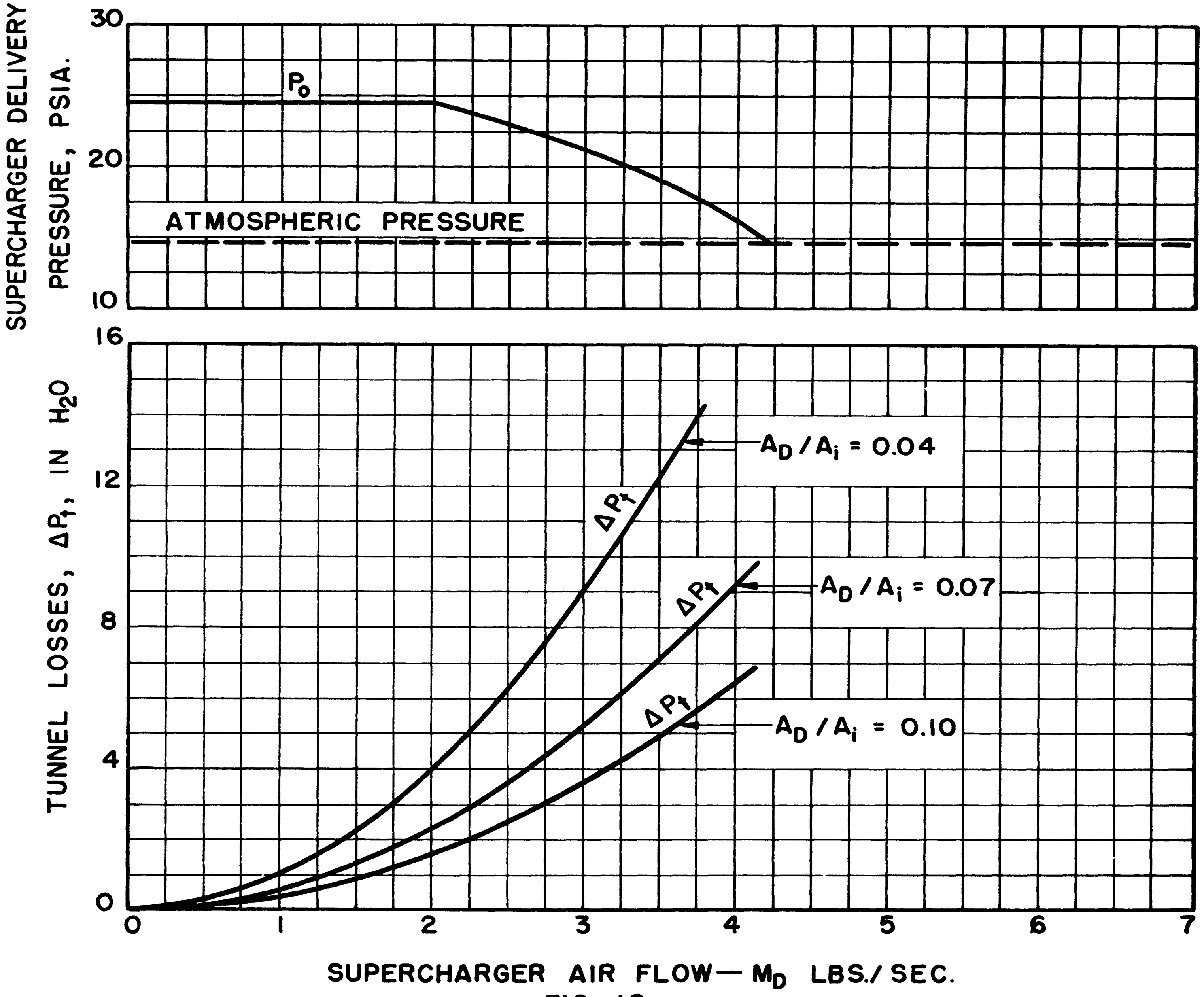


FIG. 10

Fig. 11, and it can be seen that tunnel velocity varies linearly with ejector mass flow for constant engine rpm.

The supercharger outlet air is fed into a 12-inch pipe. From this pipe 6-inch piping leads through a gate valve to the ejector reservoir and nozzle blocks (shown in Fig. 7). The ejector air is then introduced on the two opposite sides of the tunnel, where the induced air area is still one foot square.

A schematic diagram of the ejector system is shown in Fig. 12. The nozzle blocks are made of mahogany and coated with spar varnish, while the reservoir is of 1/4-inch aluminum plate. The upstream nozzle block can be rotated to vary the ejector opening from 1/2 inch to zero. At the larger opening the flow enters parallel to the tunnel centerline. When it is fully closed, there is a 2-1/2-degree angle of divergence from the centerline.

Side injection rather than center injection for the driving air was used, since it afforded an easier means of varying the exit area. This has the advantage of stripping the boundary layer, but on the other hand, produces large frictional effects, since the high velocity is next to the wall.

From equation (13) it might be noted that smaller A_D with the consequent higher V_D is favorable. This requires higher ejector driving pressures for the same flow.

Quite commonly in ejectors, constant-area mixing lengths of 5 to 10 diameters are used. For this tunnel application, it was thought that immediate diffusing would give higher mass ratios as well as benefit by shortening the overall length of the tunnel. However, provision has been made to introduce a constant-area mixing length if test results so dictate. The results obtained to date are inconclusive in this regard.

Currently, a second Rolls-Royce engine is being installed in connection with other research work. The second engine can be run in series or parallel with the first. Some thought has been given to running these in parallel to drive the ejector. If parallel operation were used, and A_D varied so as to keep V_D essentially constant, equation (13) would indicate that ΔP_t would be doubled. The tunnel velocity would thus be increased by a factor of $\sqrt{2}$.

Another interesting possibility lies in adding fuel to the Rolls-Royce air and then burning prior to the ejector. It appears that the tunnel could then be driven at sonic speed.

CALCULATED TUNNEL VELOCITY VS. MASS FLOW OF EJECTOR FOR CONSTANT ENGINE RPM (2150 LOW BLOWER)

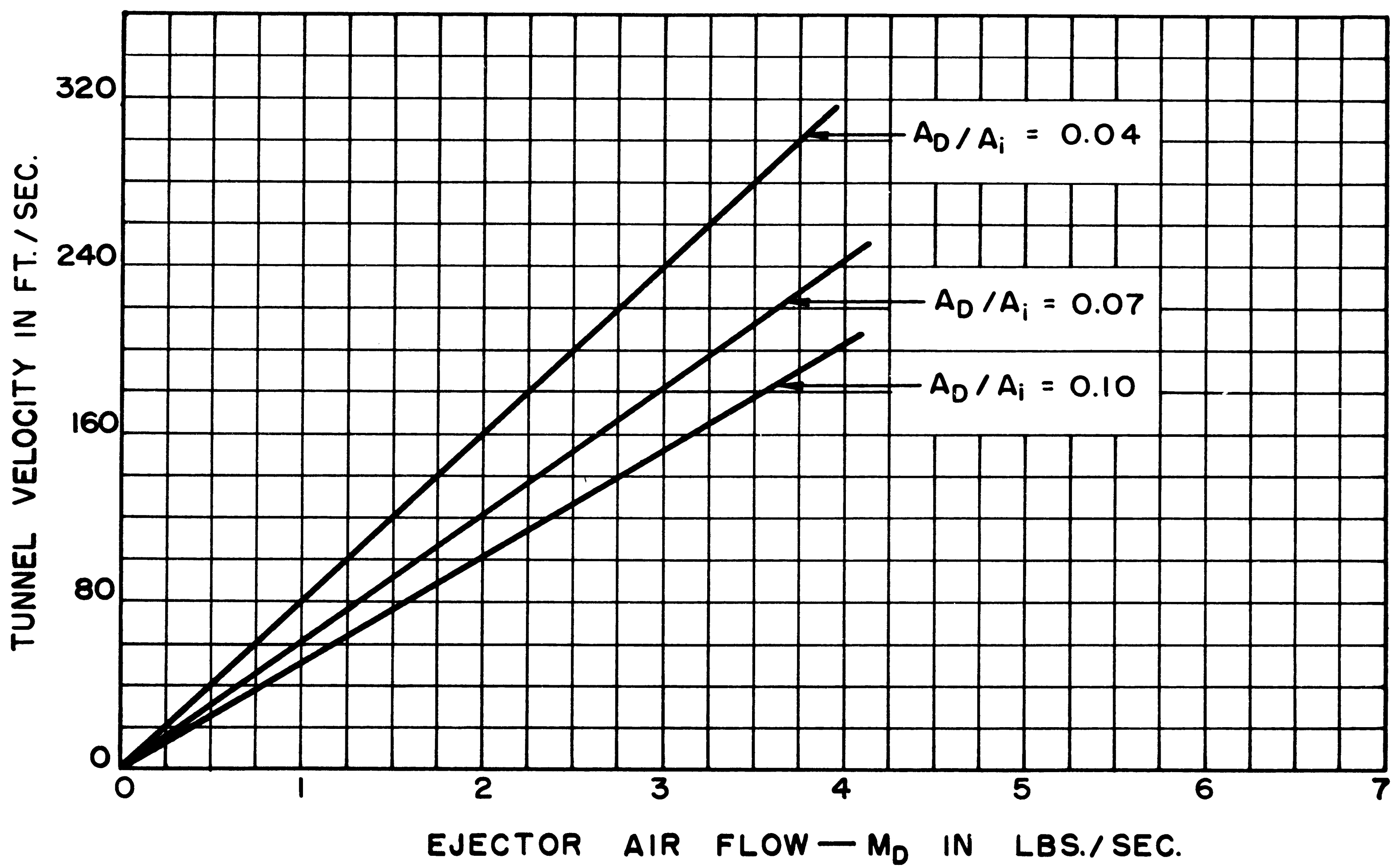
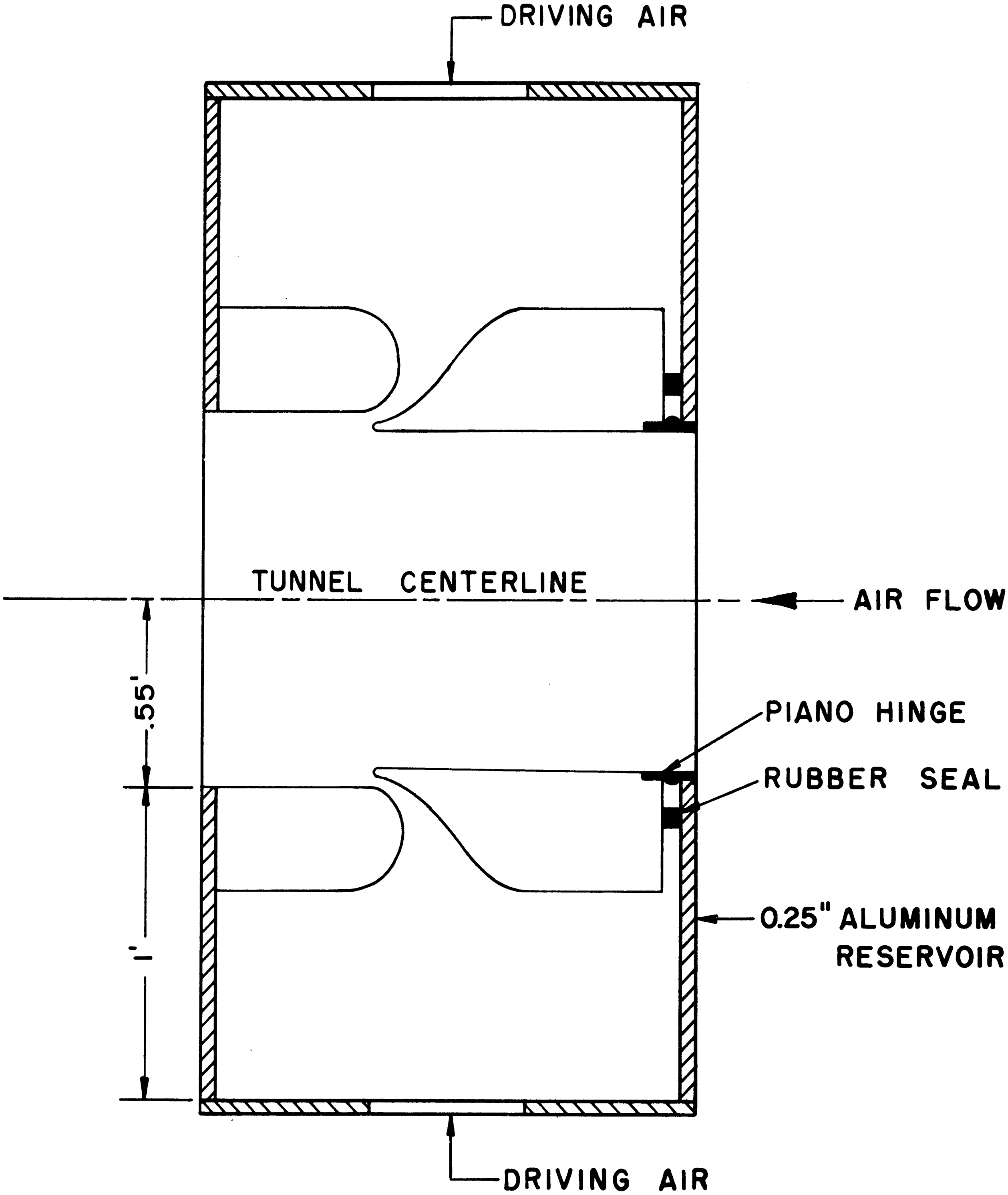


FIG. 11



EJECTOR SYSTEM

FIG. 12

Fig. 13 is a plot, obtained experimentally, of the tunnel velocity vs. Rolls-Royce supercharger rpm for a constant area ratio (A_D/A_i) of 0.0313. The supercharger gear ratios are 5.8 for low blower and 7.35 for higher blower. A calculated curve is also included for operation with two engines. The latter would surpass the structural capabilities of the present tunnel without additional reinforcing.

Fig. 14 is an experimental curve showing the variation of mass ratio (ratio of induced air to driving air) with tunnel velocity for one area ratio. A smaller A_D should give higher mass ratios.

Transition Section

Immediately following the ejector is a two-foot long transition section which picks up the constant total diffusing angle of 5 degrees. All four sides diverge, and the small angle of diffusion was chosen so as to insure against separation.

The transition section is made of 1/8-inch plywood (reinforced).

Diffuser

The diffuser maintains a constant angle of divergence of 5 degrees for 10 feet where the exit becomes 4 feet square. Hence, the discharge velocity is 1/4 of test-section velocity and 1/16 of the test-section kinetic energy is directly lost. As mentioned earlier, the transition section and diffuser also serve as the ejector mixing length.

The diffuser is made of 1/4-inch plywood.

The transition and diffuser appear to the right in Fig. 7.

Instrumentation

Instrumentation is as yet incomplete.

Two rotameters, each with a pressure and temperature gauge, have been installed to measure the air and water flow rates to the DeVilbiss nozzles. Other pressure and temperature gauges measure ejector-reservoir pressure and temperature, outisde-air temperature, and the temperature at the tunnel inlet. Six U-tube manometers are provided to measure pressure distributions either in the tunnel or on a model. One of these manometers indicates static pressure in the test section and has been calibrated against dynamic head.

ROLLS-ROYCE SUPERCHARGER RPM VS WIND-TUNNEL VELOCITY

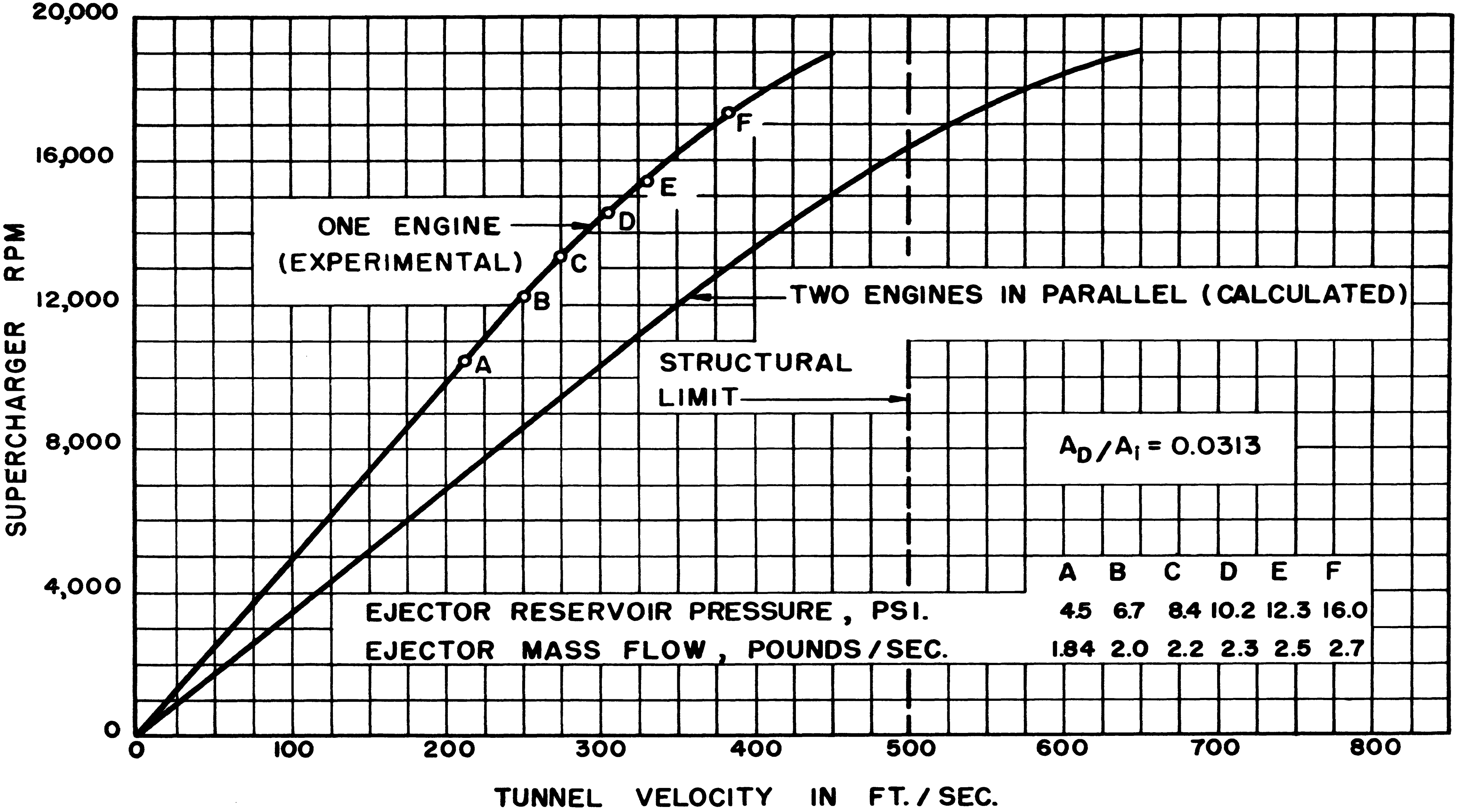


FIG. 13

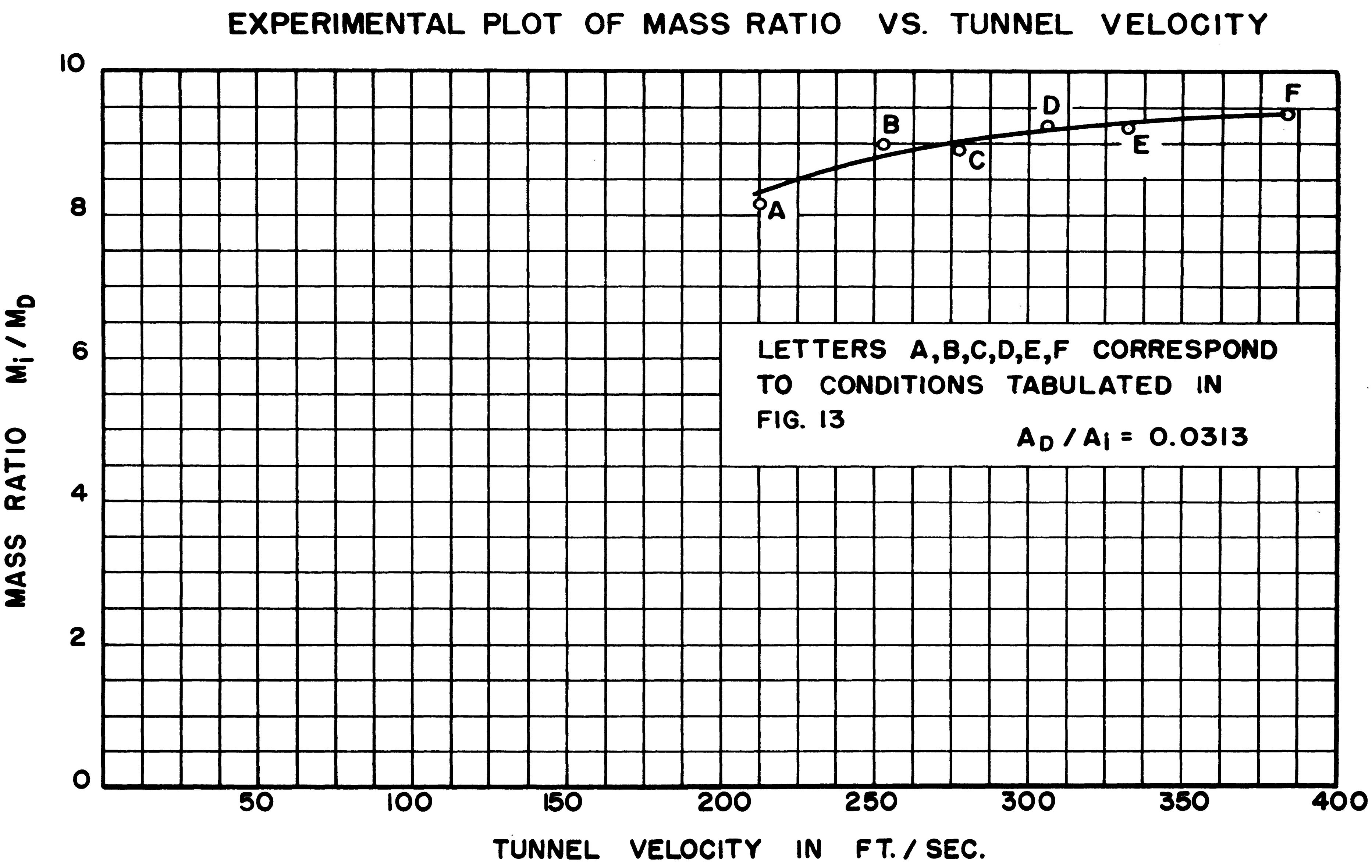

EXPERIMENTAL PLOT OF MASS RATIO VS. TUNNEL VELOCITY
MASS RATIO M_i / M_D
0
2
4
6
8
10
50
100
150
200
250
300
350
400
TUNNEL VELOCITY IN FT. / SEC.
A
B
C
D
E
F
LETTERS A,B,C,D,E,F CORRESPOND TO CONDITIONS TABULATED IN FIG. 13
$A_D / A_i = 0.0313$

FIG. 14

As mentioned earlier, the equipment using a light-scattering technique for drop-size measurement is in the process of installation.

Other instrumentation will be incorporated as tests are conceived and run.

TUNNEL HUMIDITY

If the air at the tunnel inlet is saturated, the expansion through the test section will result in supersaturation with subsequent condensation on the model, tunnel walls, water drops, and any ice nuclei present. Condensation on models has been observed at both the Mt. Washington facility and the NACA icing tunnel at Cleveland.

Fig. 15 shows the required humidity at the tunnel inlet to achieve saturation at the test section. Ypsilanti weather data show that most of the time the winter humidity is less than 60 per cent. A study of spray evaporation[5] shows that at the temperatures where icing studies are made, the time available for spray evaporation (i.e., time from spray nozzle exit to tunnel test section) is insufficient to raise the humidity appreciably. On the basis of Fig. 15, the Ypsilanti weather data, and the spray evaporation study, it has been concluded that supersaturation will not present a problem in the present facility.

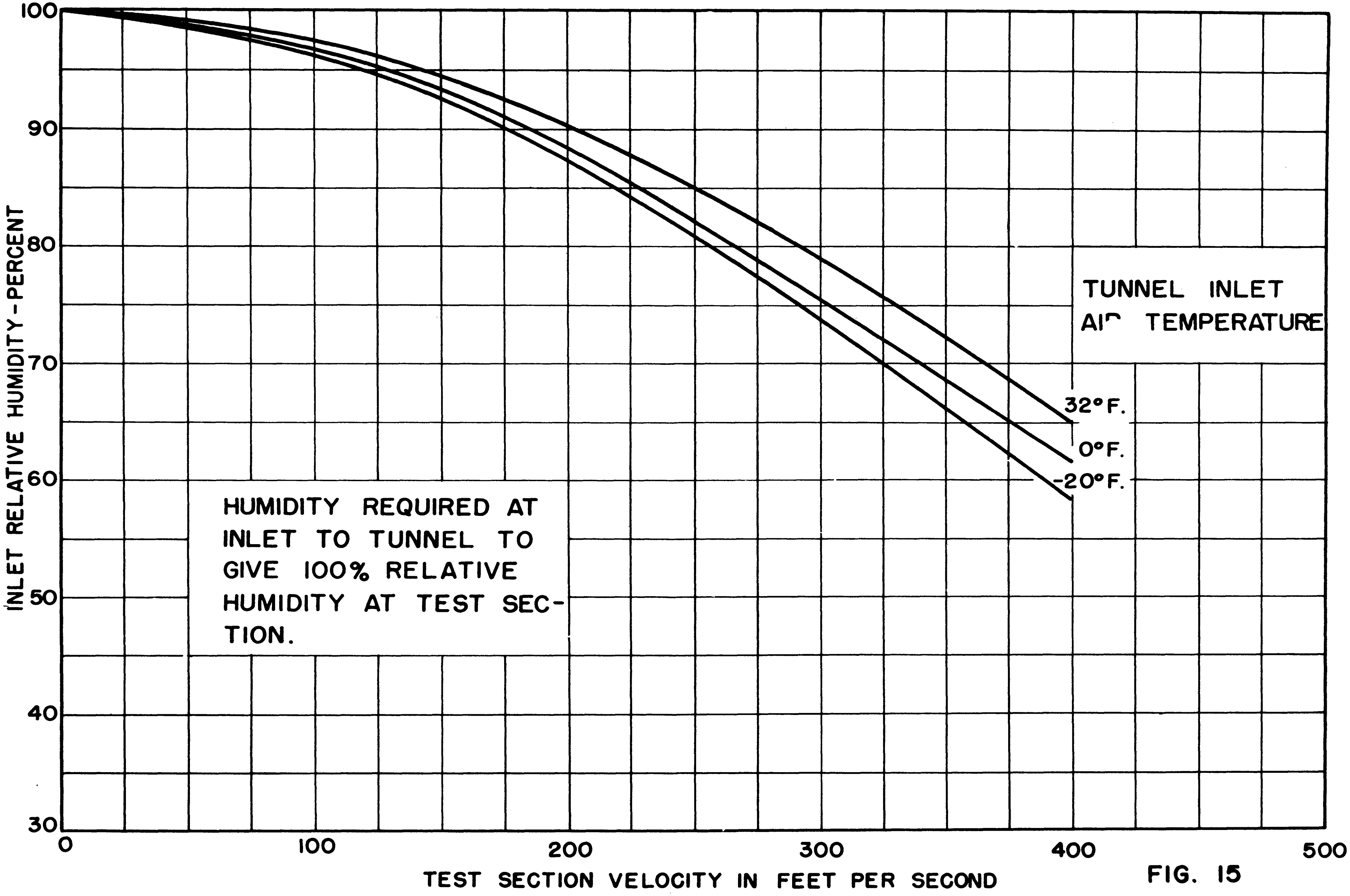

100
90
80
70
60
50
40
30
INLET RELATIVE HUMIDITY-PERCENT
0
100
200
300
400
500
TEST SECTION VELOCITY IN FEET PER SECOND
TUNNEL INLET
AIR TEMPERATURE
32°F.
0°F.
-20°F.
HUMIDITY REQUIRED AT INLET TO TUNNEL TO GIVE 100% RELATIVE HUMIDITY AT TEST SECTION.

FIG. 15

THE FREEZEOUT PROBLEM

Because of the summer weather, no significant tests relative to the freezeout problem could be made.

A literature study and conversations with such groups as Project Cirrus, National Research Council of Canada, and the National Advisory Committee for Aeronautics have indicated that freezeout above 0°F should not represent a serious problem. The Canadians* reported that when the air and water entering the pneumatic nozzles was properly preheated, freezeout was avoided. The NACA has related similar experience. These results are in agreement with the hypotheses regarding ice nuclei and spontaneous freezing advanced by Project Cirrus.

Pending winter operation, no further comments regarding freezeout can be made at this time.

*Conversations with J. L. Orr and Dr. Rush of CNRC.

PRELIMINARY RESULTS

The design velocity of 300 ft/sec has easily been met and surpassed. Structural considerations have limited the maximum velocity to 384 ft/sec, although a few planned modifications will probably allow, 450 ft/sec, the expected maximum from one engine (Fig. 11).

A test-section velocity profile taken at a cross section one foot from the entrance and on the centerline is shown in Fig. 16. A more complete survey is yet to be made.

In an attempt to assess the homogeniety of spray across the test section, liquid propane was expanded in a 1/2-inch pipe which spanned the test section on the centerline. The pressure on the propane was adjusted so as to give a temperature of approximately -15°F in the pipe. The tunnel was operated with the sprays on and a layer of ice allowed to form on the upstream side of the pipe. The ice pattern appeared quite regular along the pipe, with ice forming very close to the side walls. One such run is shown in Fig. 17.

TEST-SECTION VELOCITY PROFILE FOR ONE OPERATING CONDITION

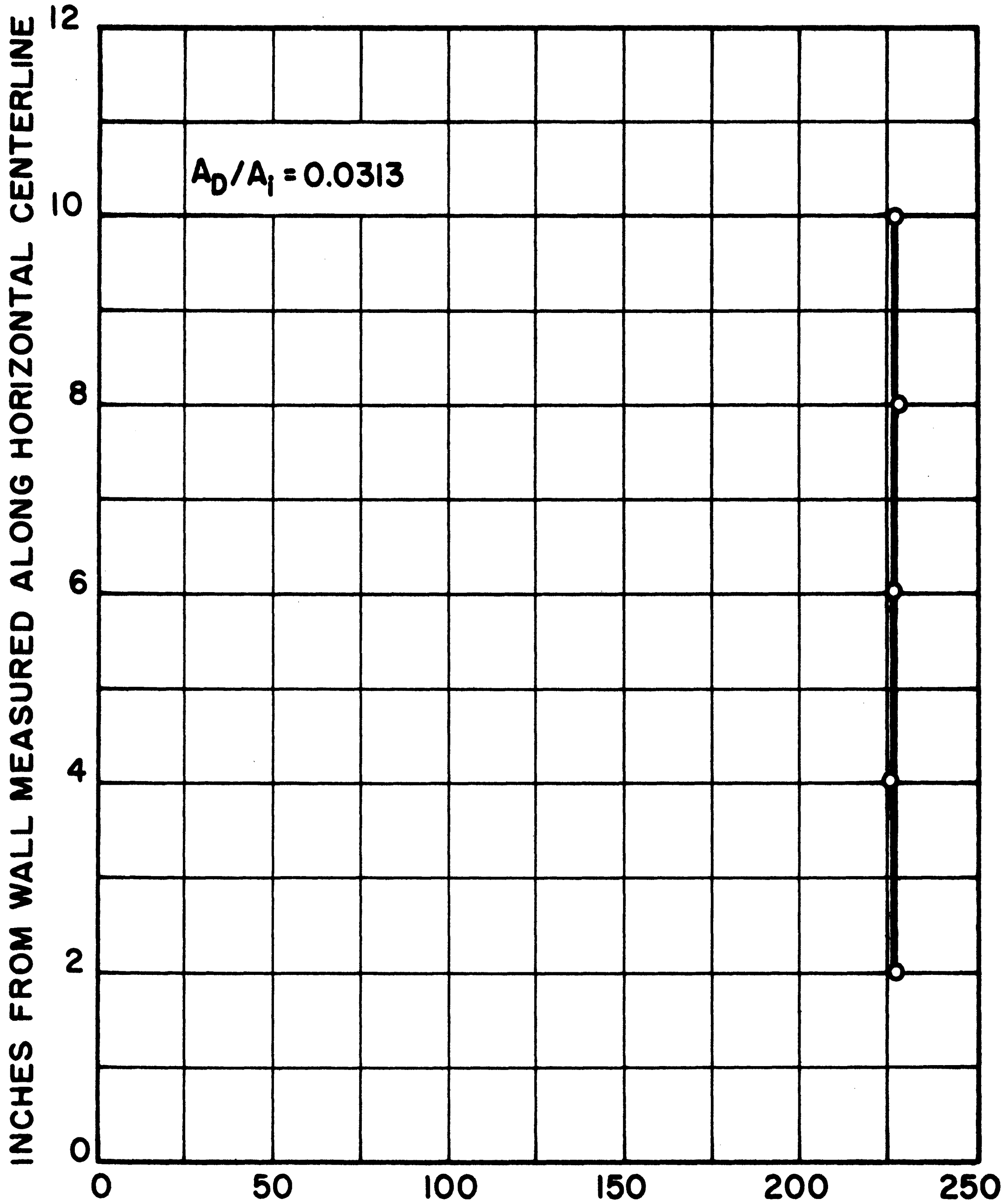


FIG. 16

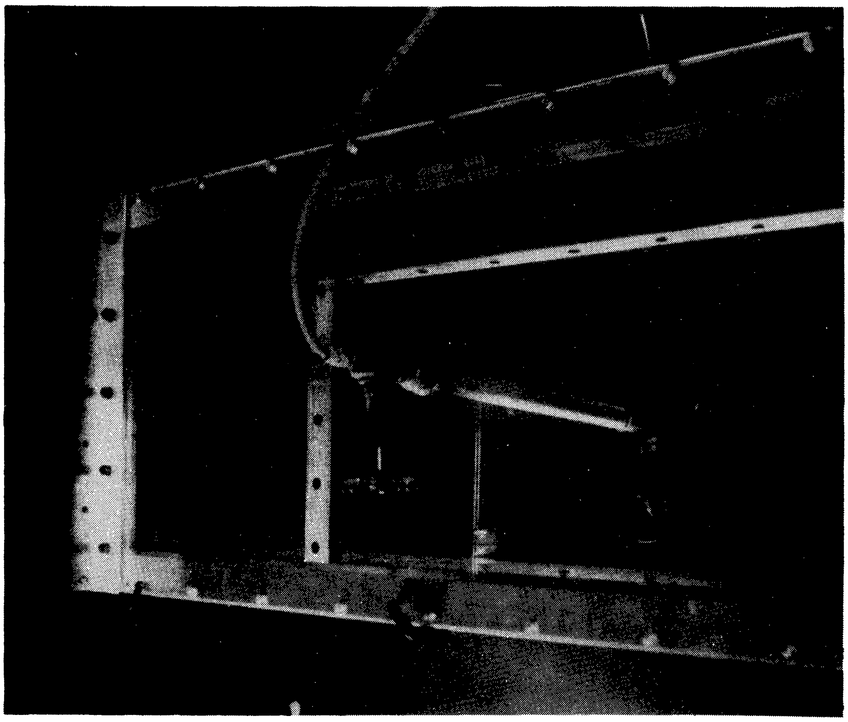


Fig. 17. Photograph of ice accretion on a refrigerated pipe placed across test section.

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