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PROJECT TUBEFLIGHT

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FACILITY T-3

A WIND TUNNEL FOR TUBEFLIGHT EXPERIMENTATION

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by

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ABSTRACT

The Rensselaer wind tunnel facility T-3 has been developed for the purpose of measuring the forces and moments on air-cushion-supported tube vehicles.

These measurements are expected to provide the necessary information for a comparative evaluation of various support systems and for a determination of the stability and control characteristics of tubeflight vehicles.

LIST OF SYMBOLS

Symbols

u_i	flow velocity (ft/sec)
ρ	air density
q_i	dynamic pressure (#/sq.ft.)
C_i	loss coefficient
F_i	frictional force
C_{fi}	friction coefficient
D_i	local section diameter
α_i	cone angle
N_i	local section area ratio
ℓ_i	axial length
L	length of model
d	diameter of model

Subscripts

i	general subscript (i = 0,1,2)
0	test section
1	entrance bellmouth
2	diffuser

INTRODUCTION

The Rensselaer Polytechnic Institute T-3 Facility is an open-circuit indraft type wind tunnel designed for the purpose of measuring aerodynamic forces and moments on air-cushion-supported tube vehicles and vehicle components under simulated flight conditions.

The facility consists of an entrance bellmouth, a test section, a wide-angle diffuser, an industrial exhauster at the diffuser end to provide the power required for operating the facility, and the aerodynamic-force measuring system.

The test section is circular in cross-section and 1 ft in diameter. These parameters are the same as the corresponding parameters of the tube-vehicle testing facility T-2 in which vehicles are tested in free flight.

Anticipated test section speeds -- up to about 200 ft/sec -- are the same as those expected in the flight tests to be conducted in T-2.

The test section features a "clamshell" arrangement which facilitates model handling and mounting.

The wide-angle (15°) diffuser represents a deviation from conventional tunnels of this type. Its use is dictated by the space limitations of the selected location.

Due to the nature of the guideway the primary flight modes of tubeflight vehicles are symmetric. The forces and moment in a symmetric flight mode are the lift, drag and pitching moment. There may be in addition a roll torque due to the presence of lift force components off the plane of symmetry.

The aerodynamic-force measuring system of T-3 has been designed to measure the three primary components and the roll torque in a symmetric flight

The force measuring system consists of a horizontal plate support

columns. The aerodynamic forces on the model are transmitted to through struts. The tensile or compressive forces on the supporting columns are measured by a system of piezo-electric force transducers, and the aerodynamic forces and moments on the model are calculated using these measured values.

The method of force measurement adopted here results in the isolation of the model mounting system from the force measuring system and affords a degree of flexibility in choosing the appropriate number and size of struts for model mounting.

THE DESIGN OF TUNNEL COMPONENTS

The Entrance Section

The entrance section of T-3 has been designed to produce a throat flow-uniformity within 1%. The contour shape required to achieve this degree of uniformity was calculated by the method of Ref. 1. In that analysis the exact analogy between the magnetic field due to two coaxial and parallel coils carrying an electric current and the velocity field due to two corresponding ring vortices was used to obtain a family of contraction shapes with a prescribed degree of uniformity at the throat.

The entrance section itself was fabricated by welding strips of steel bent to the design contour shape to give a twelve sided polygonal throat. A square flange with a central hole of the same diameter as the test section was welded in place at the throat. The inside of the throat was then epoxied to give a smooth transition to the test section.

The Test Section

Tunnels of the indraft type normally have test-section lengths of only 1 to 1½ test-section diameters. The blockage ratio in such tunnels is much smaller than in T-3. Since power requirements call for a test-section length as short as possible, it was found necessary to know what minimum length of test section was required in order to have fully developed flow over the vehicle. The minimum effective test-section length is the length of that space within which a model could be moved axially without undergoing significant changes in pressure distribution.

This minimum-effective-length question was answered by an experimental study in which the pressure distribution over a model with the same general features as a typical tube-flight vehicle was obtained with the model at various distances from the entrance to a test section.

The experiment devised for this purpose utilized the existing facilities of the Rensselaer Experimental Fluid Dynamics Laboratory. A schematic of the experiment is shown in Fig. 1. The arrangement is in essence a model of the proposed tunnel but not to scale. The bellmouth, turned out of wood with the inside finished smooth, slips over a plexiglass tube, which serves as the "test section." The rest of the arrangement is part of the flow-measuring experimental setup used for undergraduate instruction at Rensselaer. The fan exhaust at the end of the long diffuser duct has a hand-operated valve which controls the mass flow rate through the system. The ratio of model diameter to tube diameter is in the range expected in the free-flight facility. The model (Fig. 2) consists of a plexiglass tube 10" long with two aluminum tangent-ogive nose cones at the ends. The overall length of the model is 15".

The static-pressure sensing taps are located as shown in Fig. 2. Polyvinyl tubes drawn through a central hole at the end of the aft nose cone connect the pressure sensing system to a manometer bank. The mass flow rate is measured using the venturi at the entrance to the diffuser duct upstream of the fan.

Runs were made at two mass flow rates to determine if the minimum length depended on the mass flow rate. The change of pressure distribution on the model as it was moved from a position with the nose at the entrance to one with the nose at 13" aft of the beginning of the test section is shown in Figs. 3a and 3b. It is seen that the change in pressure distribution with model position is very small in both cases (less than 8% at the lower mass flow rate and less than 5% when the mass flow rate is nearly doubled). This indicates that the minimum effective length is probably not affected by the mass flow rate to any significant extent.

In order to determine whether the ratio of test-section length to length of model had any effect on the minimum effective length, runs were also made with the model in another tube whose length was about one-half the length of the first one. The resulting pressure distribution is shown in Fig. 4. It is seen that the total scatter can be as high as 18%.

The ogive nose cone in the front was replaced by a blunt-shaped nose and the tests were repeated to investigate the possibility that the minimum effective length might depend on the shape of the nose. The results shown in Fig. 5 and Fig. 6 indicate little departure from the scatter distribution with the aluminum nose cone at the same mass flow rate.

From the above results it would appear that the ratio of model length to tube length is the significant parameter in answering the minimum-length question. The distance of the model from the entrance to the tube does not appreciably affect the pressure distribution over it so long as there is sufficient length of test section aft of the model.

Using the pressure distribution shown in Fig. 4 it is seen that the pressure changes that occur at points along the vehicle when the position of its nose is changed from the entrance to one and a half vehicle diameters aft of the entrance,are less than 9%. Tubeflight vehicles to be tested in T-3 are expected to have lengths of about 8 ft. The test-section length was fixed at 12 ft. This choice of length would allow for the model nose to be moved through about 1 ft from the entrance without undergoing any significant change in the pressure distribution over it.

Further, from Fig. 10, where the displacement thickness of the boundary layer at the entrance and exit stations are plotted as a function of test-section speed, it is seen that the displacement thickness is less than 4% of the tube radius in the range of test-section speeds anticipated. In view of the above, a test-section length of 12 ft seems adequate for the purpose of facility T-3.

The test section is fabricated from nominal 12" dia pipe, identical to that used in the T-2 facility. To facilitate model handling and mounting it was decided to have a "clamshell" arrangement. Previous experience with these pipes have indicated that they tend to open up when sectioned lengthwise. To prevent this, flanges were welded normal to the pipe axis at intervals along the span and the pipe heat-treated prior to sectioning.

The Diffuser

The role of the diffuser is to convert the kinetic energy of the entering flow into potential energy. Due to frictional losses in the tunnel components and to expansion losses in the diffuser, the recovery is never complete. A fan is provided at the diffuser exit to provide the static-pressure recovery.

In conventional tunnels a diffuser angle of 7^{o} is rarely exceeded. This value of the diffusion angle is found to minimize power requirements while at the same time keeping the pressure gradients encountered in the diffuser within bounds. In this case, as has already been noted, it was found that a diffuser angle of 15^{o} would be required to keep the overall length of the facility within the space limitations imposed by its location.

A number of studies of wide angle diffusers (Ref. 2 through 8) have indicated that the performance could be improved by the use of auxiliary devices like vanes, suction, steps etc. which counteract the effect of the adverse pressure gradients in the diffuser.

In view of the above and also of the fact that the displacement thickness at the entrance to the diffuser in the range of anticipated test-section speeds is small, it was decided to use a diffusion angle of 15° and to investigate the possibility of using auxiliary devices for the improvement of diffuser performance after the facility has been installed and calibrated.

The Balance System

The balance system of T-3 has been designed to measure the aerodynamic forces and moment in the plane of symmetry. In addition, provision has been made to measure the roll torque that might result due to the presence of aerodynamic lift forces off the plane of symmetry.

The system is located under the test section. A schematic of the arrangement is shown in Fig. 7. The aerodynamic forces and moments on the model are transferred through a system of struts to a "floating" horizontal flat plate. This plate has 1/4" dia holes stagger-punched 1/2" on centers covering its entire surface. By choosing the appropriate number and sizes of struts the model attitude and location in the test section can be altered. Three pin-ended columns form the vertical support for the floating plate. The supports for the columns are bolted to the floating plate at one end and to a "rigid" horizontal plate at the other end. The rigid plate is firmly bonded in a reinforced concrete pier.

The drag and thrust forces on the model are similarly transferred to a horizontal pin-ended column which is centrally located with respect to the two horizontal plates. This column is supported by two blocks,one of which is bolted to the punched plate and the other to the lower rigid plate.

Side force and yawing moment on the model are transferred to the rigid plate by two "dummy" columns.

INSTRUMENTATION

Several available systems were compared in the light of the following considerations:

a) system response and sensitivity in measuring incremental loads at any level in the range by appropriate cancellation of "tare" components;

b) instantaneous recording of all measured forces;

c) adaptiveness of system for both static and dynamic testing;

d) cost of system, and

e) isolation of model mounting system from force measuring system.

The instrumentation selected for the T-3 facility comprises a set of Kistler force transducers, Model 912. A schematic of the mounting is shown in Fig. 7. The load cell has centrally located mounting studs which thread into the two mounting surfaces which are flat. Fafnir rod end bearings form the rest of the pin-ended column. The transducers are rigid quartz cells which have as an output an electrostatic charge signal proportional to the load applied. This output is fed into a Kistler charge amplifier No. 503 through low-noise cables. The output from the charge amplifier is recorded on an oscilloscope and/or oscillograph. The transducers in the mounted position have a nominal natural frequency of 70KC and a resolution of 0.002 lbs in the range of operation of 500 lbs tension to 5000 lbs compression.

ESTIMATE OF POWER REQUIREMENTS

The power required to operate the facility at a given test-section speed is directly proportional to the sum of the static pressure losses in the circuit. The static pressure losses are best described in terms of a loss coefficient, C_i,

$$C_i = 2\,\frac{(\text{loss/cross section})}{q_o} \qquad (1)$$

Entrance Section Losses

The losses in this section are due to skin friction on the walls. The frictional force on the walls is usually expressed in terms of the frictional force on an equivalent flat plate

$$F_1 = \int_0^{\ell_1} \frac{1}{2} \rho u_1^2 C_{f_1} (\pi D_1)\, d\ell$$

Since the continuity condition requires

$$u_i D_i^2 = \text{constant} \qquad (2)$$

The loss coefficient, C_1, is given by

$$C_1 = 2 D_o^4 \int_0^{\ell_1} C_{f_1} \frac{d\ell}{D_1^5} \qquad (3)$$

In the range of anticipated Reynolds numbers there is no significant variation in the value of the frictional coefficient over the length of the tunnel. Thus

$$C_{fi} = C_{fo} = \text{constant} \qquad (4)$$

Further, if the entrance section is assumed to be conical, Equation (3) reduces to

$$C_1 = \frac{C_{fo}}{4 \sin \frac{\alpha_1}{2}} \left[1 - \frac{1}{N_1^2} \right] \qquad (5)$$

where $N_1 = \dfrac{\text{Bellmouth entrance area}}{\text{Test section area}}$

Test Section Losses

The losses due to skin friction on the walls can be obtained from Equation (3). The flow velocity, u_{o_m}, in the annulus between the model and the tunnel wall is higher than the test-section speed, u_o. The loss coefficient,

C_{fm}, in the portion of the test section occupied by the model is given by

$$C_{fm} = \frac{2L}{D_o} C_{fo} \left(\frac{u_{om}}{u_o} \right)^2 \qquad (6)$$

The loss coefficient C_{fs} due to skin friction on the walls of the portion of the test section free of the model is given by

$$C_{fs} = \frac{2(\ell_o - L)}{D_o} C_{fo} \qquad (7)$$

The losses in the test section arising on account of the drag of the model are expressed in terms of the loss coefficient, C_{om}, where

$$C_{om} = \frac{C_D}{2} \left(\frac{d}{D_o} \right)^2 \qquad (8)$$

The drag coefficient, C_D, of the model is a function of the Reynolds number, of the blockage ratio and of the ratio between the length of model and the diameter of the tube. For purposes of this estimation the drag coefficient was obtained from Ref. 9.

Diffuser Losses

The losses in the diffuser are due to (a) skin friction on walls, (b) expansion losses, (c) kinetic energy losses at exit. Assuming the diffuser to be conical of cone angle, α_2, Equation (3) can be used to obtain the loss coefficient, C_2, for this portion of the circuit.

$$C_2 = \frac{C_{fo}}{4 \sin \frac{\alpha_2}{2}} \left[1 - \frac{1}{N_2^2} \right] + \frac{1}{2} \left[1 - \frac{1}{N_2} \right]^2 \sin \alpha_2 + \frac{1}{2N_2^2}$$

Overall Losses

The total loss coefficient, C, is the sum of the loss coefficients, C_i,

$$C = C_1 + C_{fm} + C_{fs} + C_2 + C_{om} \qquad (9)$$

The horsepower required is obtained from

$$HP_R = \left[\pi \rho U_o^3 D_o^2 \right] \frac{C}{2200} \tag{10}$$

The power required as a function of test-section velocity for the selected tunnel dimensions were obtained using equations (5) through (10).

The results are shown in Fig. 8 and Fig. 9.

Fig. 8 shows the relative magnitudes of the power required due to the drag on the model and the power required due to losses in the various parts of the circuit. Throughout the range of test-section speeds considered the losses due to the presence of the model account for a significant portion of the power required. This represents a deviation from conventional tunnels, where the losses due to the presence of the model are small compared to the losses in other parts of the circuit.

In Fig. 9 the total power required for two values of length of test section to vehicle diameter ratio is shown for a given blockage ratio. There is a 15% increase in power requirement when the length of the test section is increased from 9 ft to 12 ft for the given blockage ratio of 1.5.

It is seen from Fig. 9 that for the selected test-section dimensions a power requirement of about 55 HP would be needed for the simulation of vehicle speeds up to 300 ft/sec.

The possibility of using vane-axial fan units was investigated. There were no units available that would give the required pressure rise at the ass flow rate corresponding to a test-section speed of 300 ft/sec.

A comparison of available industrial exhausters showed that the Buffalo forge size 50AW or 55AW unit would give the necessary static-pressure recovery.

PRELIMINARY CALIBRATION

Early in the initial design of T-3 it was decided to calibrate the facility in two steps. The first calibration would be for the purposes of evaluating the overall concepts of the design and could be conducted at relatively low test-section velocities. The second phase of the calibration would be directed at a determination of the speed-power required spectrum. A report on the first phase of the overall calibration follows.

The power supply chosen for the low-speed study was a surplus Naval Troller vane-axial fan. This fan is driven by an integral two-speed motor which has a maximum output of 2.5 HP and provides a 5000 cfm maximum flow rate. This fan bolts directly onto the exit flange of the diffuser. The diffuser was designed so that with the addition of a simple adapter to the exit flange a 60 HP Buffalo industrial exhauster can be installed as the tunnel power supply. The tunnel power supply was located in an existing test cell to minimize acoustical noise. Photographs of the facility including a typical Tubeflight model installed in the test section are presented as Figures 11a, 11b.

An undesirable affect present during the testing of Tubeflight vehicles in wind tunnels is due to the presence of a boundary layer along the test section wall. This boundary layer effectively reduces the test section diameter and it can, if large, generate a serious interaction with the flow past the vehicle. In constructing this facility precautions have been taken (e.g. contouring and smoothing of all transverse joints) in an attempt to minimize the boundary layer growth.

Velocity profiles, taken one foot downstream of the test section at test-section speeds of 81 and 122 ft/sec, are shown in Figs. 12 and 13. The boundary layer displacement thickness, calculated from these profiles, is in fair agreement with predicted results.

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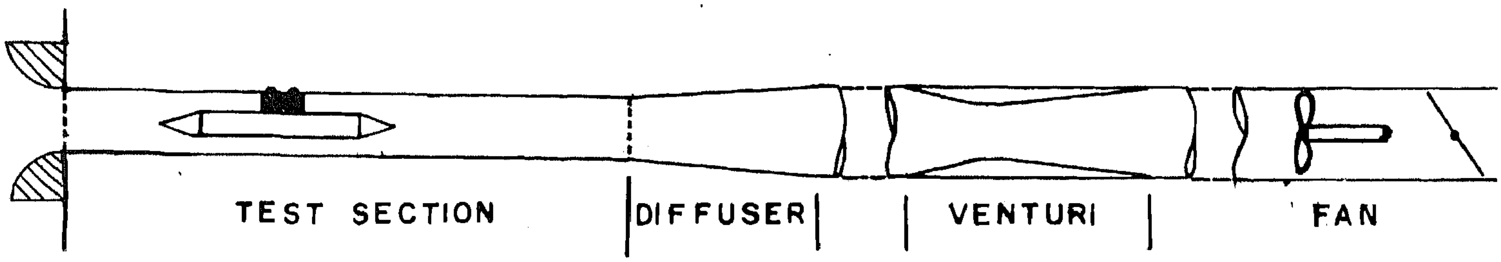


FIG. 1. Test-Rig for Pressure Distribution Studies

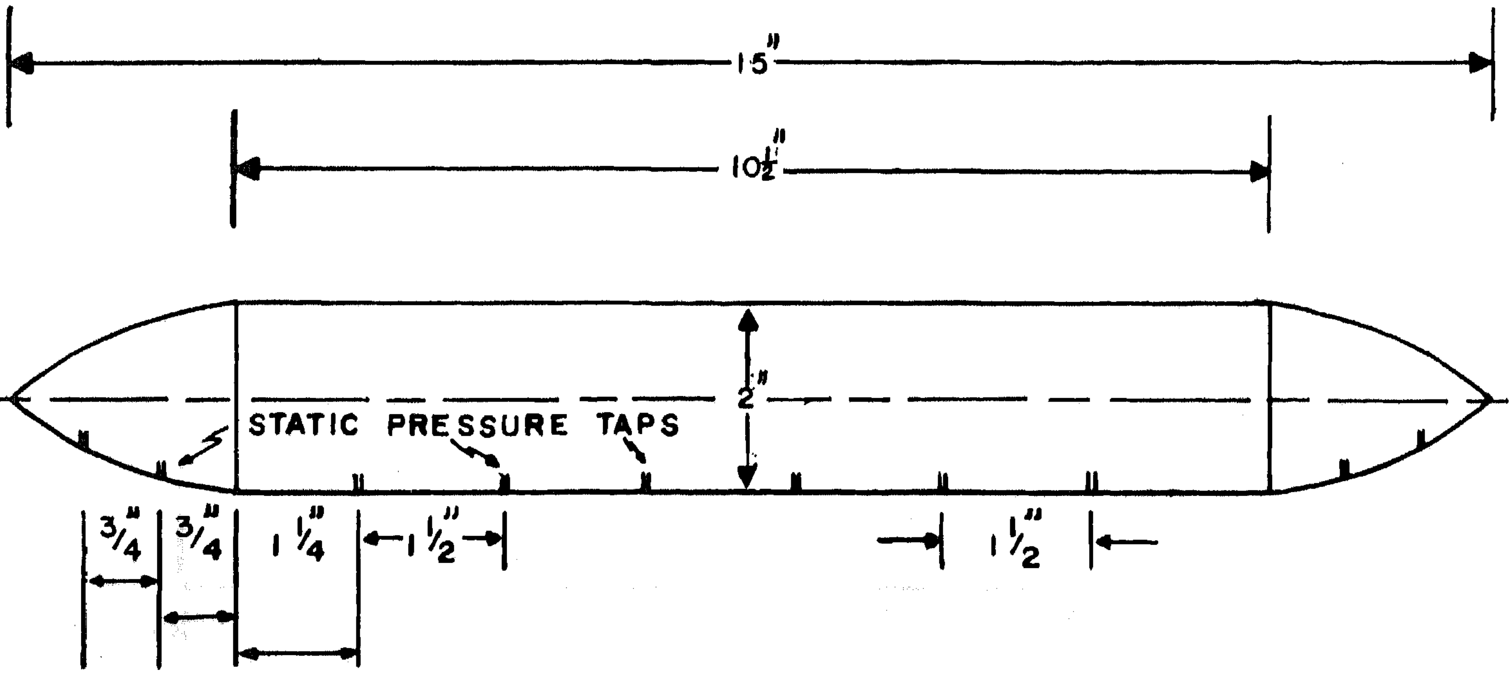


FIG. 2. Pressure Distribution Model

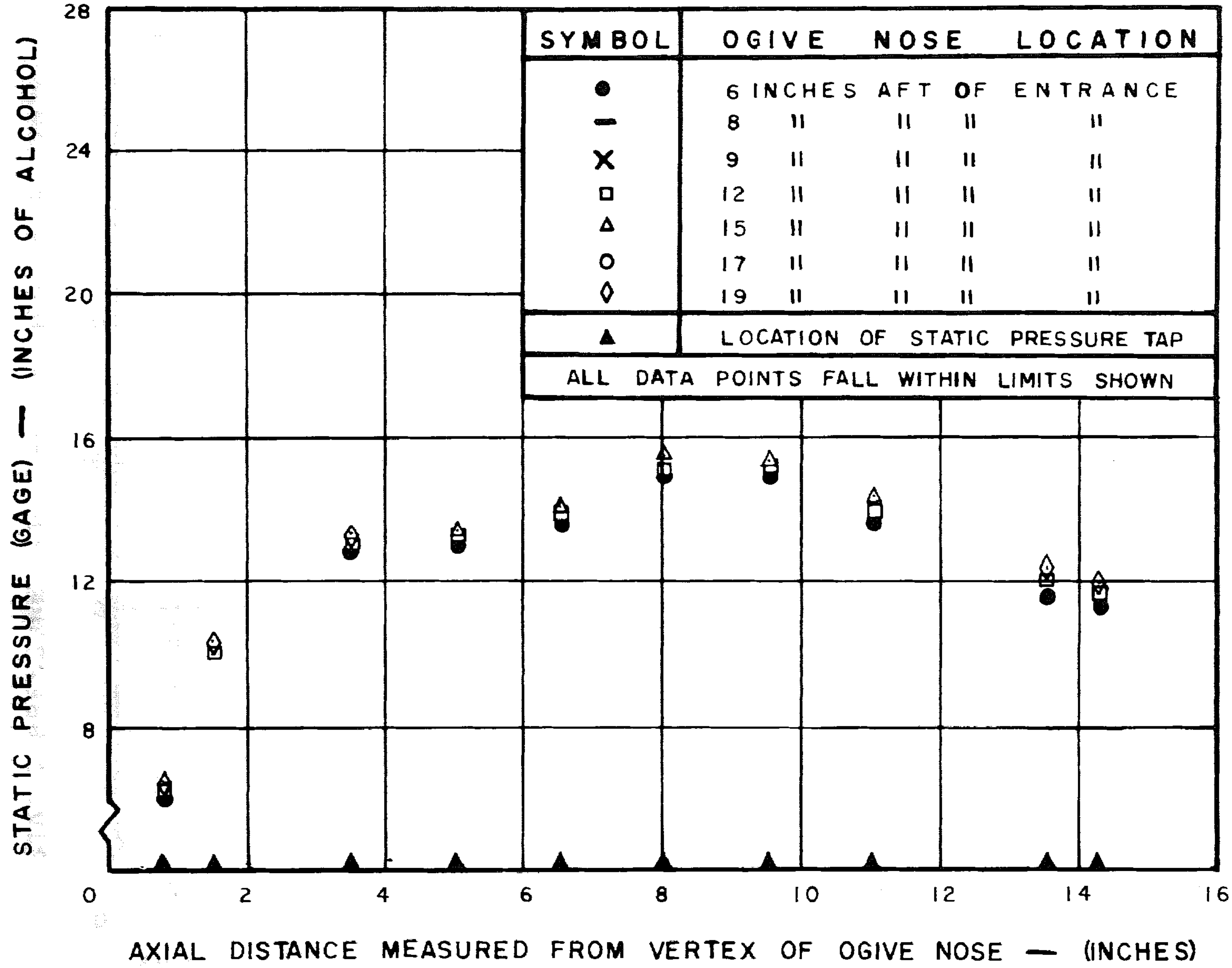


FIG. 3a. Pressure Distribution (Ogive Nose)
Test Section Length = 54 inches
Flow Rate = 600 cfm

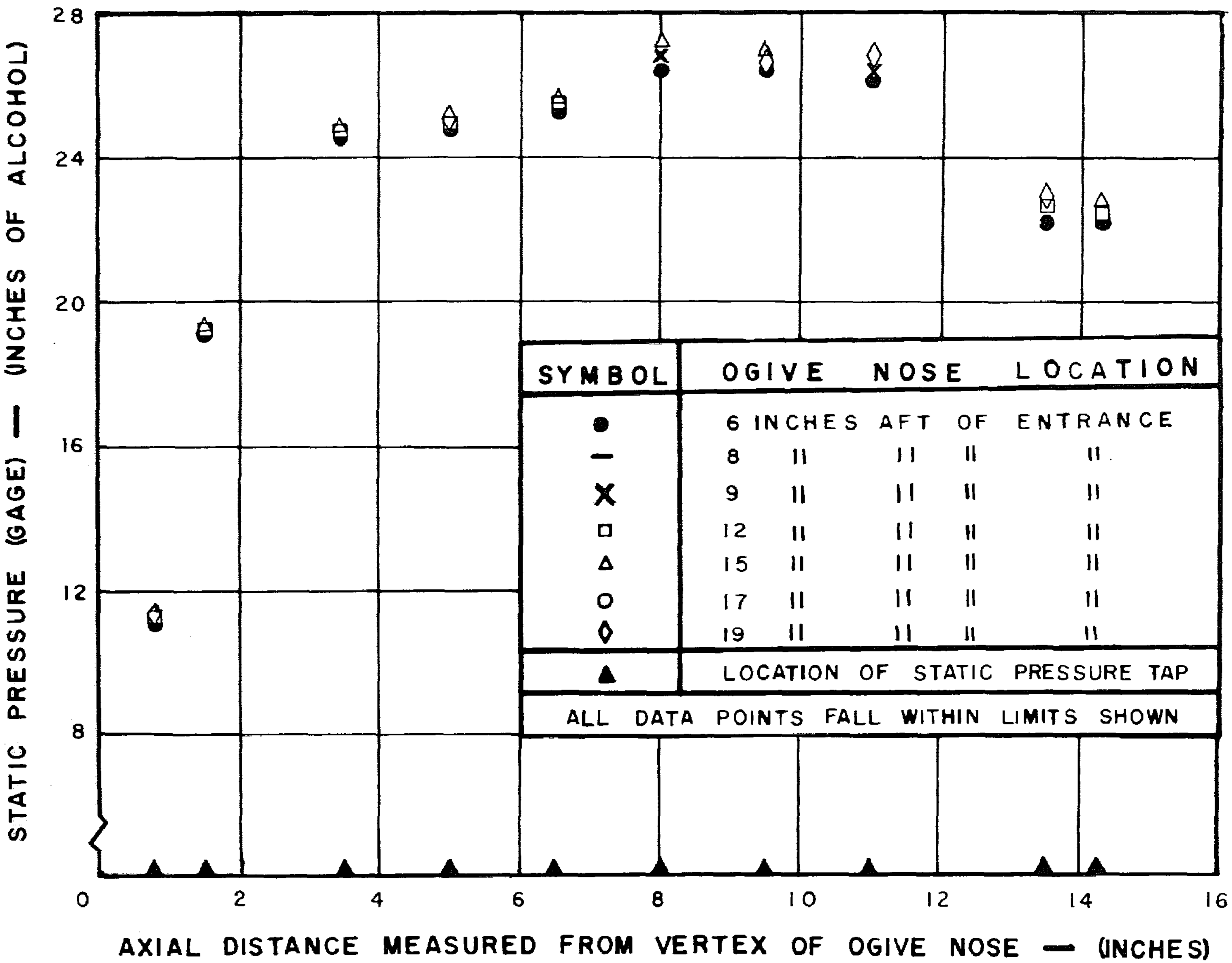


FIG. 3b. Pressure Distribution (Ogive Nose)
Test Section Length = 54 inches
Flow Rate = 1200 cfm

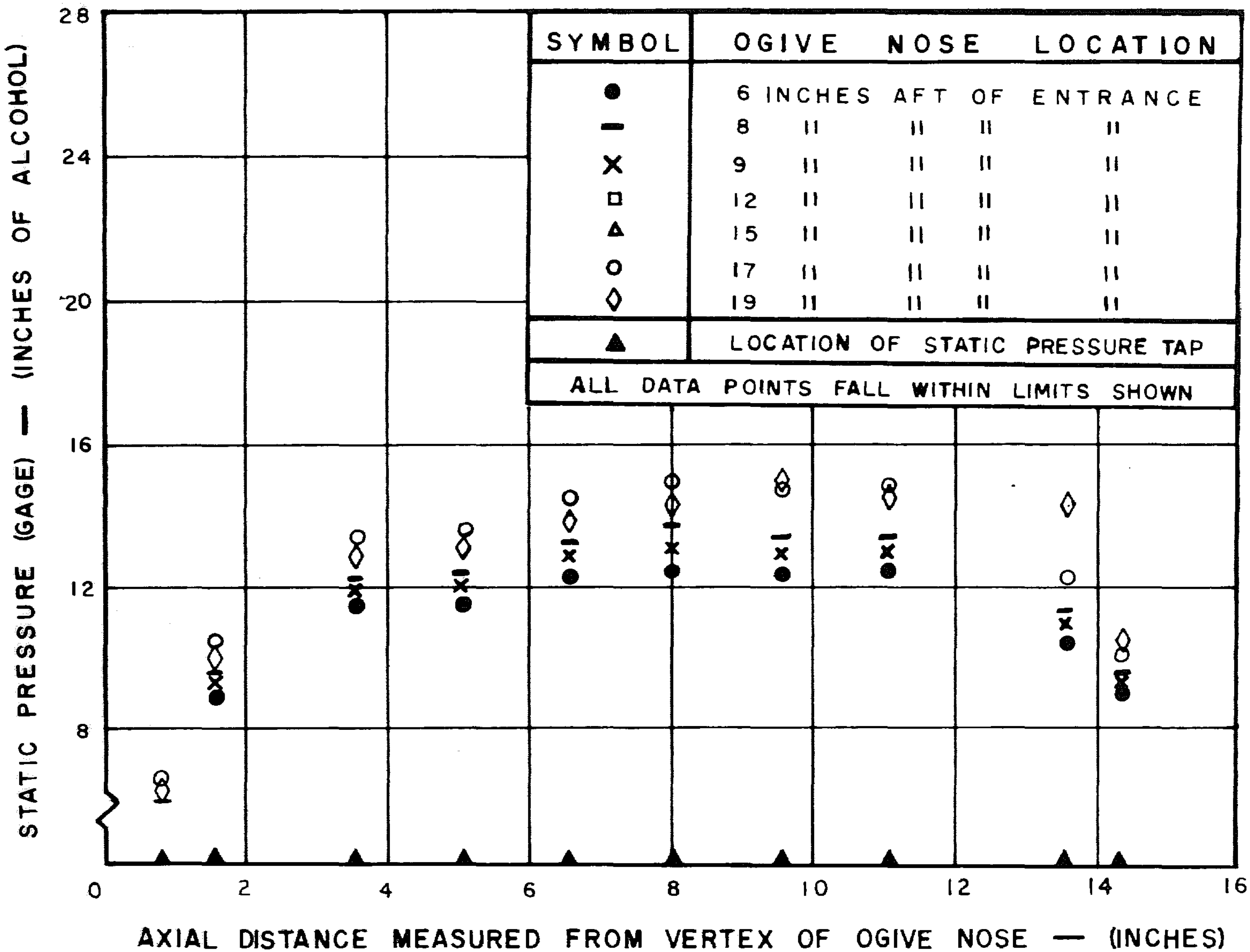


FIG. 4. Pressure Distribution (Ogive Nose)
Test Section Length = 26.5 inches
Flow Rate = 600 cfm

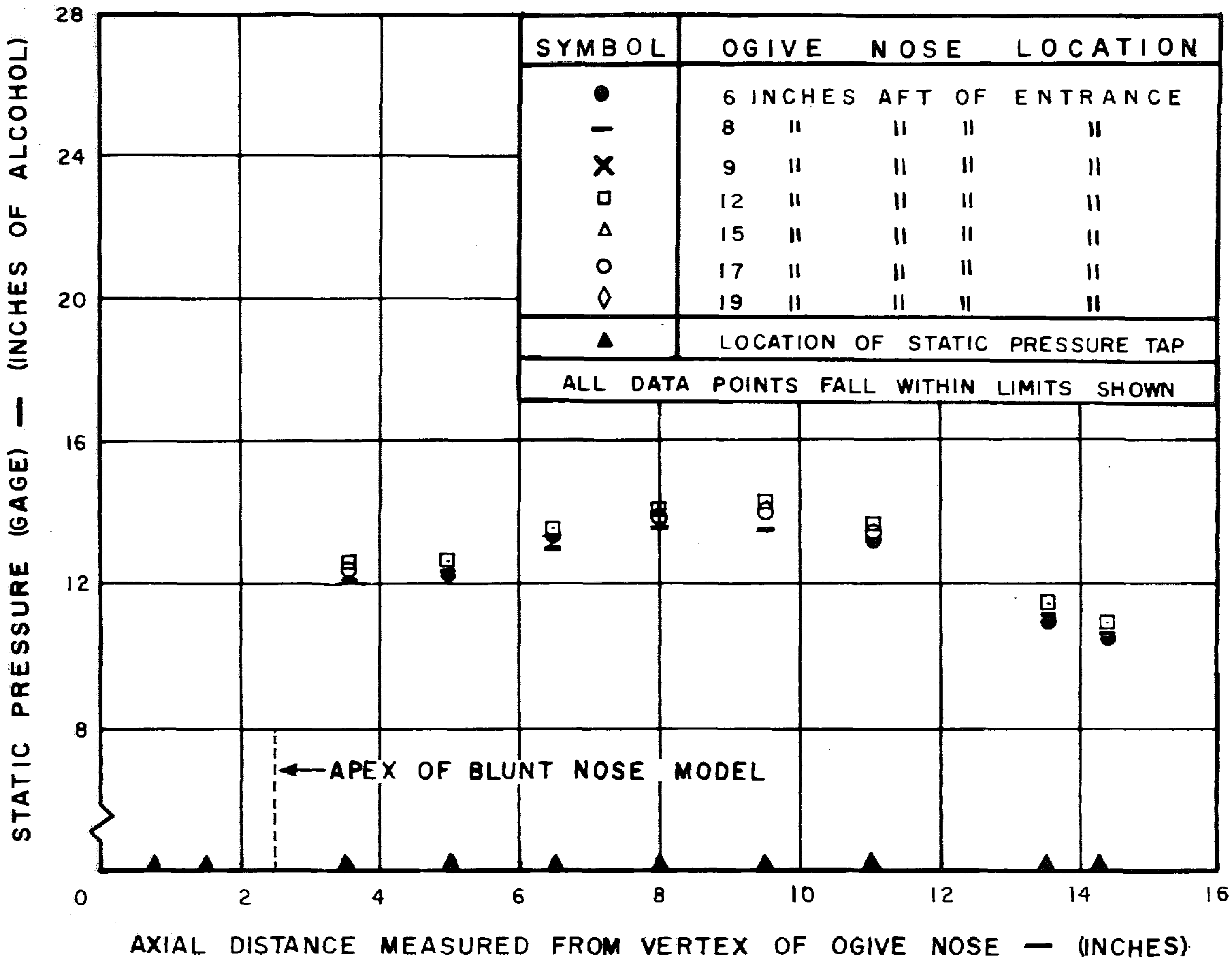


FIG. 5. Pressure Distribution (Blunt Nose)
Test Section Length = 54 inches
Flow Rate = 600 cfm

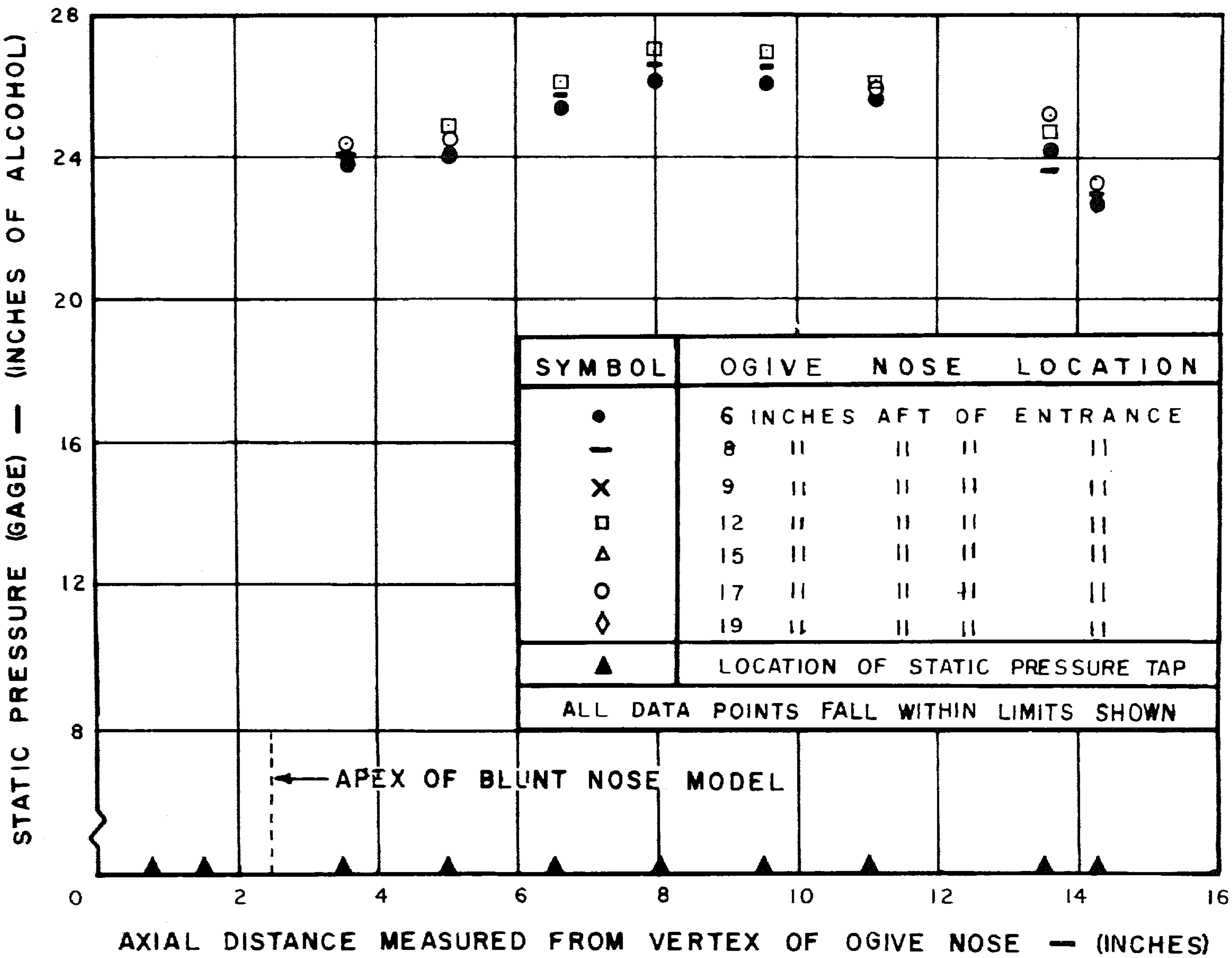
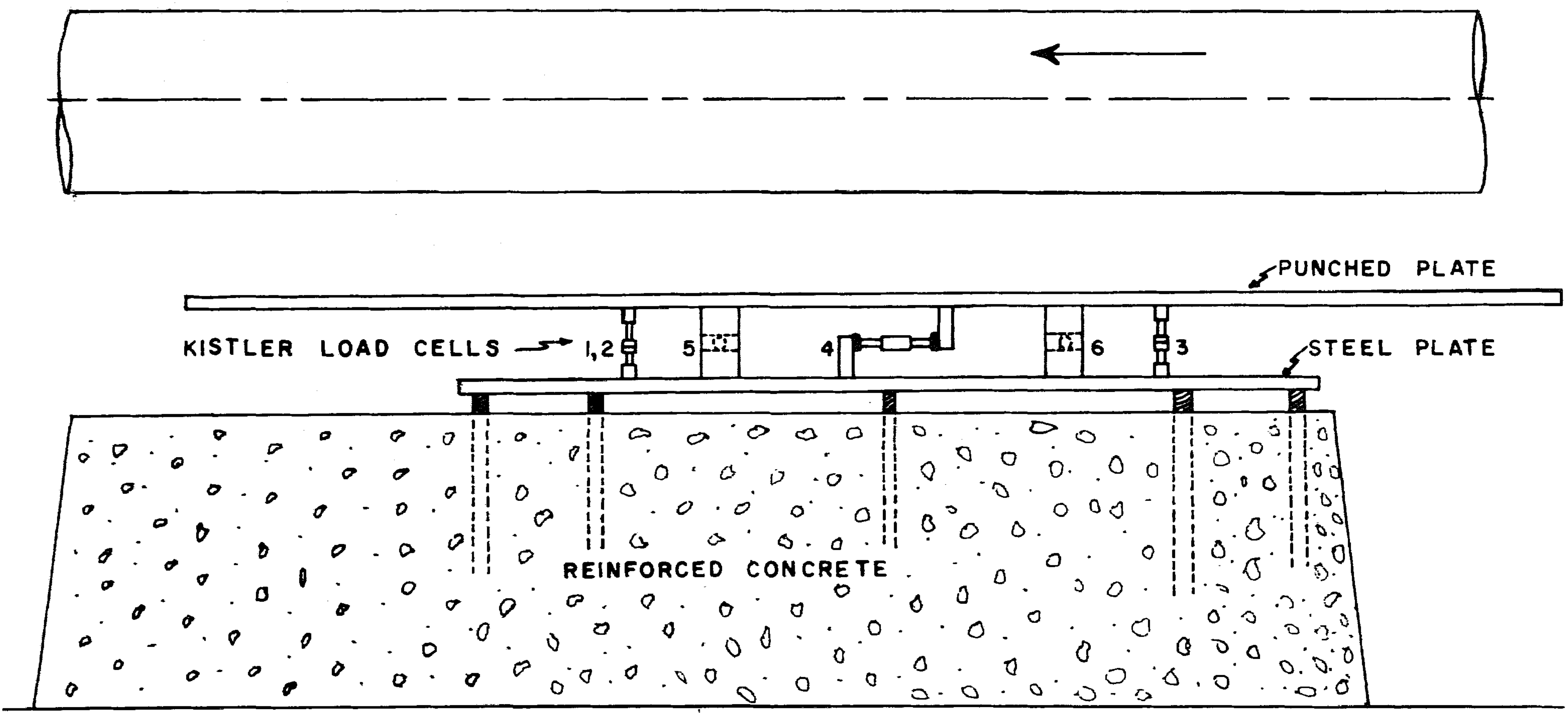


FIG. 6. Pressure Distribution (Blunt Nose)
Test Section Length = 54 inches
Flow Rate = 1200 cfm



LIFT	1,2,3	PITCH	1,2,3
DRAG	4	ROLL	1,2
SIDE	5,6	YAW	5,6

FIG. 7. Schematic Arrangement of Balance System

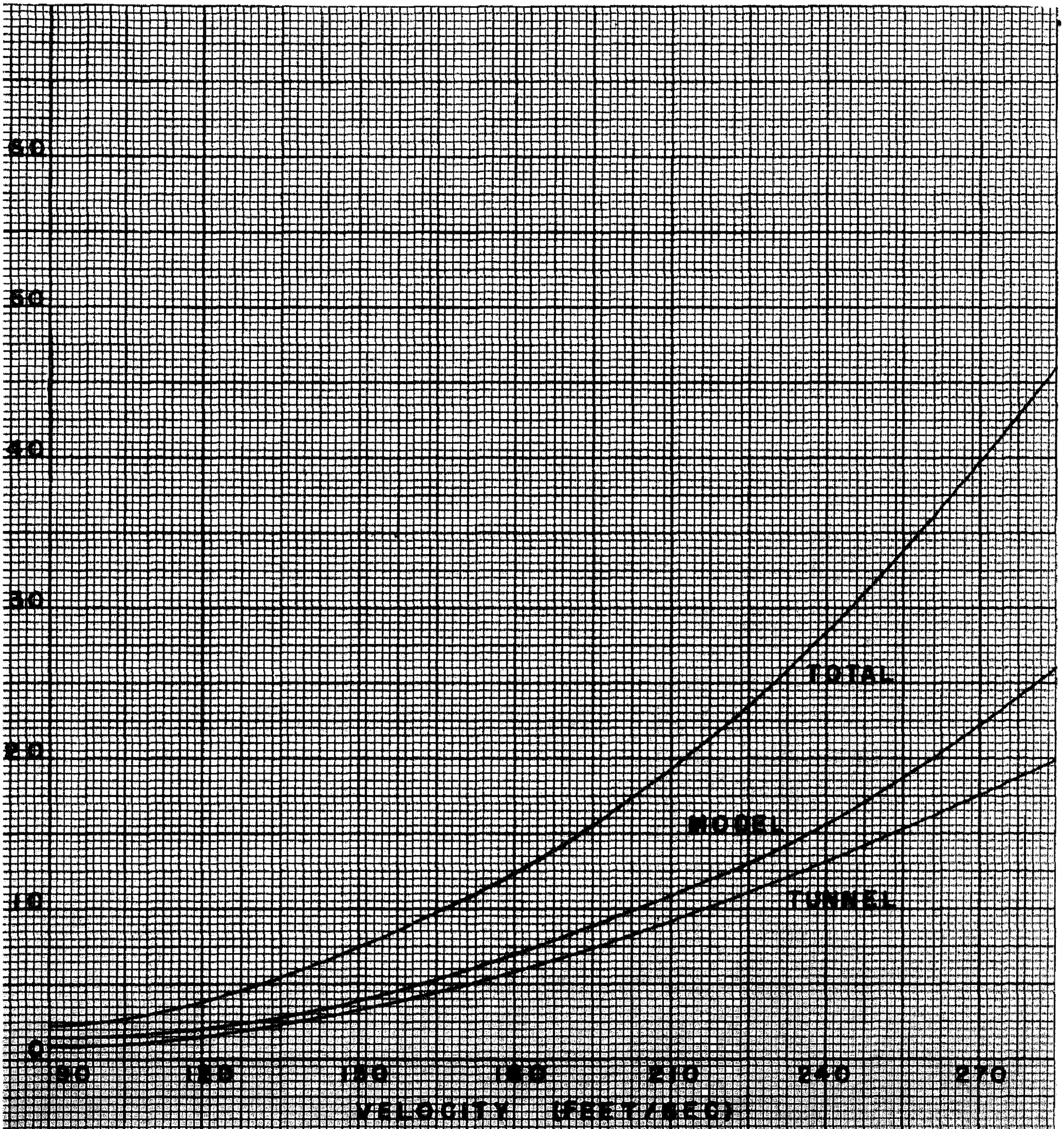


FIG. 8. Model and Tunnel Power Requirements
$D_o/d = 1.5$; $\ell_o/L = 1.5$

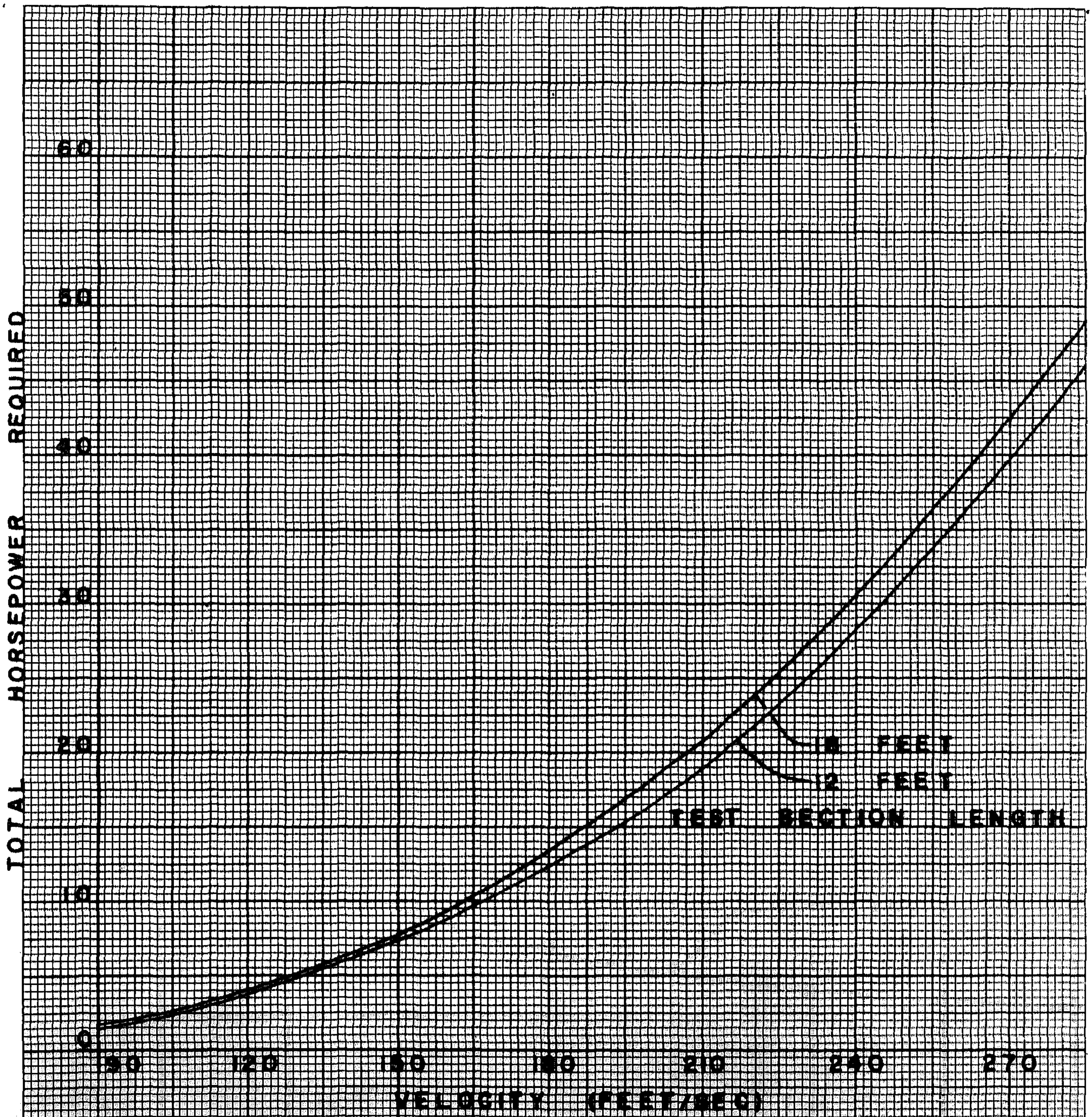


FIG. 9. Total Power Requirements
$D/d_o = 1.5$; L = 8 ft.

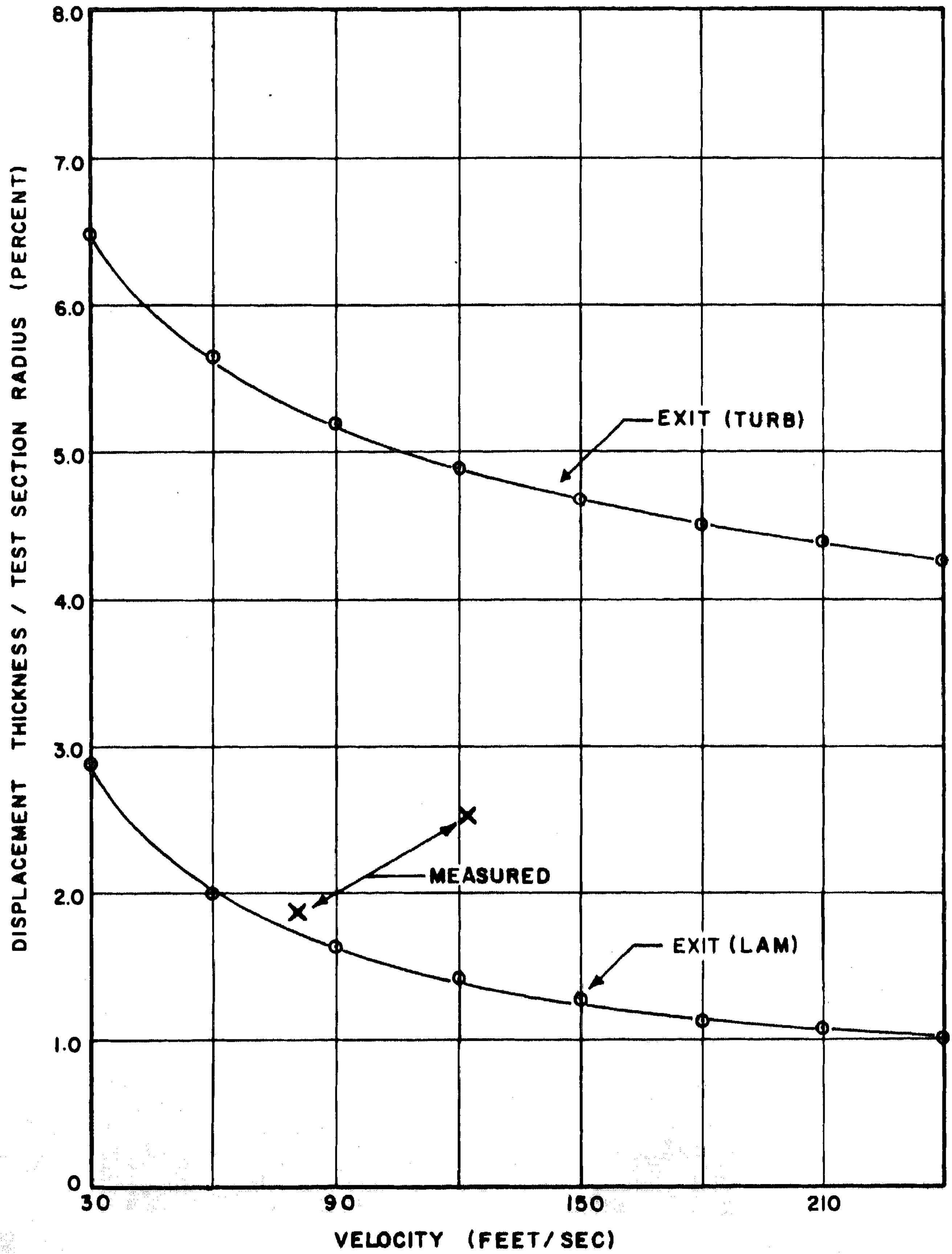


FIG. 10. Boundary Layer Displacement Thickness

FIG. 11a. Rensselaer T-3 Facility

FIG. 11b. Typical Tubeflight Vehicle Installed in T-3.

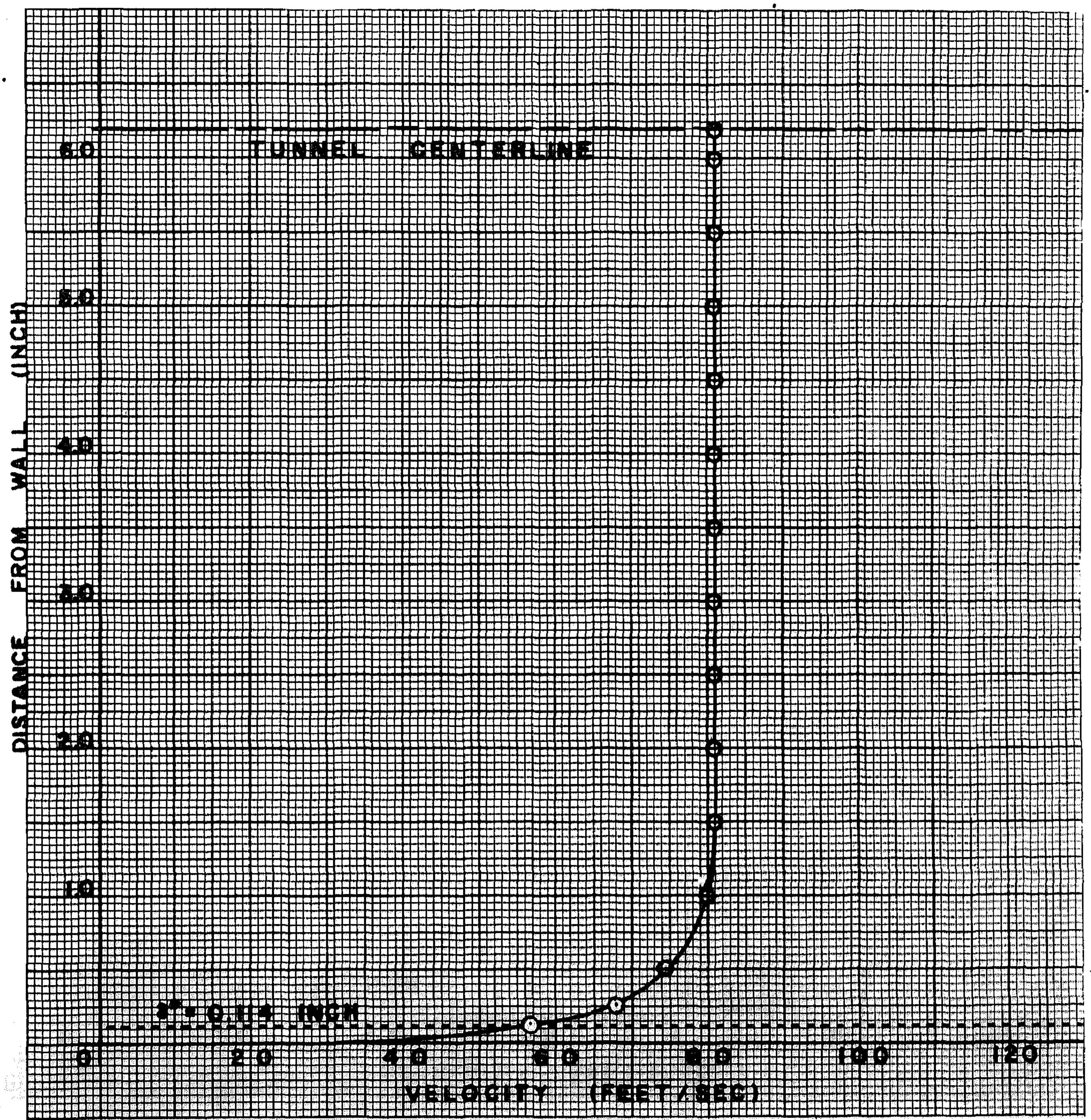


FIG. 12. Velocity Profile One Foot From End of Test Section
u_o = 81 fps

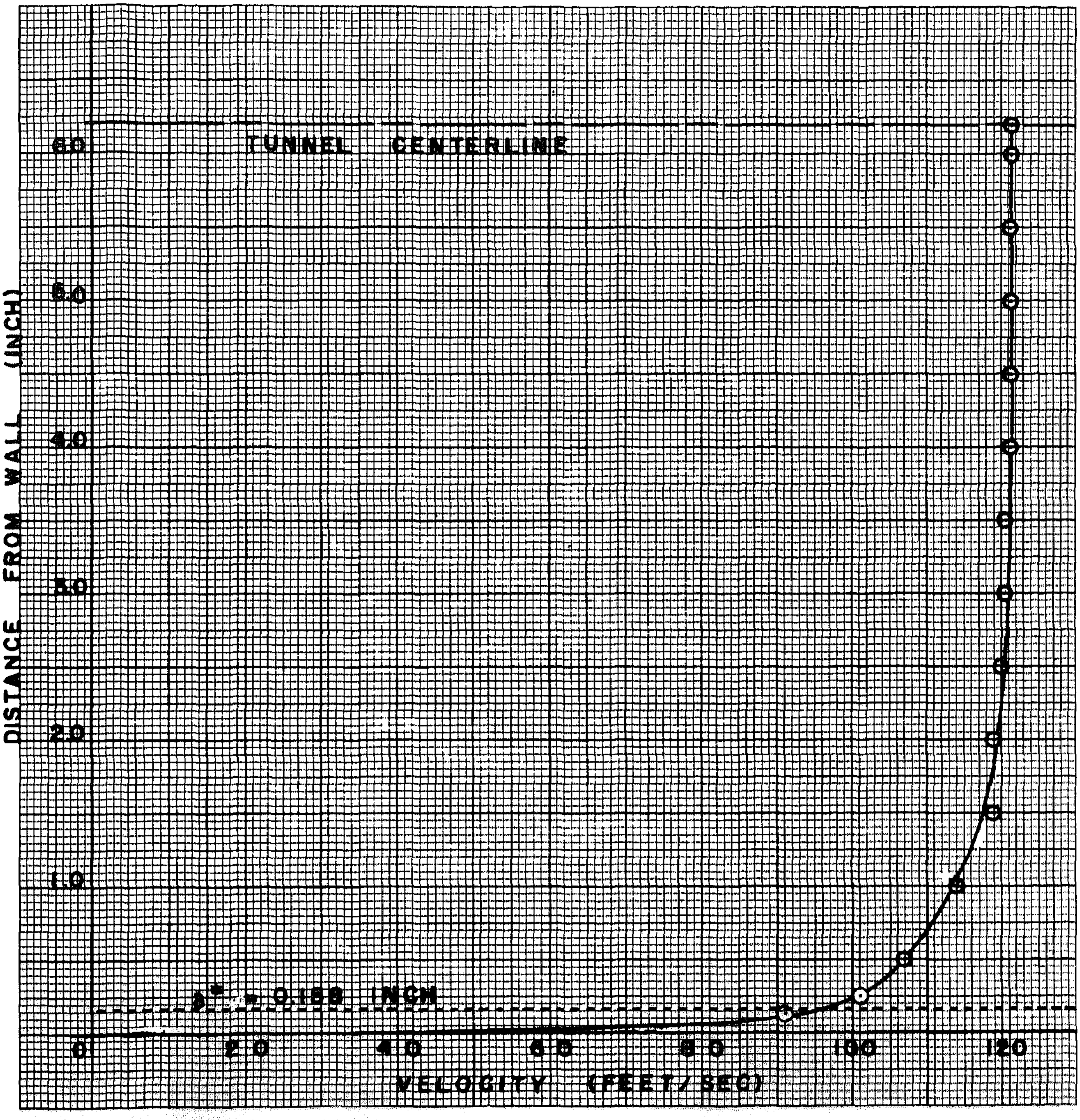


FIG. 13. Velocity Profile One Foot From End of Test Section
u_o = 122 fps