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WIND TUNNEL FOR THE STUDY OF TURBULENCE IN THE ATMOSPHERIC SURFACE LAYER

by

J. E. Cermak

Department of Civil Engineering

FINAL REPORT

The research reported in this document has been sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract AF 19(604)-1706.

Colorado State University
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ABSTRACT

Design and construction features of a wind tunnel constructed for the purpose of studying fundamental flow problems associated with the atmospheric surface layer or any application involving low air speeds with heat and/or mass transfer are discussed. Characteristics of the wind tunnel are as follows:

1. Test section size -- 6 x 6 ft by 72 ft long
2. Turbulence intensity (minimum) -- 0.001 to 0.005
3. Mean velocity range -- 1 - 100 ft/sec
4. Mean velocity variation across test section -- $\pm$ 1 percent of center velocity
5. Mean velocity steadiness -- $\pm$ 1 percent of velocity setting
6. Streamwise pressure gradient -- adjustable to zero

Completed portions of the wind tunnel are illustrated by appropriate photographs.

ACKNOWLEDGEMENTS

The financial support of the Geophysics Research Directorate of the Air Force Cambridge Research Center and the assistance and guidance of Dr. Heinz Lettau together with his successor, Dr. W. P. Elliott, Contract Monitors, were the key factors in permitting the conception of a unique wind tunnel facility to reach partial realization. For these the writer is indeed grateful.

To the following individuals, the writer is deeply indebted for their contribution during the course of this task: Dr. B. Chanda for completing many detailed designs, Mr. R. V. Asmus and his shop personnel for construction of the wind tunnel elements, Mr. Y. G. Tsuei for drafting and Mrs. E. Kruse for the typing of this report.

Administrative support by Dr. A. R. Chamberlain, Chief, Civil Engineering Section, Colorado State University Experiment Station, Professor T. H. Evans, Dean of Engineering, and Dr. M. L. Albertson, Director, Colorado State University Research Foundation is gratefully acknowledged.

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LIST OF SYMBOLS

Symbol	Definition	Unit[1]
d	diameter of damping screen wire	L
g	acceleration of gravity	LT^{-2}
h	heat transfer rate	$QL^{-2}T^{-1}t^{-1}$
k	thermal conductivity of air	$QL^{-1}T^{-1}t^{-1}$
k_s	pressure drop coefficient for one screen	
n	number of screens	
Δp	difference in pressure intensity	FL^{-2}
t_a	temperature of ambient air stream	t
t_s	temperature of heated surface	t
Δt	difference in temperature $t_s - t_a$	t
x	distance in streamwise direction measured from the beginning of the test section	L
x'	distance in streamwise direction measured from the beginning of the heated section	L
A	test section area	L^2
K	pressure drop coefficient	
P	Prandtl number	
R	Reynolds number — $U x'/\nu$	
U	ambient air speed in test section	LT^{-1}
U'	root-mean-square value of the average turbulence	LT^{-1}
δ	thickness of boundary layer	L
ν	kinematic viscosity of air	L^2T^{-1}

[1] L-length; T-time; F-force; t-temperature; Q-heat energy

I. INTRODUCTION

An experimental study to determine the effects of a negative vertical temperature gradient upon the turbulence structure of a turbulent boundary layer was initiated at Colorado State University in 1953 under Contract AF 19(604)-421. This study was conducted in a low velocity wind tunnel having a working section 6 x 6 x 24 ft. Air at speeds from 6 to 35 ft/sec were forced across a smooth, horizontal plate (6 x 12 ft) placed in the floor of the working section which could be heated to 125° F above the ambient air temperature. The primary object of the study was to yield data on the diffusion characteristics of a heated turbulent boundary layer that could be used to determine the effect of a lapse upon the diffusion characteristics of the atmospheric surface layer. Even though much useful data where obtained from the study (Refs. 8 and 1), the range of the critical parameter -- A Richardson number -- achieved did not include values large enough to include the most interesting and common values encountered in the atmosphere.

In 1956 Contract AF 19(604)-1706 was initiated in an effort to design and construct a wind tunnel facility capable of attaining values of the Richardson number comparable with those commonly found in the atmospheric surface layer. By creating such a facility research could then be pursued which would relate vertical temperature gradients produced by heating or cooling the wind tunnel floor to the mean velocity distribution function and the eddy diffusivity for mass, heat and momentum. In order to achieve the desired range of a Richardson number or Froude number, a wind tunnel with a long test section was designed to attain a boundary layer up to 2 ft in thickness and a floor heating system capable of maintaining a boundary temperature 250° F above the ambient air temperature at low air speeds near 6 ft/sec.

In conjunction with the design and construction of the new wind tunnel facility an experimental program was conducted to determine some of the effects upon the diffusion of heat and momentum from a plane, rough, heated boundary. The data were obtained in an effort to evaluate the design requirements of the new wind tunnel and to yield fundamental knowledge in an unexplored area of heat transfer phenomena. Results of this study appear in Ref. 2.

This report has three primary objectives. These are:

1. To discuss the design criteria for the new wind tunnel facility.
2. To discuss and describe the various design features, and
3. To discuss plans for further development of the facility.

Each of the three objectives are pursued separately in the following sections.

II. DESIGN CRITERIA

In this section the considerations leading to a final working design for the new wind tunnel and heated boundary are discussed. The areas for consideration may be classified as a general plan-including wind tunnel type and dimensions; aerodynamic characteristics; drive characteristics; and boundary thermal characteristics. Basic references used as a guide for the design are Refs. 3 and 4.

Wind Tunnel Type

A low-speed, recirculating wind tunnel with the following features is ideal for the creation and subsequent study of thick turbulent boundary layers with density stratification created by heating:

1. Closed throat test section
2. Adjustable walls or ceiling

Low-speed (1-100 ft/sec) is desirable with the range 1-50 ft/sec for studies of mixed free and forced convection flows with the higher range 50-100 ft/sec available for creating flows predominately of a forced convection nature. Recirculation of the wind tunnel air stream by means of a return duct provides several advantages over a non-recirculating tunnel. These advantages are as follow:

1. Good control of the air stream velocity distribution as it enters the entrance section preceeding the test section.
2. Provides immunity of the air stream to surges which may be caused in a non-recirculating system when doors and windows of the sheltering building are opened and closed.

3. Dust and debris in the air stream can be reduced to relatively low values and controlled.

4. Greater air temperature and air humidity stability exist and their control is possible by introduction of air conditioning equipment.

A closed throat working section is necessary because of the long surface required to develop the desired boundary layer thickness and to produce a minimum possibility for disturbance of the flow. Use of a long closed test section requires that some means be provided to control the longitudinal pressure gradient. This can be accomplished by providing a ceiling or walls with provisions for adjustment to permit a gradual change in cross-sectional area.

Wind Tunnel Size and Components

With the availability of a building having the dimension of 160 x 60 ft by 35 ft clear height to house the wind tunnel, the overall dimensions of the wind tunnel were essentially limited to something less than those of the building. Of course, the possibility of extending the tunnel to outside the building is possible, but not economically feasible with the funds available to accomplish the task.

The main components of the wind tunnel may be broken down into the following sections:

1. Entrance section
2. Screen section
3. Contraction section
4. Test section
5. Power section
6. Return diffuser section

The entrance section dimensions are determined primarily by the test section dimensions and the requirement that the contraction ratio be at least 6:1. Furthermore, if the tunnel is designed as a non-recirculating system, the entrance section must provide a faired lip to allow entrance of the air with a minimum of disturbance (separation). The entrance section of a non-recirculating system requires some type of dust filter.

If a low-level of turbulence is desired in the ambient air stream of the working section, the scale of turbulence of air passing through the entrance section should be reduced before flowing through the contraction. This is accomplished most easily by passing the air through several fine mesh screens placed in series. This section of screens should precede the following contraction section by a distance sufficient to permit a major portion of the fine scale turbulence to be dissipated.

The contraction section preceding the test section has the major function of shaping the air stream entering the test section so that the stream has a uniform velocity distribution with the exception of a very thin boundary layer region near the walls. Another function of the contraction section is to promote dissipation of the turbulence in the air stream by elongation of the vortex filaments. This initial low level of turbulence has the advantage of providing an air stream in which the turbulence level in the test section can be adjusted to various levels by introduction of grids at the test section entrance.

Desirable characteristics of the test section are the following

1. Sufficiently large to permit workers to enter and work in ease and to prevent interaction of the boundary layers formed on the floor and ceiling.

2. Simple in construction so that individual portions of the test section may be readily moved.

3. Have large viewing windows along the tunnel walls.

The power section characteristics should include adequate power to attain the velocity range desired, simple and stepless speed control throughout the speed range, stable speed at a desired setting, easily operated, and simple to maintain. Components of the power system -- fan, motor, support vanes -- should be assembled to provide the least amount of disturbance to the air flow and the least amount of mechanical disturbance in the system.

Aerodynamic Characteristics

Essential aerodynamic characteristics of the wind tunnel pertain to the level of turbulence in the test section flow, the distribution and range of mean velocity over a cross-section of the test section, steadiness of the mean stream velocity, boundary layer development, and streamwise pressure gradient. Acceptable specifications for these characteristics are as follows:

1. Turbulence intensity -- 0.001 - 0.005
2. Mean velocity range -- 1 - 100 ft/sec
3. Mean velocity variation across cross-section -- ± 1 percent of center velocity (with exception of boundary layer regions)
4. Mean velocity steadiness -- ± 1 percent of velocity setting
5. Boundary layer development -- up to 2 ft thickness at 6 ft/sec mean velocity
6. Streamwise pressure gradient -- adjustable to zero

Boundary Thermal Characteristics

A section of the wind tunnel floor should have provisions for heating. The length heated and temperature rise above the ambient air stream temperature must be adequate to achieve a Richardson number

$$\frac{g}{t_a} \frac{\Delta t/\delta}{U^2/\delta^2} \doteq 1$$

at low values of U (1 - 5 ft/sec) and a thermal boundary layer thickness approaching the value of δ .

The heating system should be designed as a composite of small elements -- each element being removable and controlled for heat output adjustment. Electrical heating elements must have the desired characteristics of flexibility, simplicity and economy of installation and operation. The elements should be arranged to enable the aerodynamic surface being heated to assume a uniform temperature with a variation of $\pm$ 2° F.

III. FEATURES OF THE DESIGN

The designs chosen for various elements of the wind tunnel are described and discussed in the following sections.

Gross Characteristics

The overall features of the wind tunnel are shown in Figs. 1, 2 and 3. Because of limited funds and space within the building a non-recirculating system was adopted. In the system shown which is centered in the enclosing room (40 x 60 ft in cross-section), the room serves as a return duct. This arrangement is somewhat less than optimum because it does not afford control of the entrance flow, dust or disturbances. The air is drawn downward into the entrance section; passes through a set of screens, the contraction section, the test section; and is then discharged in a vertical jet after flowing through the propeller or power section.

The wind tunnel structure has an overall length of about 148 ft and a maximum height of 24-1/2 ft. In order to not restrict movement of the overhead traveling crane shown in Fig. 2, all features of the tunnel were limited in height above the floor level to 25 ft.

Entrance Section

Details of the entrance section are shown in Figs. 4, 5 and 6. A cross-sectional area of approximately 18 x 18 ft was chosen to permit the largest contraction ratio possible and yet not restrict the crane travel. Details of the entrance lip are subject to modification after measurements of the airflow patterns have been made. The proximity of a wall and roof truss will probably require some trial and error adjustment of the entrance configuration to obtain the desired uniformity in test section velocity.

The turning vanes were designed on the basis of findings by Silberman (7). Geometry of the vanes was chosen to give the air a complete 90° change in flow direction with a minimum amount of energy loss. A thick section for the vanes would have decreased the energy loss somewhat but the cost of construction would have been many times in excess of that for the thin vanes.

A 3 ft 10 in. straight section is provided between the screen section and the entrance section. The purpose of this is to permit placement of straightening devices such as cardboard tubes if the flow is not sufficiently parallel to the test section axis.

Screen Section

The primary purpose of the screen section is to reduce the turbulence scale and thus permit rapid dissipation of the turbulence energy as the air passes through the settling chamber and the contraction section. Figs. 7 and 8 show the screen section and a single screen, respectively.

From the results of Schubauer, Spangenberg and Klebanoff (6), a screen will not create turbulence by eddy shedding if

$$\frac{U\,d}{\nu} < 40$$

Using a wire diameter d of 0.0075 in. no eddy shedding should occur until the tunnel speed U is near 115 ft/sec. Thus, in the primary working range for which the tunnel is designed the screens should be effective in damping the turbulent air motion.

Four damping screens are believed to be sufficient to attain the desired attenuation of turbulence intensity. The measurements given in Ref. 3 show good agreement with the predicted turbulence levels based upon the expression

$$\left(\frac{U'}{U}\right)_{\substack{\text{with}\\ \text{screens}}} = \frac{1}{(1 + k_s)^{n/2}} \left(\frac{U'}{U}\right)_{\substack{\text{without}\\ \text{screens}}}$$

For the four screens chosen

$$\frac{1}{(1 + k_s)^{n/2}} = \frac{1}{(1 + 0.730)^{4/2}} = 0.334$$

Thus, the turbulence level should be reduced to one-third the value for no screens. Estimating the turbulence level with no screens at 0.006, a level of about 0.002 should result. A large value of initial turbulence compared to the 0.00265 found in Ref. 3 is assumed because of the relatively poor entrance conditions for the non-recirculating system.

Contraction Section

With a test section area of 6 x 6 ft and an entrance section of 18 x 18 ft the contraction ratio has a favorable value of 9. The contraction section profile was designed in accordance with data obtained in Ref. 5. Accordingly, the contraction profile consists of two cubic parabolas joined together with consistent slopes at the inflection point of the profile. The features of this section are shown in Figs. 9 and 10.

Test Section

Views of the test section are shown in Figs. 11, 12 and 13. The test section is composed of an assembly of 9 individual units each 8 ft in length. As shown in Fig. 13 the three downstream sections have plate glass windows which are mounted flush with the inside wall of the tunnel. All the windows may be opened to permit ready access to the interior working area. Each set of vertical supports is mounted on a set of leveling screws to permit accurate alignment and leveling of the test section.

In an attempt to provide a test section with a controlled longitudinal pressure gradient, the vertical walls were given a constant angle of divergence throughout the length. Based upon a divergence sufficient to compensate for the displacement thickness growth caused by boundary layer formation, a divergence of 1 in./8 ft was selected. This was estimated to be sufficient for a low mean velocity of about 6 ft/sec with the boundaries smooth and the ceiling parallel to the floor. To allow adjustment of the pressure gradient for other speeds and roughnesses, the ceiling was made in the form of a single diaphragm supported from above by a pair of adjusting screws at 4 ft intervals. At the downstream end of the test section the diaphragm can be given a vertical displacement of $\pm$ 1-1/2 ft from the position in which it is parallel with and 5 ft 11 in. above the floor.

The floor of each test section unit is constructed so that it may be removed without disassembly. This permits ease in installing heated and cooled boundaries or boundaries having a desired roughness.

Based upon the formula

$$\frac{\delta}{x} = \frac{0.377}{\left(\frac{Ux}{\nu}\right)^{1/5}}$$

the boundary layer thickness for smooth boundaries should attain a value of about 1-1/2 ft for $U = 6$ ft/sec and about 1 ft for $U = 50$ ft/sec. From the data on boundary layer growth for a roughened boundary given in Ref. 2, the foregoing values of δ could be easily doubled by roughening the test section floor.

Power Section

The general arrangement of the power section is shown in Figs. 14 and 15. A 10 ft diameter, 4-bladed variable pitch propeller[1] obtained as Government surplus property is used as a driving fan. The propeller is to be driven by a 275 H P DC-motor[2]. Power for the motor will be furnished by a motor-generator set of 250 KW capacity delivering 250 V DC power from a 2200 V AC source. Both of these items which were obtained from sources of standby Government equipment are shown in Figs. 16 and 17. These units will be connected as a Ward-Leonard system.

Because of space limitations the motor is designed to be closely coupled to the propeller rather than coupled to it by means of a shaft extending to the tunnel exterior. Such an arrangement has the advantage of simplifying the power transmission system but the disadvantage (if a closed circuit is used) that power dissipated in the form of heat by the motor is added to the air stream.

---

[1] Curtiss-Wright electric Model C542S-B8.
[2] Reliance Electric Engineering Co. 250 V DC generator.

An estimate of the power requirement may be made by tabulating the pressure drop coefficients K for the various elements in the system. The coefficient K is defined by

$$K = \frac{\Delta p}{\rho U^2/2}$$

A tabulation of the various coefficients is as follows:

Element	K
Entrance dust filter	0.060
Entrance	0.012
Entrance guide vanes	0.004
Screens	0.040
Straighteners	0.004
Contraction	0.002
Test section	0.192
Safety screen	0.200
Power section expansion	0.300
Power section duct	0.007
Exit guide vanes	0.325
Exit jet	1.000
	2.146

At a test section speed of U = 100 ft/sec the required horsepower delivered to the air is approximately

$$HP_{\text{to air}} = \Sigma K \left(\frac{\rho U^2}{2}\right) \frac{AU}{550}$$

$$= 2.146 \left(\frac{0.0024}{2}\right) \frac{36(100)^2}{550}$$

$$= 169 \text{ HP}$$

Estimating the propeller system to be 80 percent efficient, the driving motor must deliver

$$HP_{motor} = \frac{169}{0.80} = 210 \text{ HP}$$

The foregoing calculations indicate that the 275 HP DC drive motor is sufficient capacity to attain the desired range of air speeds.

Installation of the driving motor and power control system has not been completed. With all the necessary machinery for the system now on hand, additional funds will insure rapid completion of the wind tunnel drive.

Boundary Heaters

The length of heated boundary was chosen to be 32 ft. This length of boundary is adequate to permit the thermal boundary layer thickness to become equal to the momentum boundary layer thickness when the heated boundary is placed in the last four units of the test section.

Figs. 18 and 19 illustrate the details of construction and arrangement of the heated boundary. The boundary forming the tunnel floor is 1/2 in. copper plate heated from below by nichrome wire coils. Power for the heating elements is supplied from a 220 V AC source passing through a Powerstat to permit control of heat output. The spacing and size of the coils are such as to permit a uniform plate surface temperature -- ambient air temperature difference of 200° F for $U = 35$ ft/sec and the power voltage of 220 V when the boundary is aerodynamically smooth. Calculation of the distribution of heat output necessary to achieve the foregoing condition was based on the heat transfer relation:

$$\frac{hx'}{k} = \frac{0.0296\ R^{4/5}\ P}{1 + 0.87\ (1.5\ P^{-1/6})\ R^{-1/10}\ (P-1)}$$

Construction of the heating elements has not been accomplished due to the lack of available funds.

IV. PLANS FOR FURTHER DEVELOPMENT

Further development of the wind tunnel laboratory initiated under this Contract falls into two phases. The first phase is completion of the wind tunnel as described in this report by installation of the power system and heated boundary. The second phase consists of improvement of the tunnel design and the addition of several features to the tunnel.

In the domain of design improvement is the plan to construct a return passage so that the tunnel may be operated as a closed system. An additional feature planned for the tunnel is a temperature control system. By heavily insulating all walls of the tunnel and installing a system to either add or remove heat from the air stream experimental studies could be conducted under steady or controlled unsteady temperature conditions. Associated with the temperature control system will be some means to control relative humidity. To increase the scope of fundamental boundary layer studies possible with the wind tunnel, a cooled boundary is planned to complement the heated boundary.

The writer's objective in the foregoing planning is to develop a versatile facility in which basic problems related to fluid flow with relatively strong heating and cooling may be investigated. The need to know more about the effects of density stratification upon flow stability, diffusion rates and turbulence structure is apparent in the fields of heat transfer, chemical engineering, meteorology, oceanography, hydraulics, sanitary engineering, and aeronautics.

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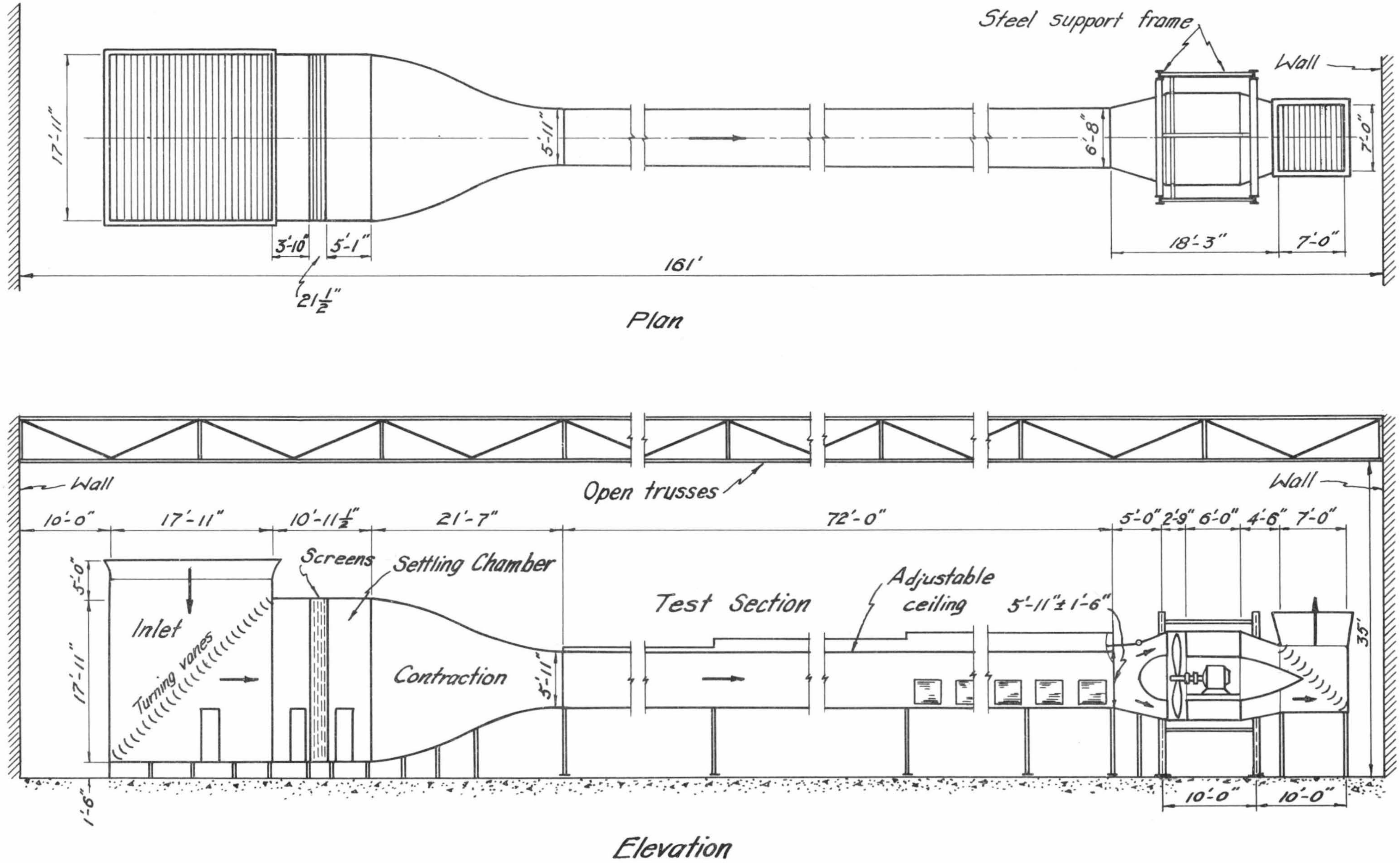

Fig. 1 Overall plan and elevation of wind tunnel

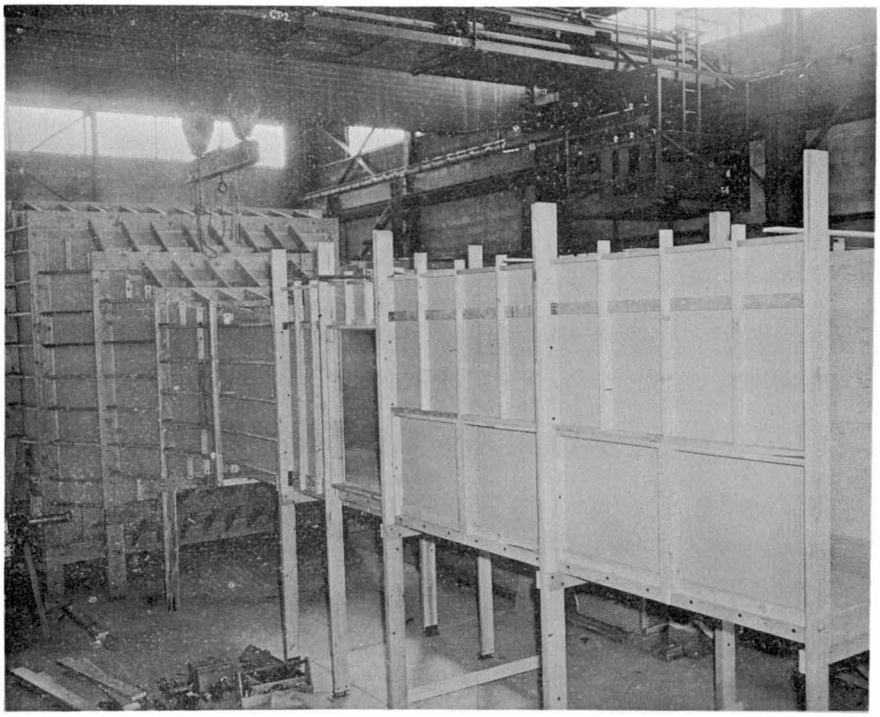

Fig. 2 Exterior view of upstream portion of wind tunnel

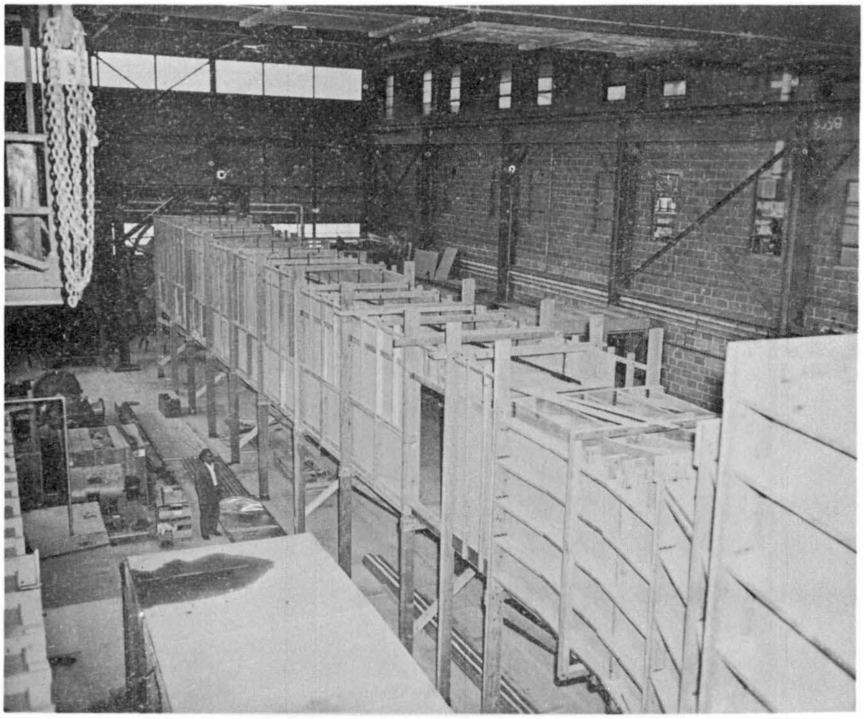

Fig. 3 Exterior view of downstream portion of wind tunnel

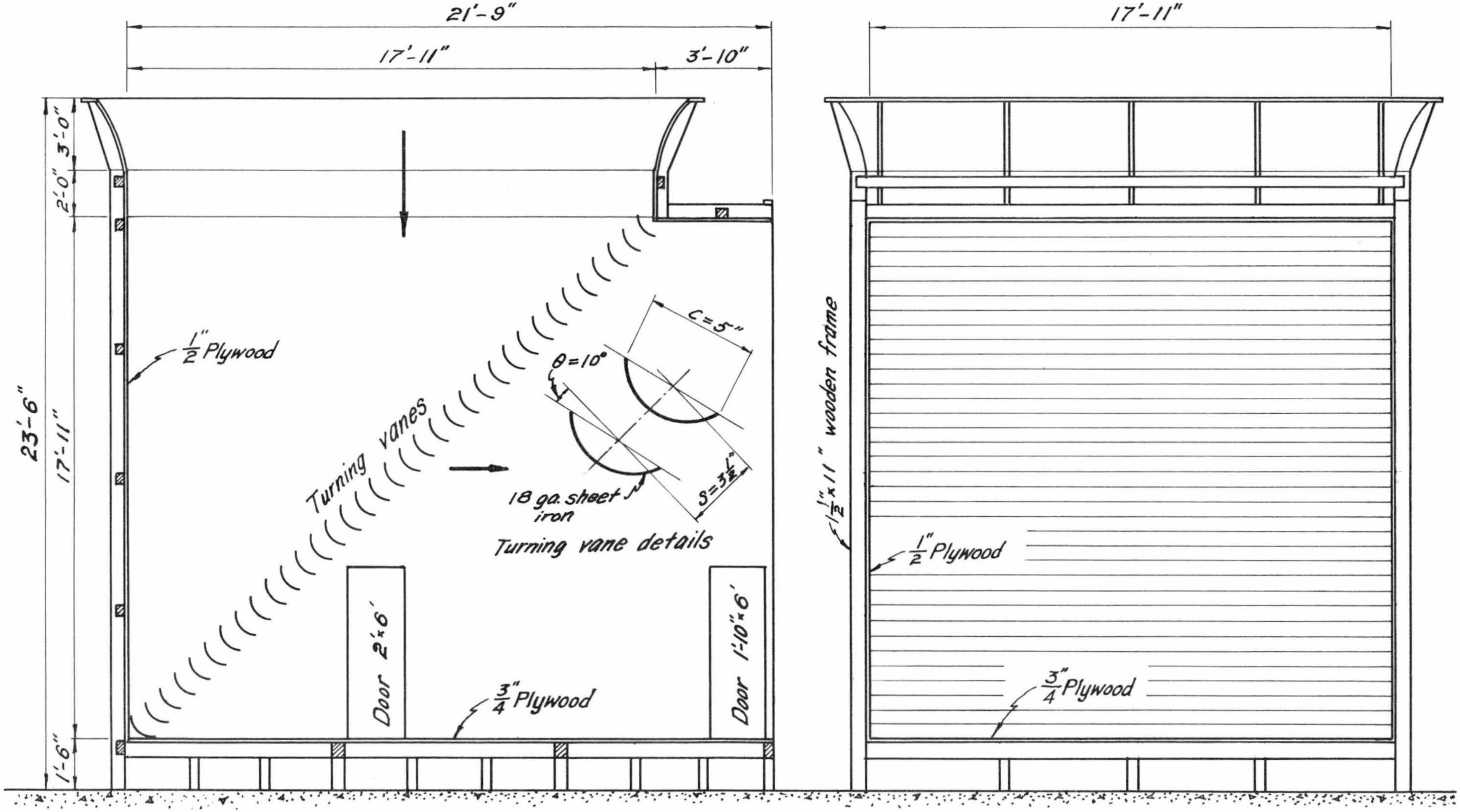

Fig. 4 Side and upstream elevation of entrance section

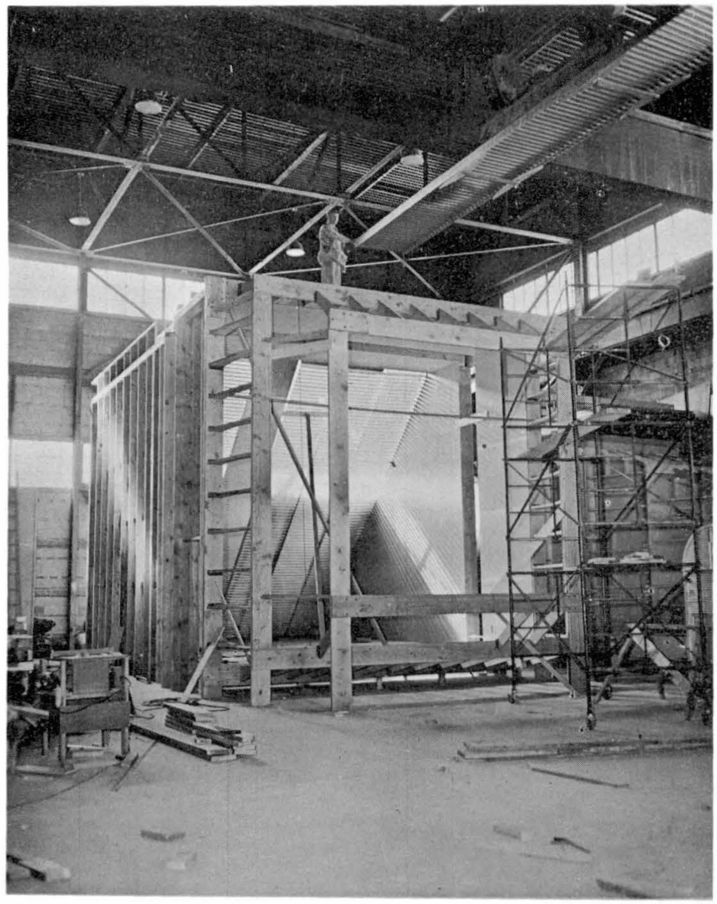

Fig. 5 Upstream view of entrance section

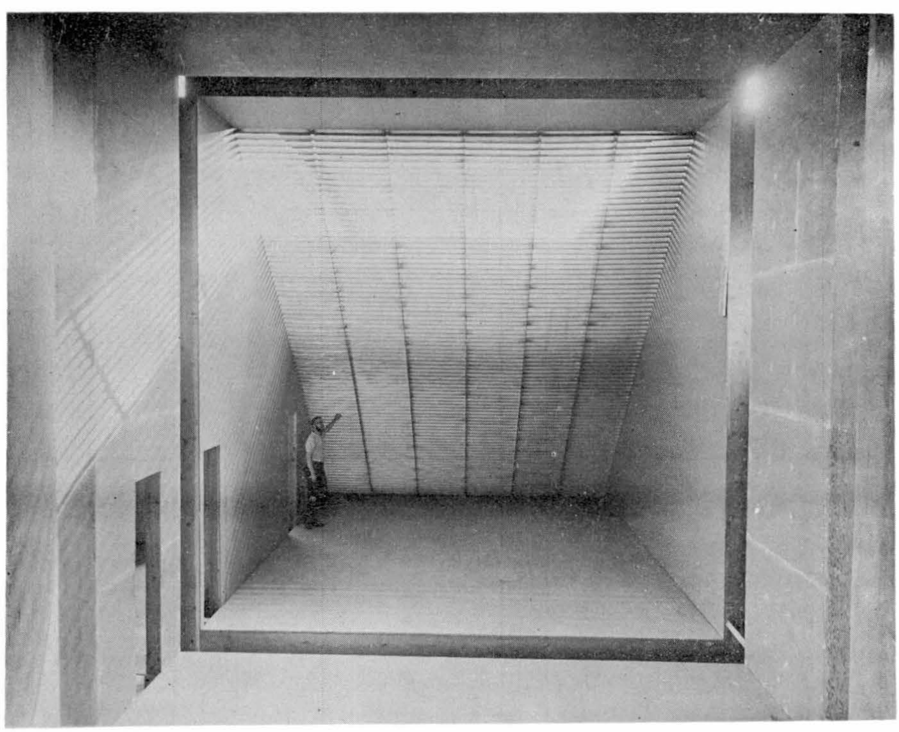

Fig. 6 Upstream interior view of entrance section

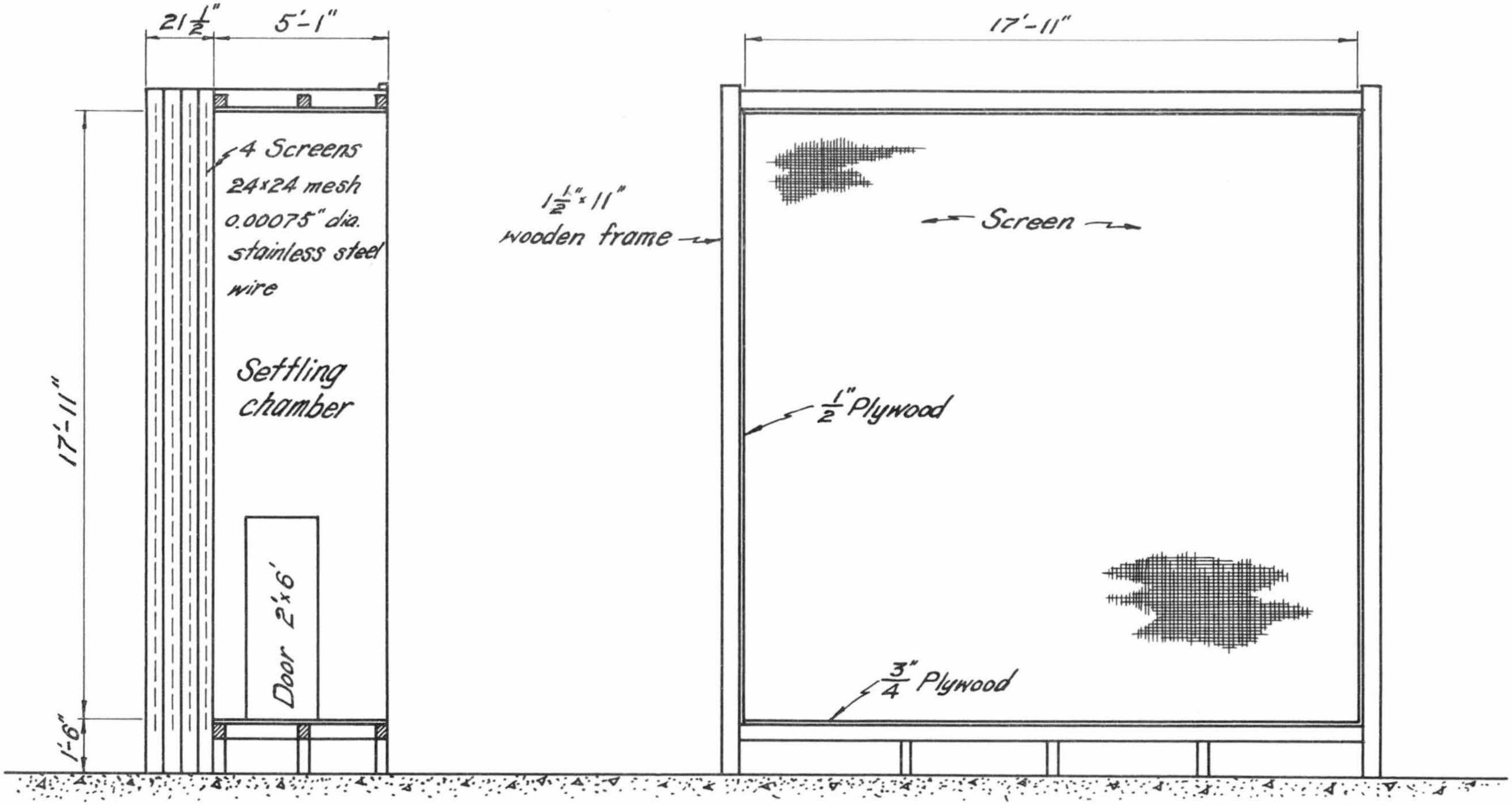

Fig. 7 Side and upstream elevation of screen section

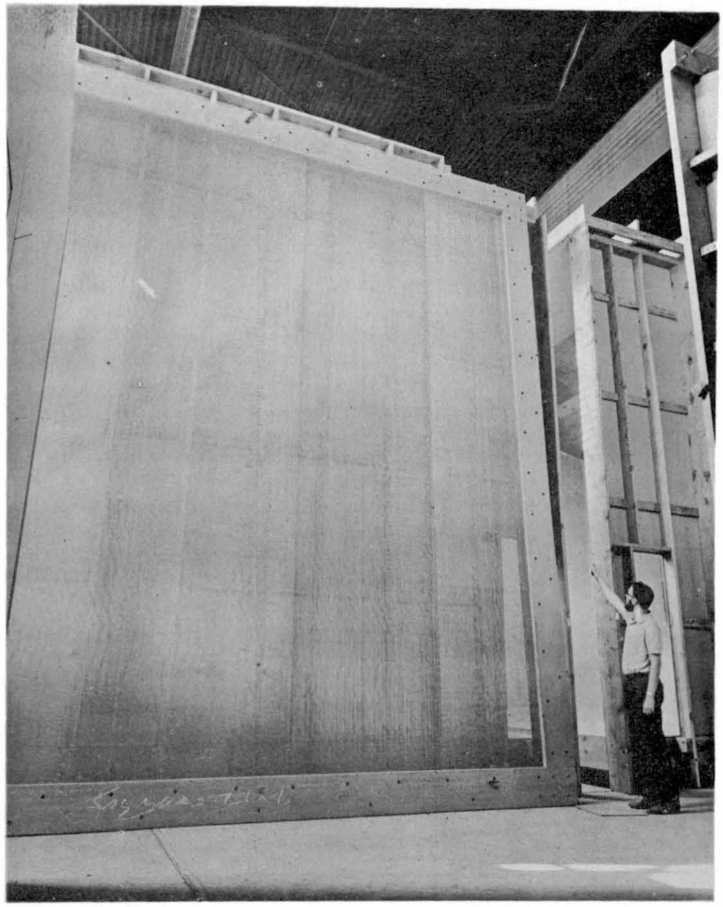

Fig. 8 View of screen and screen section

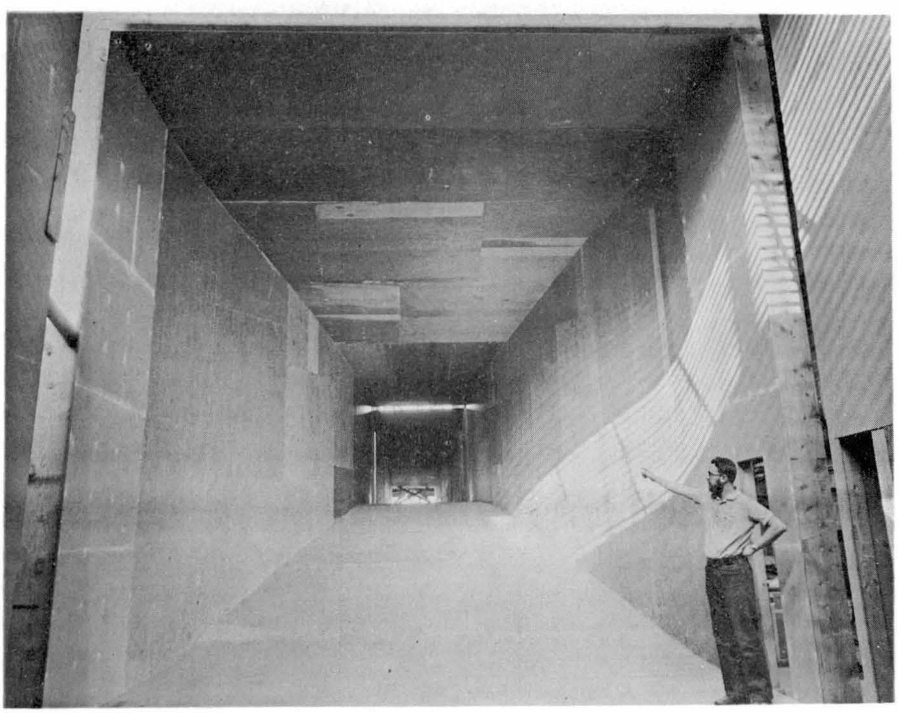

Fig. 9 Downstream interior view of contraction section

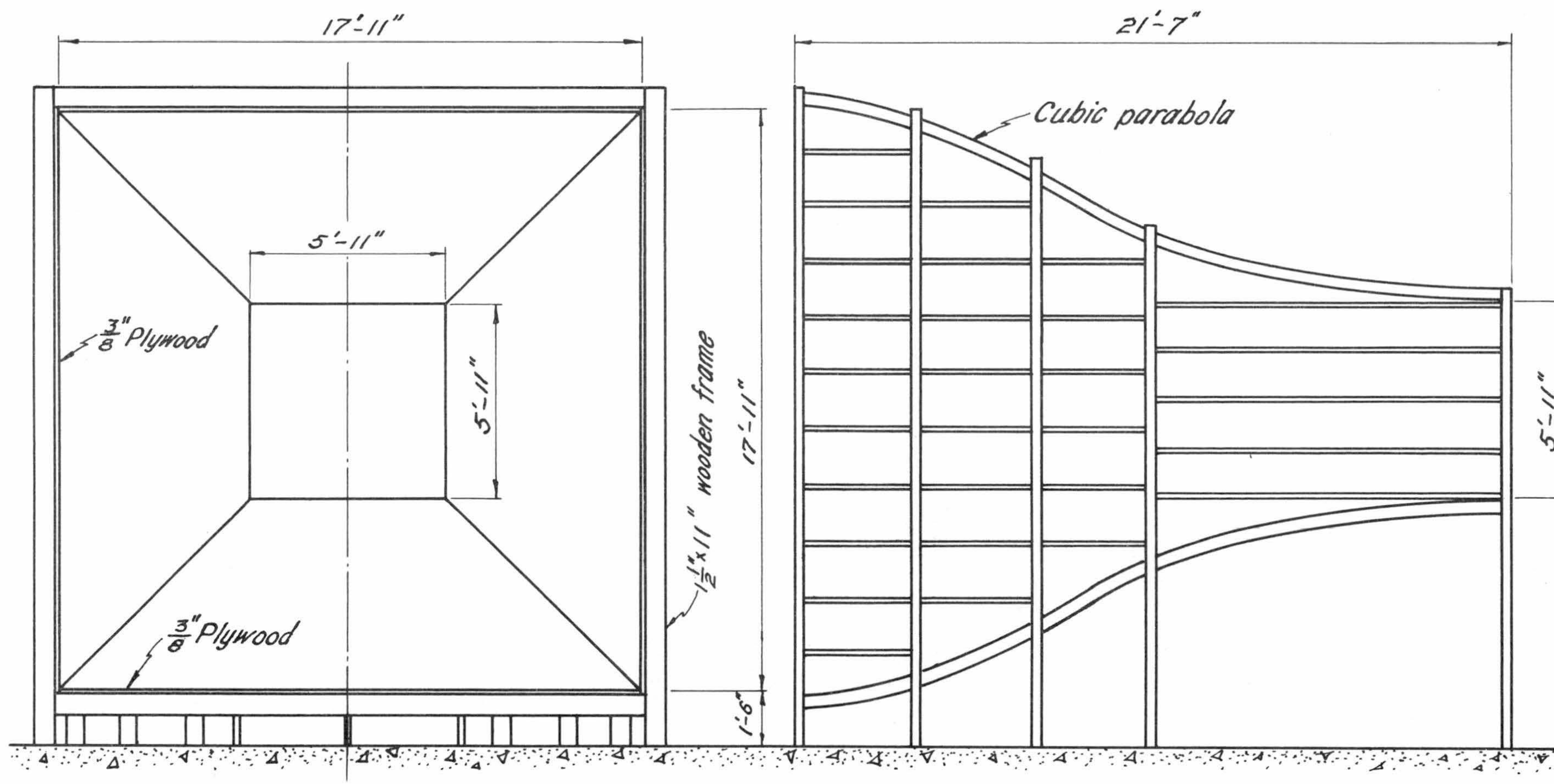

Fig. 10 Downstream and side elevation of contraction section

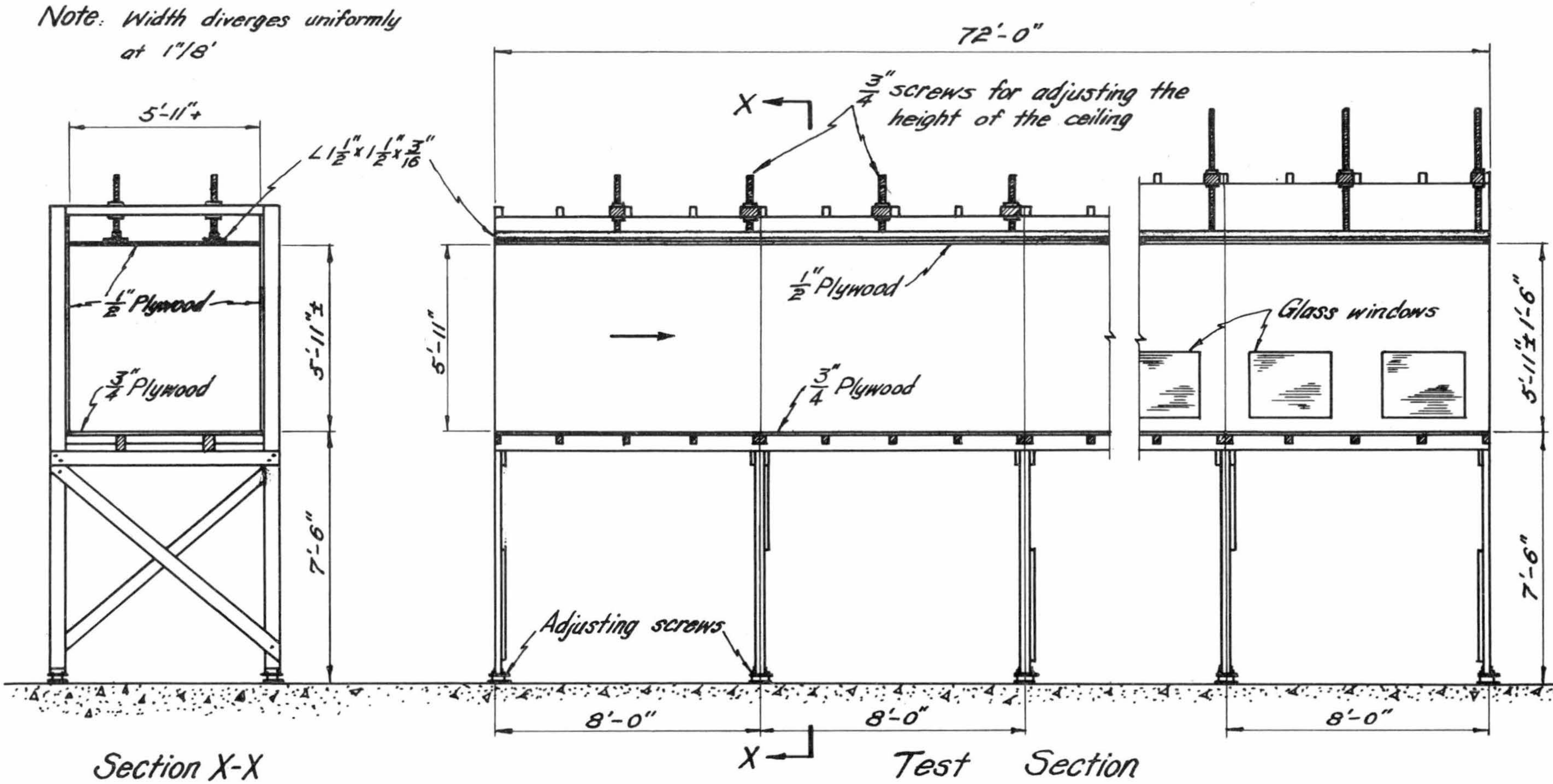

Fig. 11 Upstream and side elevation of test section

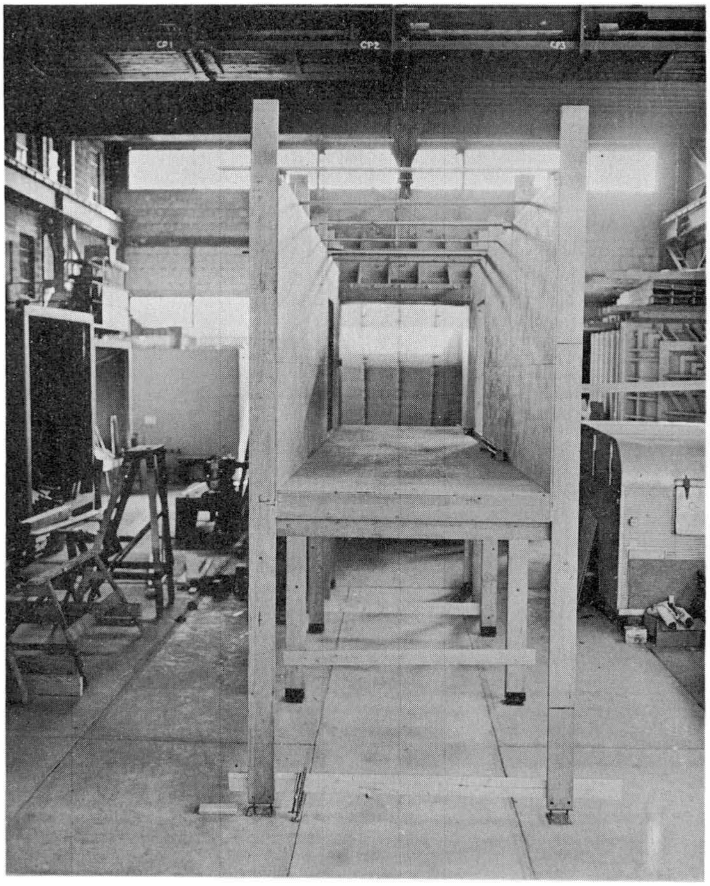

Fig. 12 Upstream view of test section

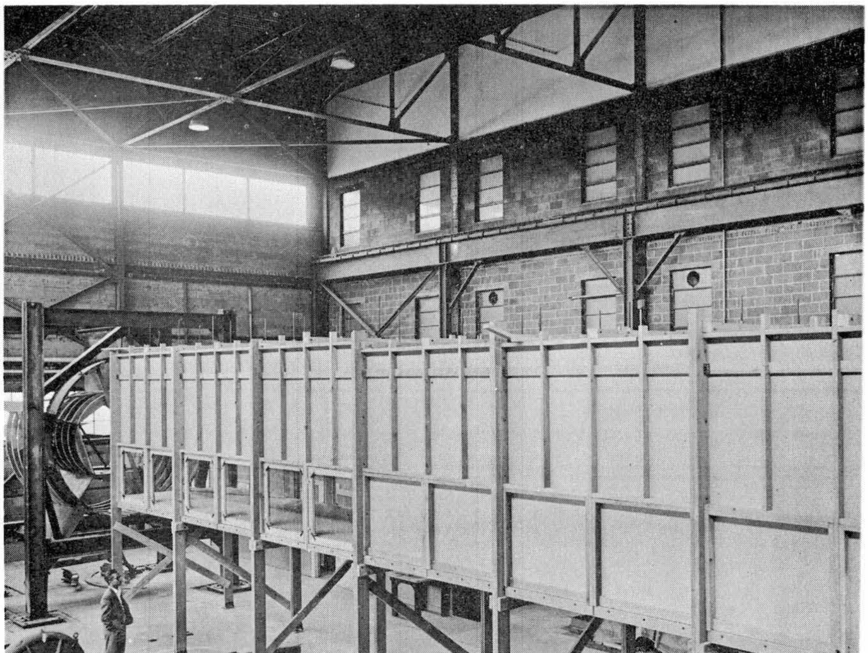

Fig. 13 Downstream exterior view of test section

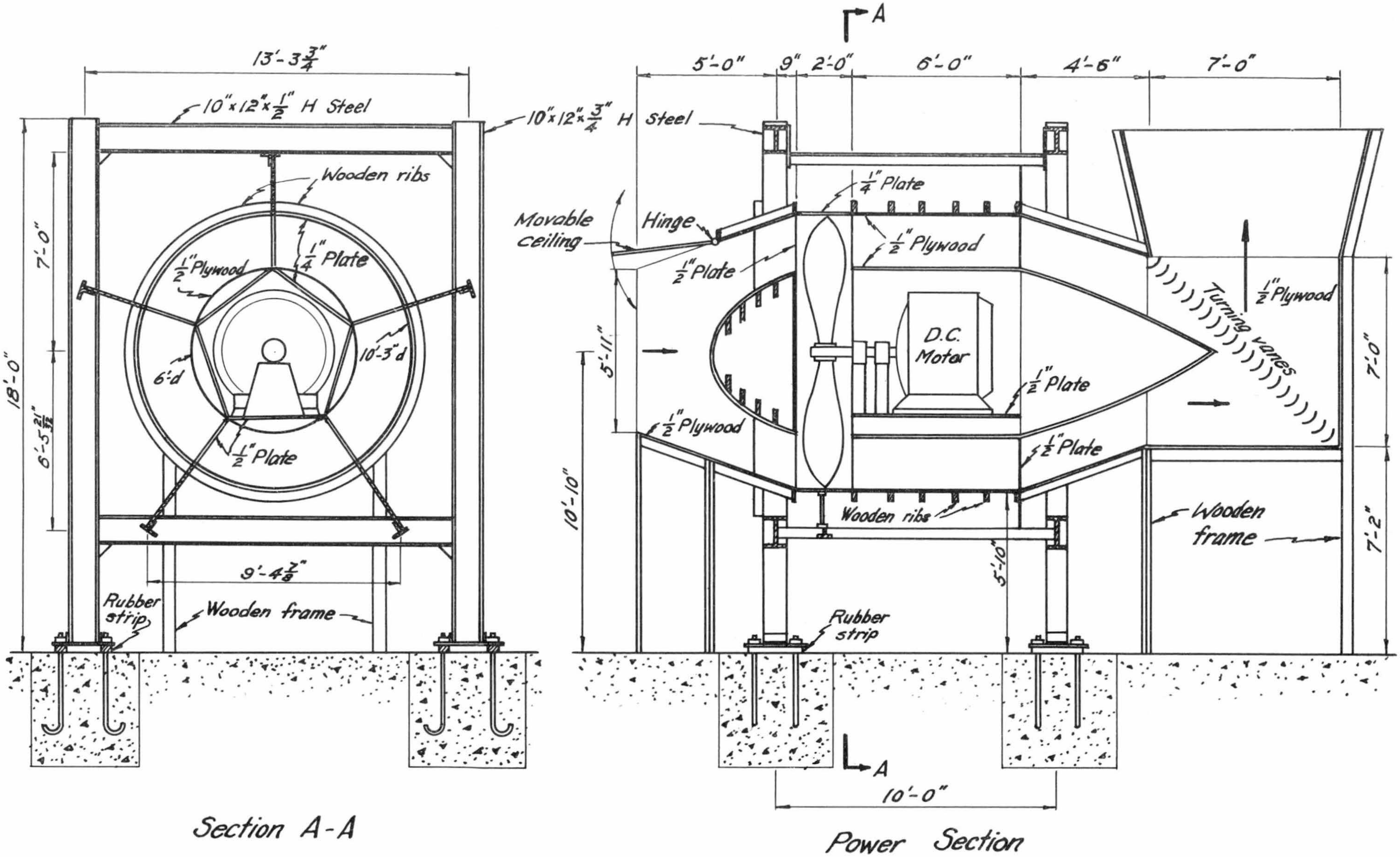

Fig. 14 Downstream and side elevation of power section

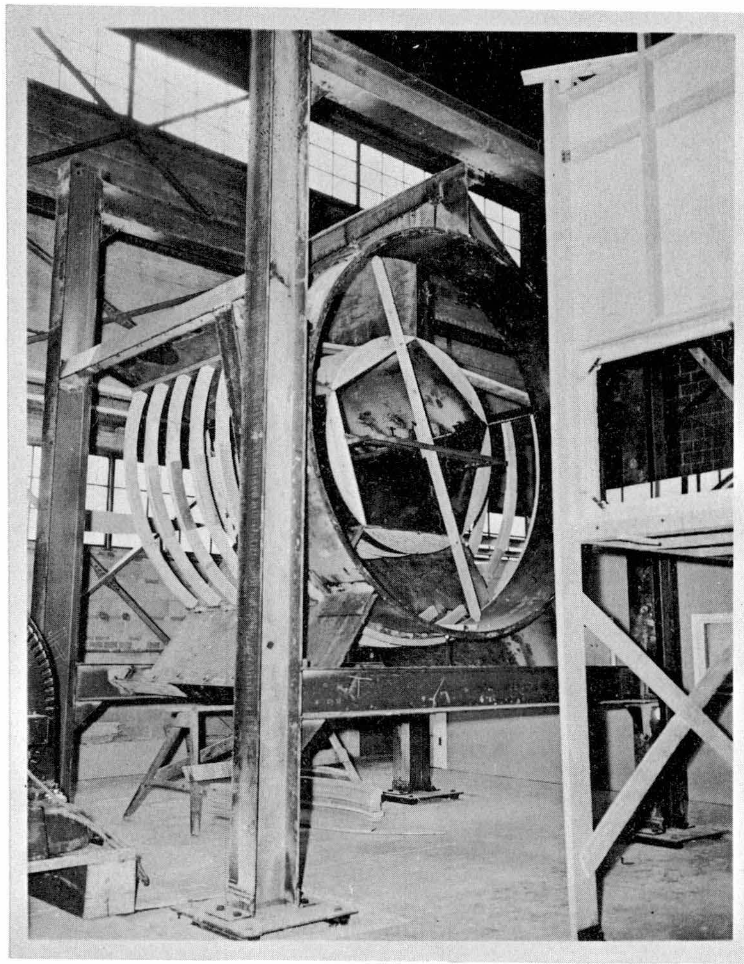

Fig. 15 Downstream view of power section

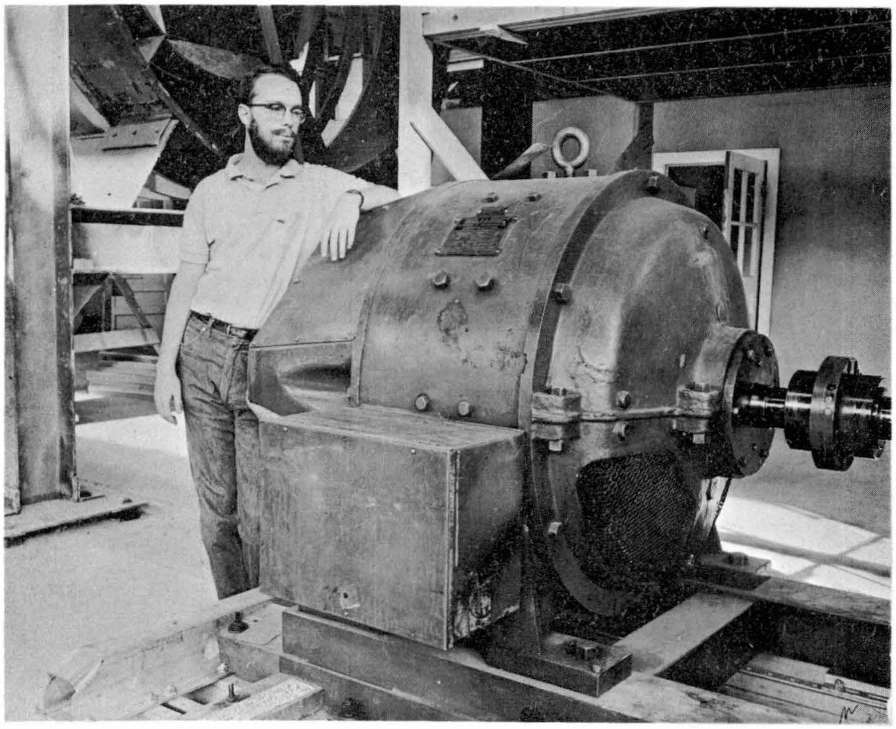

Fig. 16 Driving motor

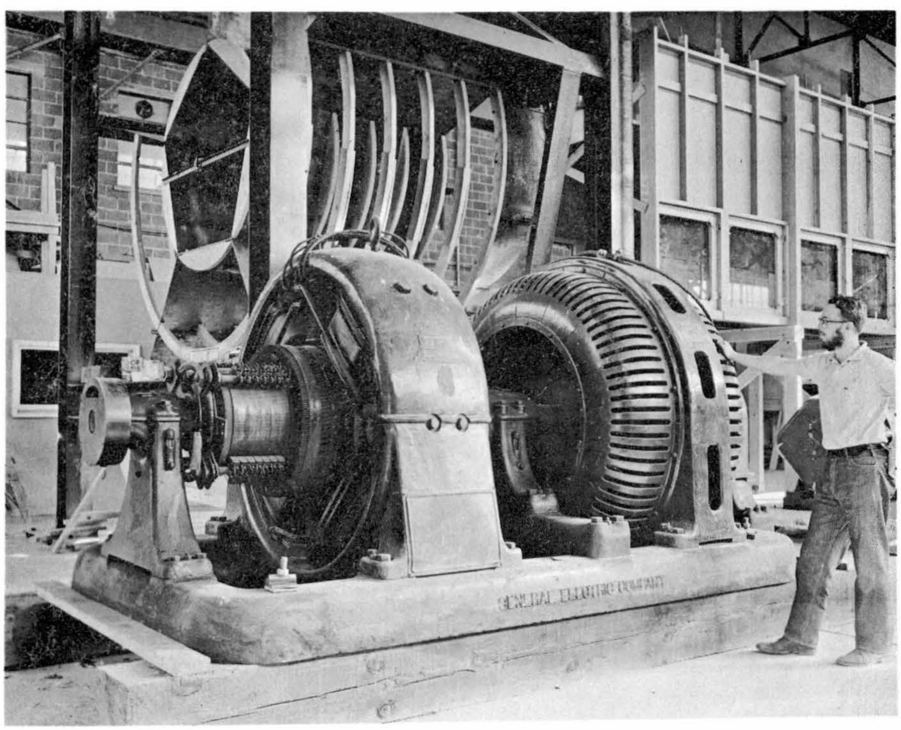

Fig. 17 Motor-generator power supply

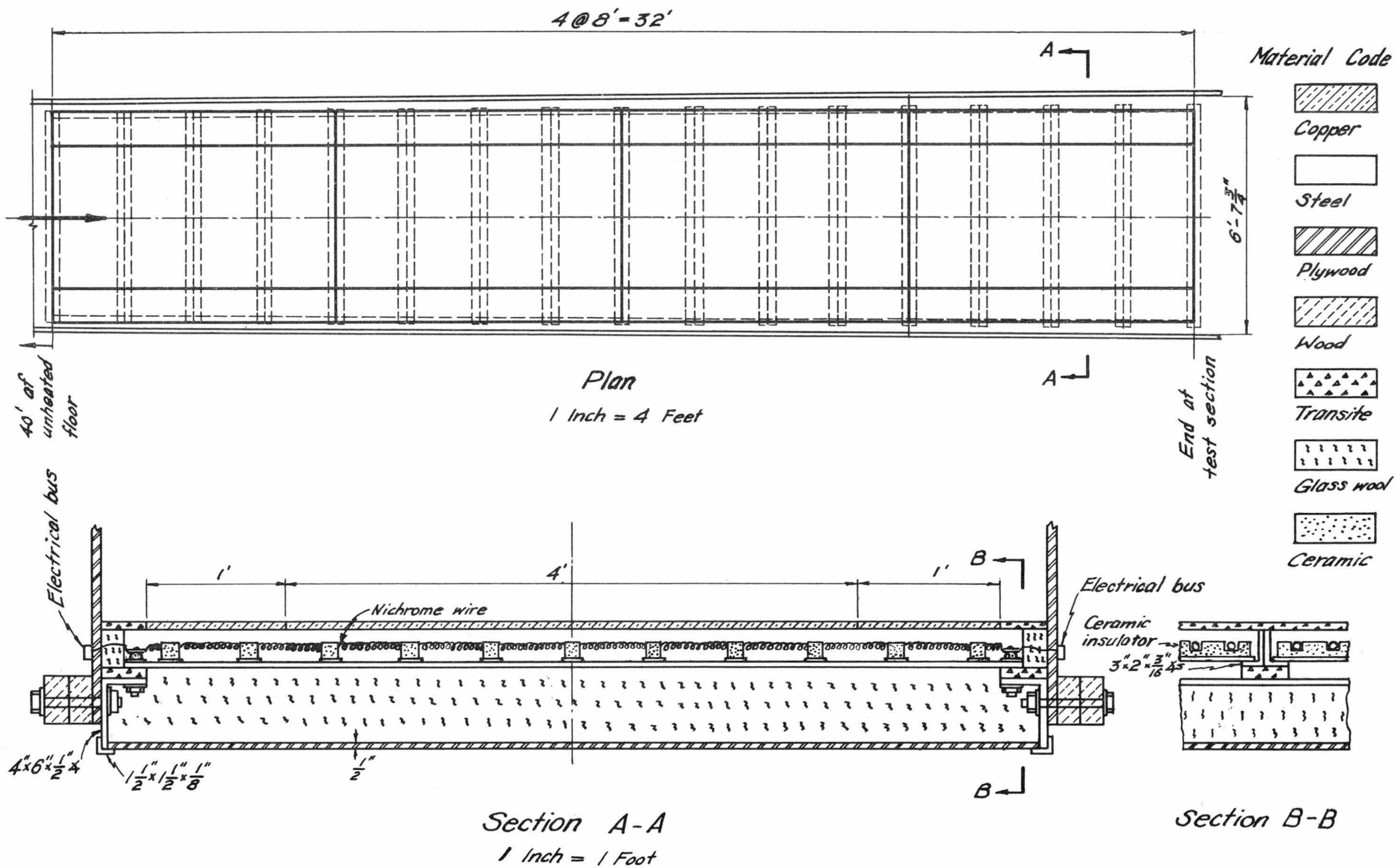

Fig. 18 Plan and section of heated boundary

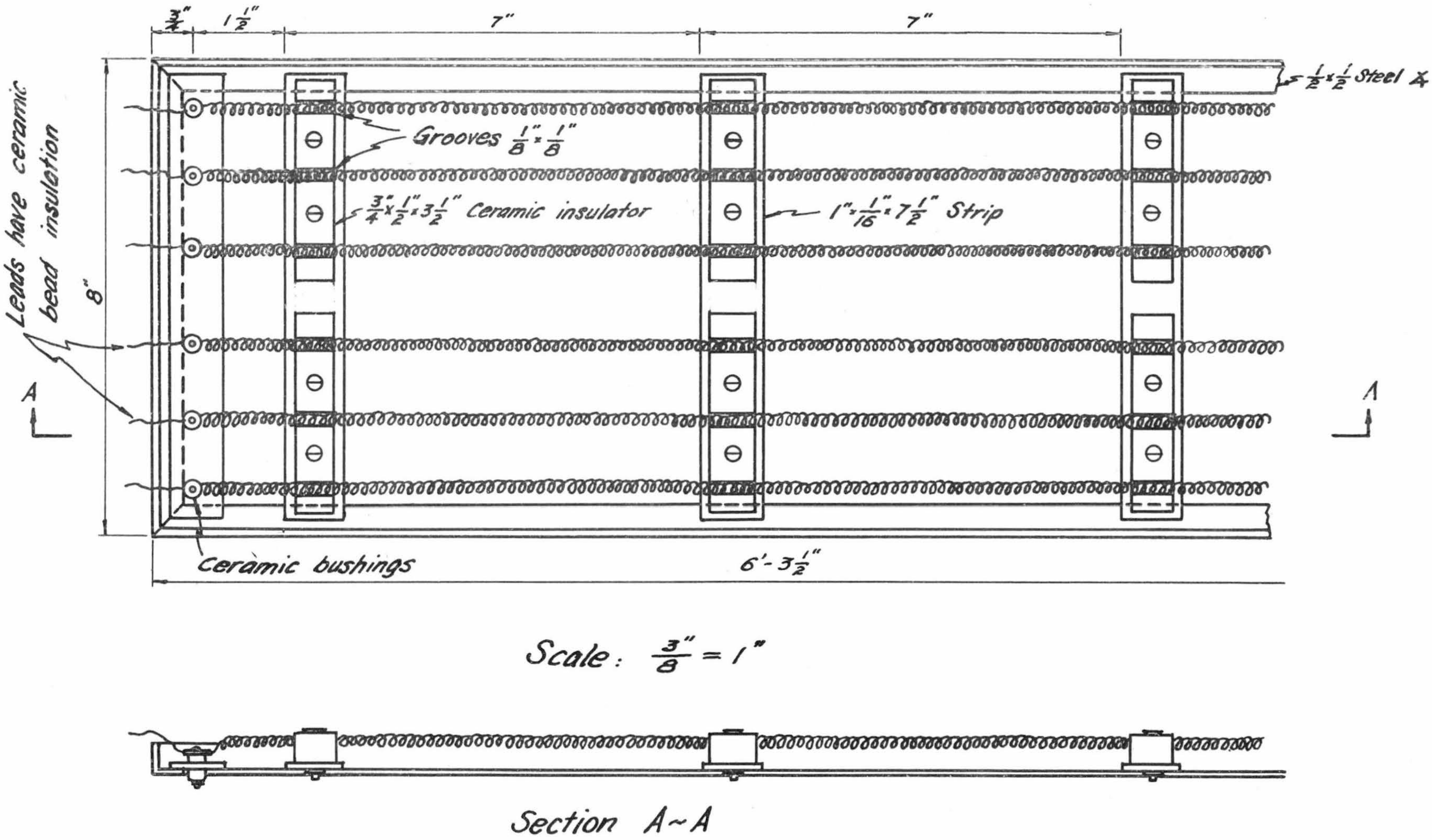

Fig. 19 Details of heating unit