MICROMETEOROLOGICAL WIND TUNNEL FACILITY

Description and Characteristics

by

Erich J. Plate

and

J. E. Cermak

Final Report
on
Contract No. DA-36-039-SC-80371
with
Meteorology Department
U.S. Army Electronic Research and Development Activity
Fort Huachuca, Arizona

Fluid Dynamics and Diffusion Laboratory
Colorado State University
Fort Collins, Colorado

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SUMMARY

The large micrometeorological wind tunnel constructed by Colorado State University for the U.S. Army under Contract DA-36-039-SC-80371 is described. This tunnel, located in the Fluid Dynamics and Diffusion Laboratory of the College of Engineering, features a test section of 88 ft length and a nominal cross-sectional area of 6 ft by 6 ft which can be adjusted for establishing negative and positive pressure gradients. A large contraction ratio of 9:1 in conjunction with a set of 4 damping screens yields an ambient turbulence level of about 0.1%.

The tunnel can be used for either closed or open loop operation. Test-section air velocities range from about 0 to 120 fps and the ambient temperature of the air can be varied from $32^{\circ}F$ to $180^{\circ}F$ at medium speeds. The humidity of the ambient air can be controlled.

The tunnel has a 40 ft section of the test-section floor which can be heated or cooled to permit temperature differences between the cold plate and hot air of $150^{\circ}F$ and the hot plate and cold air of more than $220^{\circ}F$.

A carriage system is available which permits remote placement of probes. Instrumentation associated with the facility consists of a complete system for sensing, analyzing and recording turbulence statistics and mean value of velocity, temperature and concentration (mean values only).

CHAPTER I

INTRODUCTION

Interest in the structure of the atmospheric boundary layer has greatly increased in recent years. The random wind forces on a missile during launch, scattering of radio waves, dispersion of air pollutants and other chemical and biological agents, evaporation of water from soils, plants and water surfaces are all phenomena which take place in the surface layer of the atmosphere. Due to the growing importance of these and related problems, the early qualitative or phenomenological descriptions of the flow field near the earth's surface are no more acceptable, and more detailed knowledge is required. This knowledge cannot be obtained by theoretical means because the mathematical tools available at the present time are not powerful enough to treat the mathematical equations describing the flow field. Therefore, experimental studies of the interactions between the flow field, the temperature field and the diffusion characteristics are necessary. Two approaches are available to the experimentalist.

The obvious approach is to design field experiments and let the atmosphere itself answer the questions which need to be answered. This method has, however, a number of serious shortcomings. Some of these are high cost related to problems and scope of instrumentation and to time delays due to ever changing conditions, the limited applicability of the results due to the fact that they contain influences of local topography and climatic conditions which make it difficult to apply findings to other locations, and the impossibility of being able to systematically vary the important variables.

The other method is to simulate the earth's boundary layer in a controlled laboratory environment. This is the main purpose for which the large micrometeorological wind tunnel described below has been constructed. The advantages of this method are that it is much less expensive in time and money and systematic programming of the variables is possible. Also, the instrumentation used for wind tunnel research is well developed and comparatively simple to use. The main shortcomings of wind-tunnel applications to micrometeorology are the requirement that the atmosphere must be scaled down while scaling laws for turbulent flow fields are not fully understood and that the

Coriolis forces produce effects on the flow field which cannot be simulated in the existing facility and therefore limiting the studies to small scale geophysical flows.

1.1 History of Facility

The first efforts toward wind-tunnel studies of the structure of atmospheric surface layers at the Fluid Dynamics and Diffusion Laboratory of Colorado State University began in 1954 under sponsorship of the Air Force Cambridge Research Center. These studies were made in a wind-tunnel test section 6 x 6 ft in cross section with a length of about 28 ft. A heated plate 10 ft long and 6 ft wide placed in the floor formed the main working section over which the structure of momentum and thermal boundary layers were measured. Results of these studies are given in Ref. 5 and descriptions of the wind tunnel and instrumentation are given in Ref. 4.

These early investigations showed that realistic modeling of the atmospheric surface layer could best be accomplished if the turbulent boundary layer was very thick, and if the surface could be either strongly heated or cooled. In other words, a facility was required which would permit large variations of the Richardson number to be made. On the basis of this knowledge a wind tunnel capable of wide variation in ambient air temperature and test-section floor temperature was designed having a test-section length of about 90 ft. Initial phases of the construction of this facility were sponsored by the Air Force Cambridge Research Center. The basic design of the system and construction accomplished under the AFCRC activity are described in Ref. 1

Continuation of the facility development was provided under Contract No. DA-36-039-SC-80371 through the Meteorology Department, U.S. Army Electronic Proving Ground, Fort Huachuca, Arizona. The facility completed under this sponsorship is described herein.

1.2 Specifications

Based on equality of velocities and Richardson numbers in both atmosphere and wind tunnel, a set of requirements was developed for the wind tunnel which was incorporated into the specifications of contract DA-36-039-SC-80371. These requirements also cover dimensions of the tunnel necessary to minimize entrance and wall effects.

1.2.1 Aerodynamic Characteristics

1.2.1.1 Test Section

The basic unit shall consist of a recirculating closed system type wind tunnel with a test section having approximate internal dimensions of six feet wide, six feet high, and eighty feet long, consisting of ten test section units each eight feet in length. In order to maintain zero pressure gradient along the longitudinal axis of the test section, the longitudinal slope of the test section ceiling shall be adjustable for the entire length of the test section in order to compensate for the turbulent boundary layer thickness growth specified in 1.2.1.4. The ceiling shall be supported from above by adjustment screws. The internal surfaces of the walls and ceiling units shall be aerodynamically smooth. The floor of each test section unit shall be removable. A 40 ft section of the test section floor shall be equipped with the necessary wiring and piping for cooling and heating. Boundaries of a desired roughness shall be installed over the existing tunnel floor. A total of 12 windows shall be provided in convenient locations. They shall be of thermally insulating material. The lower edge of each window shall not be higher than the top surface of the tunnel floor and shall extend at least two feet above the tunnel floor level. All windows shall be designed so that they may be easily opened to permit access to the interior working area.

1.2.1.2 Ambient Velocity

The drive motor shall be a direct current meter installed within the propeller-drive motor chamber at the exhaust end of the wind tunnel test section. Air movement through the wind tunnel shall be accomplished by a variable pitch propeller driven by the drive motor. The power installation shall consist of a motor-generator power supply; adequate wiring, switches, and protective devices; meters to monitor drive meter and propeller operations; and control circuitry to insure steady flow or permit controlled unsteady flow. The ambient velocity variability within the test section shall not exceed plus or minus two percent of the velocity setting for steady flow at the entrance test section unit. Continuous, stepless speed control in the velocity range of one meter per second to approximately 30 meters per second shall be provided for the ambient stream within the test section. Excepting the boundary layer regions, the ambient velocity variation across the entrance test section unit cross section shall not exceed plus or minus two percent of the center velocity.

1.2.1.3 Ambient Turbulence Level

The entrance unit of the test section shall be connected to a contraction section having a contraction ratio of nine to one and the contraction profile of the floor, walls, and ceiling of this section shall consist of two cubic parabolas joined together with consistent slopes at the inflection point of the profile in accordance with the design criteria of Ref. 1. The entrance of the contraction section shall be connected to a settling chamber which is provided with slots so that screens may be introduced into the entrance of the settling chamber. The screens shall reduce the turbulence intensity of the air entering the test section to 0.1 percent or less. To avoid turbulence shedding by the screen wire, the screen wire diameter shall be restricted in diameter in accordance with criteria established in Ref. 1 for the maximum ambient velocity of the settling chamber. The settling chamber shall be connected to the propeller-drive meter chamber by a suitable return duct. The return duct shall be designed with due caution to insure a minimum of turbulence generation in the recirculating air; all corners shall be provided with suitable turning vanes.

1.2.1.4 Turbulent Boundary Layer

The tunnel shall be so designed that the turbulent boundary layer in the last downwind test section unit of the wind tunnel shall be up to two feet in thickness at an ambient velocity of two meters per second with an aerodynamically smooth boundary surface. The boundary layer shall be up to three feet in thickness with an aerodynamically rough boundary surface.

1.2.2 Thermodynamic Characteristics

1.2.2.1 Insulation

The basic unit shall be provided with insulation externally covering all walls, floors, and ceilings with the exception of the windows specificed in 1.2.1.1. Insulation conductivity shall not be more than 0.07

British Thermal Units per square foot-hour for a one degree Fahrenheit temperature difference between tunnel wall and external wall. That portion of the basic unit which is at any time exposed to direct sunlight shall have a covering of reflecting material over the insulation. The basic unit shall be designed to prevent air leakage or exchange into or out of the return duct, settling chamber, and contraction section and to minimize leakage in the test section.

1.2.2.2 Ambient Temperature

The return duct shall be equipped with heat exchangers for heating and cooling the air within the basic unit. The cooling exchanger shall be operated by a refrigeration system which is located outside of the basic unit. The heat exchangers shall be designed for high efficiency with a minimum of turbulence generation. The heating unit shall be capable of raising and maintaining the air within the basic unit at a temperature of at least 50 degrees centigrade above the average temperature outside the basic unit. The cooling unit shall be capable of lowering and maintaining the air within the basic unit at a temperature of 20 degrees centigrade below the average temperature outside the basic unit with a power consumption of the drive motor at 75 kilowatts and the steady temperature of the air in the basic unit not lower than 0 degree centigrade. The heat exchangers shall consist of two separate coil systems, one of which to be either cooled or heated, and the other one cooled only. If necessary, defrosting of coils shall be accomplished by alternating temperatures between the coil systems. Automatic thermostatic control of the heating and cooling facilities shall be provided. The thermostatic control shall maintain steady ambient temperature of the air within the basic unit. For steady temperature conditions, the ambient temperature variability at the entrance unit of the test section shall not be greater than plus or minus two degrees centigrade for the temperature setting. Excepting the boundary layer regions, the ambient temperature variation across the entrance test section unit cross section shall not exceed plus or minus two degrees centigrade.

1.2.2.3 Ambient Humidity

The return duct shall be equipped with a steam spray system which is capable of adding a fine spray of steam into the air within the basic unit for humidification. The spray unit shall be located downstream from the heat exchangers. Removal of water vapor shall be performed by the cooling exchanger specified in 1.2.2.2. The humidification unit shall be capable to humidify the air in a controlled manner. The lower limit of humidification shall be given by the capacity of the air cooling equipment as determined by temperature requirements. The upper limit shall be given by the capability of the humidifiers to supply steam at a rate of approximately 2000 lb/hr, and by the requirement that excessive condensation in the tunnel must be avoided. Automatic humidity control shall maintain steady ambient humidity of the air within the basic unit. For steady humidity and temperature conditions, the ambient humidity variability at the entrance unit of the test section shall not be greater than plus or minus five percent relative humidity for the humidity setting. Excepting the boundary layer regions, the ambient humidity variation across the entrance test section unit cross section shall not be greater than plus or minus five percent relative humidity. The basic unit shall be so designated that liquid spray from the humidifier is not introduced into the test section.

1.2.2.4 Boundary Heat Source

The downstream portion of the test section shall be provided with a plane, smooth, heated floor which can be removed or interchanged with other floor units. The heated floor shall consist of separate units each having the length of 10 ft. The heated floor shall consist of four units. The heated floor units shall consist of plane, smooth, thick (1/2 inch or greater) plates of copper or aluminum heated from below by electrical heating coils. The heating coils shall be distributed so that the boundary surface temperature along the entire length and width of the heated floor is uniform. The boundary surface temperature variation shall not be greater than plus or minus two degrees centigrade. The heating units shall have sufficient power to raise and maintain the boundary surface temperature of the heated floor units at least at 100 degrees centigrade above the ambient temperature when the ambient temperature is 50 degrees centigrade, the temperature outside the basic unit is 25 degrees centigrade and the ambient velocity is 10 meters per second with aerodynamically smooth boundary. The heating units shall be insulated to minimize heat loss other than to the heated floor plates. Heat loss shall not exceed 5 percent of the heat output. The heat generation shall be continuously variable from zero to maximum heat output. Meters shall be provided to monitor the power consumption of the heating wires.

1.2.2.5 Boundary Heat Sink

The downstream portion of the test section shall be provided with a plane, smooth, cooled floor which can be removed or interchanged with other floor units. The cooled floor shall consist of separate units each having the length of the test section units (8 ft). The cooled floor shall consist of sufficient units so that the thermal boundary layer developed shall be of the same thickness as the turbulent boundary layer in the last downstream unit of the test section. The cooled floor units shall consist of plane, smooth, thick (1/2 inch or greater) plates of copper or aluminum cooled from below. The cooling shall be distributed so that the boundary surface temperature along the entire length and width of the cooled floor is uniform. The boundary surface temperature variation shall not exceed plus or minus four degrees centigrade. The cooling unit shall have sufficient power to lower and maintain the boundary surface temperature of the cooled floor units at least at 25 degrees centigrade below the ambient temperature of 30 degrees centigrade or more when the ambient velocity is two meters per second over an aerodynamically smooth boundary. The cooling unit shall be insulated to minimize heat gain other than from the cooled floor unit plates. Heat gain from other sources shall not be greater than five percent of the total cooling power. The cooling power shall be continuously variable from zero to the maximum cooling power. Instrumentation shall be provided to monitor the heat tranfer of the cooling units.

1.2.3 Instrumentation Characteristics

1.2.3.1 Sensor Mounting

The downstream part (approximately 60 ft) of the test section shall be provided internally with rails fastened horizontally to the test section walls three feet above the test section floor. The rails shall support a carriage extending across the tunnel which can be moved forwards or backwards along the entire length of the rails. At the middle of the carriage, a motor driven vertical support shall be provided. The motor drive shall be capable of moving the support both upward and downward, with the maximum possible displacement being approximately 2-1/2 feet. Another motor drive shall make possible a transverse displacement of the vertical support over a distance of approximately ± 2 feet from the center of the carriage. Indication of vertical and transverse position shall be on a panel located in the control room. The longitudinal and vertical displacement drive shall have their controls located outside of the test section. The rails, carriage, and vertical support shall be designed so as to minimize wind resistance and turbulence shedding yet maintain a steady, non-vibrating altitude when the ambient velocity is 30 meters per second.

1.2.3.2 Mean Velocity Hot-Wire Anemometer

A hot-wire anemometer unit shall be provided to determine the mean longitudinal wind speed in the range of one meter per second to 30 meters per second. The unit shall be designed to permit compensation for varying air temperature. The overall accuracy of the unit shall be plus or minus two percent of the true value throughout the above specified range.

1.2.3.3 Turbulence Measuring Hot-Wire Anemometers

Hot-wire anemometer units shall be provided to determine the longitudinal wind speed turbulence and the vertical wind speed turbulence. The frequency response of the units shall be within plus or minus one-half decibel through the range from zero to 4000 cycles per second. The overall accuracy shall be plus or minus five percent of the true root-mean-square value for each unit. In addition a computational unit shall be provided to determine the Reynolds stress from these hot-wire anemometers units to an accuracy of plus or minus five percent of the true value.

1.2.3.4 Mean Temperature Instrumentation

A temperature measuring unit shall be provided to determine the mean temperature in the range of zero to 150 degrees centigrade. The overall accuracy of this unit shall be plus or minus two percent of the true value in the specified range.

1.2.3.5 Plate Temperature Recording

A total of approximately 40 copper-constantan thermocouples shall be embedded in the plate which forms the cold or hot part of the test section floor. Their output shall be recorded on a two-speed multipoint strip chart recorder and shall be used for monitoring the manual adjustment of individual heating or cooling units.

1.2.3.6 Data Handling System

The data handling system shall permit the computation of the raw fluctuating data, cross correlations between two signals, root-mean square of randomly fluctuating signals, and spectra of such signals. The accuracies of instruments for these computations shall be compatible with each other and shall correspond to overall accuracies of approximately ± 5 percent of measured true value. The system shall consist of an rms-meter, a wave analyzer, a multiplier, a X-Y-recorder and an integrator, with all accessories necessary for proper operation of the system.

In this report the actual facility meeting these specifications will be described. The description will include the important points of the design without reviewing the design formulas or procedures. The former are either standard engineering principles applied to the specific tasks at hand, or the applications of formulas which have already been presented in an earlier report (Ref. 1) on the initial planning of the tunnel. The design of individual sections and parts went through numerous stages of development, and the final result is the product of a chain of improvements which were made even during construction. Experiences gained by shop and engineers during the design and construction of a wind tunnel for White Sands Missile Range (Ref. 2 and 3) have been very helpful at all stages.

CHAPTER II

BASIC LAYOUT OF THE WIND TUNNEL

2.1 The Laboratory

The large size of the micrometeorological wind tunnel exceeded the available space in the laboratory existing at the time development of the facility was commenced. Costly modifications to the building would have been required; and it became eminently desirable to move the whole laboratory into more spacious quarters. The decision of the University's administration to provide a new laboratory building for the Fluid Dynamics and Diffusion Laboratory was of considerable benefit to development of the facility especially since the new building could be designed to meet the requirements of the large micrometeorological wind tunnel.

The new laboratory building was utilized as shown in Fig. 1. The large wind tunnel occupies most of the East side of the building, extending out of it to the North. The part which is at present located outside of the building will at a later date be covered by a mezzanine between an office wing and the laboratory proper so that it all eventually will be inside.

A convenient space for the power-conversion equipment was found in the Southeast corner of the building. The power room is accessible for heavy moving equipment from the East driveway, and is separated from the remainder of the building to avoid excessive noise in the building.

Other conveniences included in the new building are a well equipped electronics shop, machine shop, and a small chemical laboratory. These services help make the laboratory self sufficient and contribute towards the goal of efficient and high quality research.

2.2 The Wind Tunnel

The layout of the wind tunnel is shown in Figs. 2 and 3. The tunnel operates generally on the closed circuit principle. The air leaving the power section is slowly expanded in a duct whose angle of divergence does not much exceed 7 degrees. At the end of this section the air passes through a set of coils which controls the air temperature to a desired level and with the aid of a set of steam nozzles, controls the humidity. In the corner sections the air stream is, at low speed in the large area of 18 ft x 18 ft, turned 180° to enter the converging transition section through the turbulence damping screens. Screens and transition sections serve to break down and eliminate all large scale velocity fluctuations, and to straighten and homogenize the air flow. Thus, when it enters the test section, the air flow is uniform across the entire tests section entrance and has a very low ambient turbulence level. Measurements taken at low wind speeds (about 30 fps) showed that the turbulence signal in the ambient air stream was hidden almost completely in the instrument noise, resulting in the conclusion that the turbulence level was well below the maximum permissible value required in 1.2.1.3 of the specifications.

The mean air speed in the test section was difficult to predict in advance, due to lack of adequate design information on the surplus equipment used. However, the maximum velocity obtained, namely 120 fps, exceeds considerably the maximum design speed of the requirements (item 1.2.1.2), and also the uniformity required was met or exceeded.

The tunnel can be converted from closed loop to open loop operation. The former is desirable if closely controlled environmental conditions with a minimum of air-flow variability is desired. In this case, the air is, as shown in Fig. 4a, guided through turning vanes in the south corner to return to the entrance of the power section. The open loop operation, manditory for diffusion or air pollution studies during which large quantities of tracer gases or materials would contaminate the ambient air stream if recirculated, can easily be obtained by opening the door which forms the south end of the southwest corner after lowering the turning vanes, and by turning the the southeast corner as a whole as shown in Fig. 4b. The modifying operation can be performed in less than a day.

2.3 Electrical Layout

The complex operation of the large micrometeorological wind tunel required an intricate supply system of all types of electrical power as shown in Fig. 5. The main lines are located underground. These are the 440 V 3 phase line from the main power panel to the bus ducts which supply the heating power to the test section floor, and the 440 V 3 phase line running from the main power panel to a convenient location near the brine chiller for furnishing the required power to pumps, compressor and controls of the temperature-control system. The third underground line leads from the DC drive to the motor of the power unit. Other outlets have been provided from the two main AC panels to furnish the power for the control room, lighting at the test section, the ventilation fans for the transformers of the test section heaters, and the housing in which the main DC drive motor is located.

Figure 5 shows the locations of the electrical outlets; the functions of the equipment connected to it will be described later. In general, an attempt has been made to keep all the power-conversion equipment concentrated in the power room, where the 200 KW motor-generator set provides power for the propeller of the drive, the 28 V DC motor-generator set furnishes DC power for all power needs in the whole laboratory. An inverter is also available to convert 28 V DC to 28 V 400 cycles. The 28 V DC and the 28 V 400 cycles supplies make it possible to use almost all aircraft electrical components, so that extensive use can be made of surplus equipment.

2.4 Layout of Refrigeration Equipment

The principle of the operation of the refrigeration and humidification equipment will be described in a later chapter. The physical layout of the system, however, shall be discussed in this section. It is shown in Fig. 6.

The main unit of the system is the brine chiller which supplies cold brine for all functions with the help of the pumps P1 to P4 and P6, and the equalizing tank. The cooling tower necessary for cooling the brine chiller's cooling water is located on top of the power room. The air intake and outlet for the cooling tower are connected to the outside of the building.

The control system for the refrigeration system is pneumatic. The air compressor for the control system is located near the south end of the east wall. The settings for the controls are done on the refrigeration-control panel in the control room, and the sensors for the system are fastened to the east wall of the test section entrance.

The humidifiers are located downstream of the refrigeration coils. They are directly supplied through control valves from the heating steam of the laboratory building. The same source is also used to supply the heat exchanger of the brine-heating system.

CHAPTER III

THE POWER SECTION

The design of the power section was to some extent determined by the propeller and drive obtained as surplus property. The design characteristics of the fan were only partially known, and no reliable calculations could be made on the maximum obtainable velocities. Furthermore, the design calculations as put down in Ref. 1 were based on open-circuit operation, and only minor revisions in the design could be made after the decision to use a closed-loop tunnel had been made. Under these circumstances, great care was used to make the air flow through the power section as smooth as possible, and to eliminate or minimize the known sources of energy losses. The end result was quite satisfactory, and comparatively quiet operation at test section velocities up to 120 fps were obtained.

3.1 Supporting Structure

The power section shown in Fig. 7 obtains its strength from 14" I beams which were received as surplus property. The four legs of the steel frame are supported by foundations separated by expansion joints from the rest of the floor. In order to further minimize transmission of power-section vibrations, rubber mounts are provided along two edges of the 1" steel plates welded to the legs. Plates and rubber mounts act together in damping vibrations.

The motor and propeller supports are connected to the main frame work by steel plates arranged pentagonally as shown in Fig. 7. The plates which connect the pentagon to the frame serve at the same time as straighteners for the air flow. Wooden-layer ribs are fastened to the pentagon, and a layer of 3/8" plywood screwed to the ribs completes the round motor housing.

A 1/2" steel plate forms the front end of the motor housing, and I-beam supports securely hold the pillow-block bearings (SKF spherical roller bearings Type 22224) which guide the propeller shaft. The shaft is directly connected to the propeller and transfers the propeller thrust to the pillow blocks. The connection to the motor is through a heavy duty flexible coupling (Type Dodge Paraflex PX 140) which compensates for small misalignments of shaft and motor.

The outside of the wind-tunnel duct at the power section is also formed by lumber ribs over which 1/4" or 3/8" plywood has been fastened. Between the ribs, insulation material was placed. This type of construction was used only over the length of the motor housing. Flanged circular sheet-metal sections were provided between motor housing and the end of the power-section structure. Sections adjacent to the power section were connected to it through channel-shaped rubber rings so as to not transmit vibrations through the connections. The rubber connections were bolted to steel flanges, with steel rings arranged inside the channel profiles in order to prevent air leakage.

3.2 Air Flow Guiding

Great precautions were taken to make the air flow in the power section as smooth as possible. The air enters through a transition section in which the cross-sectional area is gradually changed from square to round. This is accomplished by inserting a sheet metal section into the lumber section preceding the power section. It may be noted that this method of construction - square parts in lumber, transition parts in sheet metal - combines the lumber advantages of sound proofing and thermal insulation with the convenience of making difficult shapes of sections from sheet metal. The same type of structure was also used downstream from the power section.

It was thought that tip losses of the round tipped propeller might cause not only a considerable reduction in efficiency but might also introduce severe disturbances in the air flow. In order to avoid the tip effect as much as possible, the cross section diameter just before the propeller was narrowed gradually and the propeller tips were made to move in a groove inside the wall. The groove was produced with the help of soft polyethylene foam held in place and shaped by sheet metal sections.

The large obstruction offered to the air flow by the motor housing was smoothened by a nose cone and a tail section. Both were made from epoxy resin coated fiberglass stretched over wooden ribs which were fastened to a supporting structure of steel. The front end is of hemispherical shape, and it is so constructed that the bottom part of the hemisphere can be removed to permit major repairs on the pitch-control motor. The gap between motor housing and nose cone required for the propeller is wide enough to permit access to the propeller hub for smaller repairs. No need was felt to close this gap during operation, even though there exists no doubt that some of the noise heard in the test section at higher speeds must be generated here.

The tail end has a longitudinal cross section consisting of two circular arcs which have a horizontal tangent at the motor housing. The length of the arc is determined by the length of the section downstream from the power section. This section contains the transition from round to square leading to the expanding return duct. It was put on heavy casters so that it can be moved if repairs or major maintenance work is to be performed on the drive motor. It can be moved far enough to permit complete removal of the drive motor. For this purpose, all the bolts which connect this section with the power section and with the return duct have to be removed, an operation which requires about two days. To avoid going through this procedure during routine maintenance checks, the grease leads and oil lines of the bearings have been connected to nipples and wells respectively located on the outside of the power section.

3.3 Air Drive and Speed Control

The air drive consists of a variable-pitch, 4-blade Curtiss Aircraft propeller driven by a stabilized DC-motor which is air cooled by a DC ventilation fan. The major components are the propeller, the DC-motor and its controls, and the ventilation fan. They are schematically shown in Fig. 8.

The propeller consists of the four blades which are mounted in a common housing fastened to the drive shaft. The diameter of the propeller from tip to tip is 10 ft. At the shaft end the blades have gear teeth which mesh into the drive gears of the heavily reduced 28 V DC pitch-control motor which is located in a hub cone screwed to the propeller housing (so that the pitch-control motor is rotating with the fan). The leads of the electrical connections end in commutator rings in the drive shaft from which they are taken by a brush assembly and connected to stationary equipment. There are a total of 5 leads, one for each direction of rotation, one for the limit indication of each extreme position, and a common lead. Two more leads have been added to permit indication of the pitch. One of them is the ground which is connected to one side of a potentiometer winding strip glued to the bottom end of one of the propeller blades. The other lead starts at the potentiometer wiper which is fastened to the pitch-motor housing. With change in pitch the propeller blade is rotating with respect to the pitch-motor housing, thus changing the potentiometer resistance. The lead from the wiper is connected to an insulated pin located at the center of rotation of the hub front. A spring loaded carbon brush presses against this pin. It is fastened to the stationary supports of the fiberglass nose cone, thus completing the circuit.

All leads are run into the pitch-control unit located in the control room. The control circuit is shown in Fig. 9. The essential parts of the control circuit are the switch which permits change of direction of pitch, the two lights which indicate the reaching of the limit of the pitch setting, and the voltmeter which indicates the voltage drop across the potentiometer and thus the pitch position.

The limit switches are located on the pitch-control motor. They can be changed to permit operation within different pitch ranges. However, under normal conditions the limit switches are set in such a manner that the minimum pitch setting permits slightly backward speeds in the test section, and the maximum pitch setting permits running the fan to full load at the nominal speed of 1150 rpm. The latter setting makes it impossible to exceed the safe current without first reading the maximum voltage, which means that the electrical efficiency is always near optimum; and also that the maximum power capabilities of both motor and MG-set can be utilized.

The propeller is driven by a 250 HP DC motor with a maximum voltage of 230 V DC. The speed of the propeller is regulated within approximately ± 1 percent of setting by a DC control actuated through a feed-back signal which is produced by the tachogenerator located on the DC-motor shaft. The tachogenerator voltage can be read on an rpm meter (volt meter) in the operation station located in the control room. The DC volts and the current applied to the DC motor can also be read from meters in the operation station. This station also contains besides the start-stop push buttons for MG-set, ventilation fan, and DC motor, the potentiometer across which the reference voltage for the speed-control circuit is established.

The DC control panel has been supplied by Cutler Hammer Mfg. Co. It operates entirely with solid state devices. Some of the interesting features of the controller are the limiting of the inrush current during changes of the reference voltage, and the braking provided during deceleration by utilizing the generated power of the idling DC drive motor. The temperature and time stability for the present application is remarkably good. The present system uses, in addition to the DC control, a Clark Co. starter for the synchronous motor of the 200 KW motor-generator set which supplies the power for the propeller drive. The MG-set had to be re-aligned and the commutators reground before using, but otherwise the set could be used as received through surplus equipment channels.

Since the ambient air temperature of the wind tunnel might be as high as about 180°F, some precautions had to be taken in order to avoid overheating of the motor under full load in the heated aristream. For this reason, thermistors have been wound into the field windings of the DC motor, and if a temperature of the windings should be reached which after some time might cause damage to the motor, an alarm light flashes on the operator's panel in the control room.

In order to prevent temperature build-up, a ventilation fan has been installed which constantly blows outside air over the motor. The ventilation fan is a 2 HP axial fan (Wing Co.) with 230 V DC motor which was obtained from surplus equipment. A selenium rectifier bridge is used to convert 3 phase 208 V AC into 230 V DC. The ventilation fan is started from the operation station in the control room, and an interlock exists which makes operation of the DC propeller motor impossible unless the ventilation fan is started first.

CHAPTER IV

WIND TUNNEL DUCT

For the construction of the wind tunnel duct a standard design as shown in Fig. 10 was chosen. This consists of an outside supporting steel I-beam and channel frame to which 2 x 6 lumber frames-bolted together at the four corners-were fastened. Against the inside of the lumber frame 3/4-in. plyboard was screwed. In order to avoid moisture from penetrating through the plyboard, great care was taken to carefully caulk all joints, and the 3/4-in. plyboard was painted on both sides with aluminum paint before it was fastened to the 2 x 6 frames. After installation another coat of paint was applied to the inside.

The two coats of paint for the inside of the return duct have been of considerable concern. This paint has to withstand temperatures of up to 180°F without cracking or permitting the plywood to be damaged by either temperature effects or high humidity. In order to find a combination of paint which would serve this purpose, a number of tests were made. One test was made in a dry oven. The temperature of the oven was raised to 200°, and samples that had been painted in different ways were placed into it. The second test consisted of placing samples painted with different paints into a basin filled with boiling water for at least 12 hours. Both conditions were considered to be more serious than any that would ever be encountered in the section of the wind tunnel. The best combination of paint was chosen as a result of these tests. It consisted of two coats of aluminum paint, one of which had been obtained through GSA surplus equipment. However, some blistering of the paint under severe humidity and temperature conditions must be expected and appears to be unavoidable.

Against the outside of the 3/4-in. plyboard, that is, between the 2 x 6 lumber frames, a high quality insulation material was glued. This insulation material had to have the properties that its thermo-conductivity would not exceed 0.07 BTU per square foot hour per degree Fahrenheit as required in paragraph 1.2.2.1 of the specifications. Additional requirements were that the material should not settle under the type of vibrations that are to be expected. The insulation material chosen was a 4" layer of No. 75 "Ultralite" insulation material made by the Gustin-Bacon Mfg. Co., which consists of resin-bonded long glass fibers.

4.1 Return Duct

Downstream from the power section the return duct expands slowly from a circular section with a 10-ft diameter to a square area with a 18 x 18 ft^2 cross section. The angle of expansion is approximately 7^o, thus no separation need be expected due to the unfavorable pressure gradient in the expanding section.

At the end of the expanding duct section the cooling coils of the refrigeration control system are located. The arrangement of the coil section is shown in Fig. 11. The refrigeration coils are bolted to channels which form the wall supports. In the center of the section a column has been built of angle irons arranged in a manner resembling a streamlined strut. Between the angle irons steel plates are welded on which the refrigeration coil can slide. The coils are not fastened on this end to permit sliding of the coils under the influence of temperature. The three columns holding the coils in place are placed on separate concrete foundations. The bottom parts of the coils are lowered below the plywood level, and a stainless steel drip pan has been placed underneath them. The drip pan has drains to permit safe draining of condensate during operation at high humidities.

The headers and the control valves for the refrigeration coils are hidden in insulated wing sections right and left of the coils. Access to the headers for routine inspection is obtained through a door which leads from the inside of the tunnel duct into the header chamber. For removal of the coils or for larger repair operations, the back end of the header chambers, which consists of three individual panels, can be removed. It might become necessary to take the refrigeration coils out of the wind tunnel for using the large 18 x 18 ft sections for models of large scales.

The humidifiers (which are not shown in Fig. 11), consists of perforated pipe covered with a wick like material. They are located directly downstream from the refrigeration coils. Into each half of the return duct a set of 4 humidifier pipes are horizontally placed at equal intervals.

Downstream from the refrigeration coils the air is turned 180° through large sets of turning vanes. These turning vanes are located in that part of the duct which is outside of the wind-tunnel building. Additional protection had to be provided on the outside of this section. The walls of the outside duct are covered with corrugated sheet metal, and a sloping roof is placed on the top.

After leaving the corner section, the airstream moves through a short stilling chamber and then through a set of screens. The screens are made of stainless steel mesh with a wire diameter of 0.0075 in. and with 24 x 24 meshes 1 in.^{2} The screens have been mounted in 2 x 12 lumber frames under tension. The lumber frames are made from clear fir. The screens can be removed for cleaning or replacing.

The transition section starts directly downstream from the screens, without any additional stilling chamber. The curvature of the walls follows the shape of two cubic parabolas whose apexes are at the horizontal ends of the section, and which join with a common tangent. The 8 ft long section downstream from the transition is shaped to provide a smooth transition from the entrance to the slowly expanding sides of the test section. In this entrance section, the sensors for humidity and temperature which control the ambient air humidity and temperature are located. The test section itself is described in 4.2.

The corner sections downstream from the test section have been designed to facilitate the conversion from open to closed loop operation described in 2.2. For this purpose the south west corner was made to consist of a heavy steel frame. The turning vanes were constructed so that with the vanes in closed loop position their bottom plate closes the tunnel floor and the vanes rest on a bolt pushed through the angle irons which form the guides for moving the vanes. When the vane section is lowered and resting on supports welded to the steel legs of the section the top plate of the vanes forms the closure to the outside. The vanes are raised or lowered with the help of a fork lift.

With the turning vanes in the tunnel duct (closed-loop operation) the door which forms the south end of the corner section is held firmly closed by the vanes resting against it. For open loop operation, the door is opened. This is not difficult since the door is made to move easily on heavy hinges and has a caster built into its bottom part to prevent sagging of the door under its own weight. The open-loop duct to the outside has been designed to expand gradually, and its ceiling is curved to better streamline the flow to the outside. It can be closed by a large sliding door against the outside to prevent dust, snow and other subjects from collecting in it when it is not in use.

The duct between the two corners diverges from a 6 ft - 9 in. by 6 ft section at the exit of the southwest corner to an 8 ft - 10 in. squared section at the entrance to the southeast corner. The southeast corner (Fig. 12) consists of a heavy steel frame which serves mainly for supporting the large cup bearing which holds the turntable centershaft and carries the main weight of the rotating corner. Floor and bottom turntable of the corner have some additional support from casters which are fastened at those points of the turntables where least support from the turning vanes or the walls can be expected. The caster tracks are fastened to the corner steel frame.

The conversion of the southeast corner from open to closed loop operation is more difficult than the conversion of the southwest corner. The rotation requires more torque than can be supplied by man power alone, and an added problem is that all gaps must be sealed after each conversion.

The duct to the outside from the southeast corner is also not insulated. It is only about 10 ft long and can be closed by a sliding door. Into its entrance opening a set of filters has been inserted which make it possible to keep dust out of the tunnel during open-loop operation. The filter frames are permanently mounted. The filter elements however, can be replaced conveniently.

4.2 Test Section

A test section which meets the numerous requirements set down in the specifications had to be designed with considerable care. No attempt will be made in this description to cover all the points considered and the basis for the final decisions except for the major features.

The test-section construction was governed to some extent by the fact that the majority of the 8 ft sections of which the test section consists were already available and had to be adapted to the requirements for the modified tunnel. Most of the modifications resulted from the installation of a steel frame on the outside of the tunnel which became necessary for increasing the stability of the test section legs and for providing a support for the aluminum plate which forms part of the test section floor. The details of the frame work are shown in Fig. 13.

The test section is gradually expanding from a width of 6 ft to 6 ft 9 in. at the rate of 1 in. every 8 ft. This expansion was provided for maintaining the pressure gradient along the test section at approximately 0 for average velocity conditions. For modifying the pressure gradient for test requirements the ceiling has been made adjustable. This posed three design problems. The first was to support the ceiling so that it can be moved up and down in the expanding wind-tunnel test section. This was accomplished by fastening two threaded rods of 1/2" boltstock every 4 ft to the ceiling supporting 2 x 4's in such a manner that they could freely rotate without moving up or down. The other end of the rod was screwed through a nut welded on angle irons which form the top of the steel frames. The screws can be turned by using a hand crank. The end of the ceiling was clamped across the test section width to the end of the transition section so that the tangent to roof of transition section and ceiling remains continuous.

In order to permit free motion of the ceiling in the expanding section, the gap between the ceiling plywood and the side walls had to be fairly wide. This gap posed the second design problem because it would seriously disturb the air flow if left open. A mechanism was designed which permits sealing of the ceiling against the sidewalls by the throw of a lever. This consisted of a rubber j-seal fastened to the ceiling which could be pushed against the sidewalls or could be retracted through an angle iron - pushrod arrangement as shown in Fig. 13 (see also detail A of Fig. 15). The pushrods are fastened to a long rod running along the length of the adjustable ceiling which is connected to a lever as shown in Fig. 2.

The third major problem resulting from the adjustable ceiling was the joining of the free end of the ceiling to the fixed ceiling at the downstream end of the test section. The resulting design is shown in Fig. 14. In this part the test section did not expand, the moving parts could therefore be parallel edged. The ceiling consisted of sheet metal sliding in guiding slots and supported by sliding brackets on top. No attempt was made to seal the ceiling in this part. Instead, a permanent roof was placed over this wind tunnel section, and a gate is used to close the roofed section from the outside.

The expansion of the test section necessitated also a special method of fastening the carriage rails. A wedge 1-5/8" thick was placed between rail supporting angles and the walls. However, it did not seem advisable to extend these wedges over the total length, since this would have meant a wedge width of approximately 5-1/2" at the downstream end of the test section. Instead, the carriage was designed so that it could be expanded by 4 in., and the rail was spaced 4 in. wider apart in the downstream 50 ft length than in the upstream part of the test section.

The floor of the test section partly consists of plywood panels which can be removed from below (by removing first the insulation and its cover from the floor bottom), and partly of aluminum sections which can be heated or cooled.

A detail of the aluminum floor is shown in Fig. 15. To the bottom of the plate, 104 rectangular aluminum conduits with an inside cross sectional area of 1/2" (height) by 1" (width) have been welded. Special care had to be used during the welding process so that the plates would not warp under the influence of thermal stresses. After detailed investigations of numerous possible methods, it was decided to use a special high speed aluminum welder for this purpose and to only spot weld the ducts to the plates. The small deformations which were, according to preliminary tests, still to be expected, were avoided by a compensating predeformation. The welding of cooling ducts was one of the most crucial problems of the whole construction, and the highly satisfactory results were most gratifying. Measurements on the installed plate showed differences between minimum and maximum elevations of not more than 1/16".

The brine conduits are closed on both ends and holes are drilled to their undersides near the ends into which connectors for the copper coils leading to the brine supply headers are welded. The connectors are of a type that permits small rotations without breaking the seal. This design was necessary to accomodate dimensional changes during the large temperature changes of the plate.

The brine ducts are spaced such that a uniform flow of brine of equal and minimum temperature through them will cause, at an ambient air temperature of 180°F and an air velocity of 30 meters per second in the test section, a constant temperature along the length of the plate of about 40°F. This required spacings ranging from 2" between duct centers at the leading edge of the aluminum plate to 5" everywhere along the last 30 ft of the plate. The spacing at the downstream end could have been larger for meeting specifications; it was feared, however, that the uniformity of the temperature distribution along the plate would suffer if the spacing was too large and a spacing of 5" was considered, on the basis of heat transfer calculations, the maximum permissible distance between conduits.

In order to avoid temperature gradients transversely across the plate - which might induce secondary convective currents especially in low velocity air flows, or disturb flow patterns under conditions where forced and natural convection processes are of equal importance - a total of 4 brine headers were installed, with alternate brine ducts under the plate supplied from alternate sides. The ducts were dimensioned to allow a temperature drop across the section of no more than 1°F.

It was calculated that the change in temperature from the top of the aluminum plate to the cooling ducts at most severe operation conditions would be about 18°F; for a minimum temperature of about 40°F to exist at the plate surface, therefore, a brine temperature of less than 22°F is required - a condition which determined the lowest brine temperature.

Cooling of the plate is controlled in two different ways. The overall temperature level is governed by the brine temperature, which therefore was made adjustable. Fine control of local temperatures to meet the specifications or the test requirements is accomplished by adjusting the flow rate of cooled brine through the individual ducts. The procedure for accomplishing the former is explained in Chapter V, while the procedure for the latter consists of throttling the valves of any duct to the required degree. It is anticipated that the adjusting of the valves for setting a desired test condition may take considerable time, however, the time for each adjustment to reach equilibrium in the new state appears to be only of the order of minutes, so that with some practice it should be possible to adjust the settings of the 104 valves to a new test condition in one or two days.

For heating the plate, tubular heaters were fastened to the aluminum plate between each pair of cooling ducts. The heaters were tightly clamped by a screwed on conduit clamp to the aluminum plate, thus insuring a good rate of heat transfer directly to the plate. They were designed by using existing heat transfer equations for forced convection from a flat plate of constant temperature; with coefficients which had been modified to incorporate results obtained with the heated floor section of the small wind tunnel of the Fluid Dynamics and Diffusion Laboratory. Each of the tubular heaters has a rated capacity of 3000 Watts at 220 Volts AC, and they are connected two in series and used on a 440V AC supply. The voltage to each pair of heating elements is supplied from a variable-voltage transformer. The heaters are never used at full capacity; they are designed to produce a heat output sufficient to meet the requirements at a temperature of the heater surface which is well below the melting temperature of the aluminum plate. At present, the heat input into the plate is limited by the maximum transformer current of 9 Amperes (or 1300 Watts per heater) through the series connected heaters. This can, if a demand for higher temperatures becomes apparent, be increased to a maximum current of 13.5 Amperes without changing either transformers or heating units.

The 52 transformers are connected through a system of fuses - one on the input side, and one on each load lead - to the heaters and the bus duct. Between heaters and input a switch panel is connected which makes it possible to determine the power input into each pair of heating units by separately measuring the input voltage and the input current. A switch is provided to open a path for the amperemeter and to shut down individual heating units.

The bus line supplying the power for the heaters is made of aluminum bars, joined and reinforced every 10 ft, and supported by heavily insulated steel angles. The transformers rest on sheets of asbestos cement plates - transite - to decrease the chances of accidental shorting. Transformers and bus bars are completely enclosed by: a hinged rear door to which the fuse holders are bolted, a drip cover of stainless steel on the top, the control panel in front, and the transite covered plyboard floor. At the downstream end, the enclosure has a cover into which a small ventilation fan has been placed which provides cooling for the variable-voltage transformers.

The heating of the plate is adjusted by means of the variable-voltage transformers. Initially, the transformers are set at an approximate value, and fine adjustments are made as required.

For monitoring the temperatures of the plate, copper-constantan thermocouples are embedded into the plate at 1 ft intervals along the plate centerline. The thermocouple is cemented with a ceramic cement into a hole drilled axially into a 1/4" bolt in such a way that the junction protrudes slightly through the end of the bolt. The thermocouple is then screwed into appropriate holes of 13/16 in. depth into the 7/8 in. thick aluminum plate. The thermocouple output is read out and recorded on a multipoint strip chart recording potentiometer made by Minneapolis-Honeywell. The recorder is equipped with two speeds, one which prints at about one point per second, and the other at about one point per minute. The latter will be used for providing a continuous record of plate temperature during an established experiment. The high speed is used for checking the temperature distributions during the initial set up period when the local temperatures are being adjusted.

Since there are only 24 points on the recorder while a total of 40 thermocouples have to be read - at least during set up time - 20 thermocouples each are combined in a high accuracy connector and the desired set of thermocouples is plugged into the receptacles of the recorder. The recorder is located on the refrigeration control panel of the control room, thus faciliating convenient checking of all thermocouples at temperatures up to 400°F.

The structural design of the aluminum plate's supports was governed by the requirement of strength, of thermal expansion, and of removability of the individual sections. In addition insulation is required which shall help to keep the heat losses from the bottom of the plate at low values and which shall prevent the structural steel from transmitting excessive heat to the plyboard of the tunnel walls in order to avoid fire hazards. The problem of allowing for the thermal expansion under the large temperature differences between minimum and maximum operating temperature - a total of 2.5 in. extension between maximum and minimum must be expected - required that the plate as a whole be entirely separated from its steel supports so that it can expand independently. For this purpose, all aluminum plates were fastened together at the ends, and only the center is bolted to the steel substructure. The substructure consists of two 1/2 in. x 6 in. steel plates which support the plate edges directly, and two I-beams connected to the plates through welds on 1/2 in. x 4 in. steel plates. The cooling conduits rest on the I-beams as shown in Fig. 15.

An attempt was made to keep steel supports and aluminum plate as the only parts that would be subjected to large temperature changes, and then control the direction of expansion by fastening one point only to the test section structure. The device for restricting the freedom of motion consisted of two 4 in. x 1/2 in. steel plates, whose 4 in. side was parallel to the test section axis, and which connected to both 1/2 in. x 6 in. plates of the aluminum substructure and to the 6 in. channels which form the main support (item 7 of Fig. 15). These spring like plates permit expansion of the aluminum plate in the transverse direction but hold the center in place with respect to motion in the axial direction of the test section. In order to make sure that the aluminum and its support would actually slide instead of binding to the supports the steel support rests on a double layer of sheet metal on a 1/4 in. steel strip. The latter has the additional purpose of spreading the load evenly over the asbestos-magnesia blocks which serve as insulation between the fixed part of the test section and the aluminum plate.

The magnesia-asbestos blocks shield the sides and the support surface against excessive heat from the plate in a very effective manner. During one test run at which the plate temperature was raised to about 260°F with the air temperature at approximately $60^{\circ}F$, the aluminum edging - which forms the outside corner of the lateral asbestos cement insulation to prevent it from being damaged at the windows - stayed at about room temperature. Also, no indication of much temperature elevation was noticed on the steel frames outside of the insulation.

The supporting structure of the plate which connects to the outside steel frames of the test section is made in 10 ft sections which can be unbolted and removed if so desired. However, this will never be an easy matter, and should be done only in exceptional cases.

The front end of the supporting structure forms the control panel with the handwheels of the valves for the cooling ducts, and with the transformer knobs and dials of the heating system. The panels which provide outlets for measuring current and voltage of heating units are also located on the plate control panel.

Two by four beams have been fastened to the cross angle irons of the supporting structure. The bottom insulation of the aluminum plates is placed on these over expanded metal lath.

The copper tubings leading from the brine supply headers to aluminum cooling ducts had been shaped to permit some motion with the expansion of the plate. They will not contain any brine during tests with a hot plate because of the possibility of generating high pressures in the line due to heating of the brine. Instead, the brine will be pumped out and stored in the mixing tank of the refrigeration system before the plate is heated.

CHAPTER V

THE REFRIGERATION SYSTEM

The refrigeration system constituted the largest subcontract on the whole wind tunnel construction project. Considerable efforts of both the subcontractor - York Corporation - and Colorado State University engineers went into its design, with an exchange of ideas taking place which resulted in a final system satisfying to both parties.

5.1 Design Cases

The first problem in designing the refrigeration system and its controls was to translate the contract requirements into a set of engineering specifications. For this purpose, the exchanges of heat and humidity at the coils, thermal flux rates, defrosting problems, and the influence of the plate under heated or cooled conditions, were considered and it was found that a refrigeration system would meet all the specifications if it could meet the requirements of the eight cases presented in Table 1.

Table 1. Specifications for Refrigeration System

Case	Power input of drive (KW)	Air			Plate Temp ^{o}F	Heating (H) or Cooling (C) requirements (BTU/hr)		
		Velocity fps*	Temp ^{o}F	% Relative humidity		Plate	Bank 1	Bank 2
1	20	30	180	Low	40	50,000 C	250,000 H	50,000 C
2	20	30	180	---	Ambient	-----	200,000 H	40,000 C
3	75	70	35	Low	Ambient	-----	230,000 C	230,000 C
4	75	70	35	High	Ambient	-----	460,000 C	(460,000 C)
5	75	70	35	Low	200÷300	el. heating	460,000 C	(460,000 C)
6	75	70	35	High	200÷300	el. heating	460,000 C	(460,000 C)
7	200	110	50	---	200-300	el. heating	460,000 C	460,000 C
8	200	110	80	---	40	250,000 C	230,000 C	230,000

*Estimated velocity in test section

Case 1 represents operating conditions for which, due to the fact that the heat input from the fan is low, additional heating of the air flow is required by heating of the brine flowing through parts of the coil area. However, for maintaining humidities at controlled levels, part of the coil area must also be cooled to remove excess humidity faster than the plate alone can do. The same conditions are to be satisfied for case 2, except that due to no requirements on the plate temperature, the humidity may be controlled at a higher level.

Cases 3 to 6 are approximate average conditions with air temperature kept low and plate temperature at ambient or high temperatures, while humidity is either high or low controlled. These cases differ only in area requirements for cooling coils, with a maximum cooling requirement well within the limits set by cases 7 and 8.

Case 7 determines the maximum requirements for cooling the air and heating the plate. The requirements somewhat exceed the contract specifications, but the capacities are not excessive in view of the fact that considerable cooling capacities are required for controlling ambient humidities.

Case 8 represents the other high-speed extreme at which the plate is cooled and the ambient air is at high temperature. Initially during the build-up time this case may actually require heating of the brine, however, when equilibrium is reached the heat input from the propeller is so large that cooling becomes necessary. Case 8 mainly sets the maximum plate-cooling requirements.

On the basis of these design cases it was found that the refrigeration system must have the following features:

a. the coil area must be adjustable,
b. the coils must be designed to permit independent heating and cooling of parts of the coil areas,
c. plate cooling and coil cooling must be simultaneously possible,
d. plate heating and coil heating must be simultaneously possible,
e. plate cooling, and coil heating and cooling must be possible simultaneously.

5.2 The Refrigeration System

A system which satisfies the design cases of Table 1 had to consist of essentially three independent loops, one for the supply of the plate, and two for supplying the cooling coils which are located in the widest part of the wind tunnel downstream from the expanding return duct section.

The coils were connected to the two systems in a checkerboard pattern as schematically indicated in Fig. 16. This particular pattern, though requiring two additional headers on each side, has the advantage that even with one loop only in operation a comparatively uniform temperature distribution within the airstream can be obtained.

Naturally, the individual coils have their inlets and outlets on the same side, in contrast to the schematic representation of Fig. 16. Therefore, an approximately equal flow rate is obtained for each coil. For corrections the valves which make it possible to completely disconnect the rest of the system from the coils, can be used for throttling the brine flow.

The arrangement of the headers for the plate cooling system has already been described in paragraph 4.2.

The principle of operation of the refrigeration system is as follows:

The brine chiller provides cold brine which is held at a desired temperature down to approximately 18°F by a thermostat. The thermostat switches off the brine chiller if the temperature in the chiller loop and in the storage tank reaches the desired value. The brine from chiller or storage tank is distributed by a 20 HP pump through the supply pipes to the three controlled loops for plate and coils.

The control loops for plate and coils are each equipped with a separate pump which circulates the brine through a closed system as long as the three-way control valve permits. If the brine temperature rises above the value set on the control panel, then the threeway valve admits cold brine from the chiller loop to replace some of the brine in the respective loop. The brine temperature is controlled for the plate loop by a controller whose sensing element is inserted into the brine. The two coil system loops are indirectly controlled by sensors which are mounted in the airstream.

Into one of the coil systems a second loop is introduced which leads through a steam heated exchanger. If the controls are set to require brine heating, the threeway valve controlling the particular coil-system loop shuts off the brine supply from the chiller, a control valve for the steam opens, and the threeway valve which usually disconnects the heat exchanger loop connects the exchanger into the circuit.

The controls have all been incorporated into one control panel which is located in the control room. (See Fig. 17). The panel contains the temperature set knobs, the pneumatic thermometers, humidity indicators, and pressure gages, and electric switches for starting and stopping the pumps. A temperature and humidity recorder is also installed for continuously recording the temperature and the humidity of the ambient air during operation of the temperature-control system. The controls are easily observed, and the setting of a particular test condition is quite convenient and changes from one test condition to another can be accomplished in satisfactorily short times.

CHAPTER VI

INSTRUMENTATION

The instrumentation used for equipping the large micrometeorological wind tunnel is the most modern available for the special purpose of air-velocity fluctuation and temperature measurement. The instrumentation system consists of two parts: the data-acquisition system, and the analog data-handling system. For both systems, the components have been bought individually, and the final assembly has been made by Colorado State University personnel.

6.1 The Data-Acquisition System

The primary data to be collected with the instrumentation acquired under the contract are mean and turbulent velocities, and mean and fluctuating temperatures as functions of space. The space coordinates are given by the position of the probe, which usually is placed on the instrument carriage.

The electrical connections for the carriage are permanently installed as described below. The instrument probes and accessory instruments are connected through outlets in the wind-tunnel walls which can be closed by steel plugs if not used for cables or tubes. These outlets are located every 8 ft along the test-section length.

6.1.1 Instrument Carriage

The instrument carriage permits the probes to be positioned anywhere within a test area of about 28 in. height and 40 in. width within the test section at distances between 4 ft and about 80 ft from the test section entrance. It is shown in Fig. 18.

The vertical positioner of the carriage consists of a pipe structure which is held on tracks on the transverse beam by cantilever action. It supports the actual drive mechanism which consists of the instrument holding nut with its stabilizing carriage, the guide bar for the stabilizing carriage, and the positioning screw. The screw is driven by a small DC motor, and each revolution of the screw moves the instrument holding nut by 0.025 in. To prevent the nut from either rotating with or binding on the screw, a stabilizing carriage whose 1/2 in. diameter rods carry the instrument probes is provided which travels on the guiding bar - a bar of ground flat steel against which the four wheels of the stabilizing carriage are firmly pressed by spring action.

The vertical positioner can travel on the transverse beam by rotating a screw in the transverse beam to which it is connected through a screw held to it through a bolt. This bolt is free to move up and down without disturbing the travel of the vertical positioner, thus it follows the deflections of the screw without causing the nut to bind.

Both vertical travel and transverse positioning of the instrument probes is done remotely from the control panel. The small DC motors and the position indicating devices on the carriage are supplied with power through the 14 tracks mounted underneath the rails along the wind tunnel wall as indicated in Fig. 18. The power is taken off the tracks by a brush assembly. This arrangement avoids inconvenient long cables. The position-indication devices are potentiometers which can be rotated indefinitely, thus producing a saw-tooth like resistance pattern per revolution, the voltage across which is used to indicate the position in two ways. The voltage is read directly from a voltmeter which serves as an indicator for distances corresponding to less than a revolution. The breakdown of the voltage during each revolution is used for generating a pulse which actuates a magnetic add and subtract counter. The counter indicates full revolutions of the screws. In this manner it is possible to indicate positions over the full transverse and vertical distances with an accuracy of about ± 0.1 of a revolution, or for the vertical positioner of ± 0.0025 in. and for the horizontal positioner of ± 0.005 in. The circuit which makes this operation possible is shown in Fig. 19.

A change in longitudinal position is in general much less frequently required as those for vertical and transverse position. Therefore, it was considered quite adequate to move the carriage manually through a chain drive with a hand crank which is located outside of the tunnel. Two chains are fastened to the carriage on both sides of the tunnel, and the crank which is used for moving the carriage is acting on both drive sprockets which are on a common axis. In this manner, the carriage will always move straight. The position is indicated by measuring tape which is fastened to the carriage in the same manner as the chains. It runs over a pulley outside of the tunnel, and the position can be read off the tape by a pointer on the tunnel wall. The accuracy of the position indication is governed by the resolution of the tape, the tape deflection by its own weight, as well as uneven chain backlash on both sides. It should however be adequate for almost all applications, since an accuracy of ± 1 in. would suffice most of the time.

If desired, a multiturn potentiometer can be connected to the vertical or horizontal positioner, or integrating circuits or devices can be used in conjunction with the counter pulse circuit. These devices can be used to obtain a voltage proportioned to distance from some reference position for application to the x-axis of an x-y-plotter for direct recording of temperature or velocity profiles. This is part of an ultimate goal of taking data in a semi-automatic way.

6.1.2 Velocity Instrumentation

The wind tunnel is equipped with three different types of instrumentation for measuring mean velocities. The most reliable of these is the Pitot tube or Pitot-static tube, in conjunction with the Flow-Corporations Type MM-2 micromanometer. This is the standard used in the laboratory. However, for large-scale data acquisition, the use of a Pitot static tube is unsatisfactory, because of the very slow response of the manometer, and of the fact that the output of the manometer cannot readily be converted into an electrical signal, thus making direct plotting of results not feasible.

The second of the mean velocity devices is the mean-velocity, hot-wire anemometer bridge. It has been designed at Colorado State University, works with rather thick wires (about 0.001 in. diameter), and gives a steady galvanometer reading due to its slow response even in fluctuating air flows. Though not as reliable as a Pitot tube, it can hold its calibration for a long time and needs little special care. The present bridge, shown diagrammatically in Fig. 20, can easily be converted into a feed-back controlled unit with slow response by adding a feed-back amplifier parallel to the present galvanometer and with it control the motion of a servomotor which adjusts the current through the bridge. Also, the current can be used to provide a signal for an electric x-y-plotter.

The third method of mean-velocity measurement uses the turbulent hot-wire anemometer. Use of this instrument, a Type 3A hot-wire amplifier made by the Hubbard Instrument Co. of Iowa City, Iowa provides the fastest method, but the fragility of the wires (of a thickness of 0.00014"), the amplifier drift, and the large meter fluctuations under the influence of slow velocity fluctuations make it less reliable than the other methods. Its main application is for the static calibration of the turbulence probes. The instrument will be used generally only for measuring turbulent quantities, and for mean velocity measurements one of the other methods will be relied on.

Turbulence data are taken with the two channels of the Hubbard anemometer. This instrument has a feed-back amplifier which permits one to obtain undistorted data at frequencies up to about 10,000 cycles per second. The data are, through a linerization stage, converted to voltages proportional to velocities which are, in general, recorded on magnetic tape and stored for later use.

The two types of hot-wire anemometers need calibration, and different equipment is available for different velocity ranges. At low speeds, the mean-velocity hot wire is calibrated by means of a rotating-arm tank in which the revolutions of the arm to which the probe is fastened can be converted to air speeds. For large velocities, the probes are placed side by side with a Pitot static tube in the test section of the wind tunnel, and the manometer is used as a velocity standard.

For checking turbulent intensities, or the response of the turbulent hot wire to high-frequency fluctuations, two methods are used. A direct method is not yet known, therefore, both are indirect. The first consists of determining the frequency response of the feed-back system by interrupting the feed-back loop and measuring the gain and system phase. The other method consists of placing the hot-wire probe into the center of a pipe flow for which some turbulent quantities can be predicted independently on the basis of experimental and theoretical investigations.

6.1.3 Temperature Measurement

The instrumentation for temperature measurement consists of either a thermocouple and associated circuitry, or of a resistance thermometer consisting essentially of a wire which is operated like a hot-wire anemometer but at very low current.

The thermocouples usually consist of simple junctions of copper and constantan which are individually spot-calibrated. The junction is exposed to the air and fastened to the carriage or other suitable supports. The output of the thermocouple is recorded on a Minneapolis Honeywell single-channel recorder.

The resistance thermometer for measuring fluctuating temperatures was developed at Colorado State University, and is described in Ref. 4. Essentially it is a two-channel unit with feed back amplifiers which are very similar to those of the Hubbard turbulence hot-wire anemometer amplifiers except that they have additional amplification stages. Signal to noise ratios of this instrument are quite high, and modifications are desirable.

6.2 Data-Analysis System

The data-analysis system provided under Contract DA-36-039-SC-80371 is only a part of the total analog computing system available for the analysis of turbulent-velocity data shown in Fig. 21. Cooperation with the National Center for Atmospheric Research at Boulder, Colorado has made it possible, in addition to a gift from NASA'S Lewis Research Laboratory, to provide a computing center which permits calculation of all commonly used turbulence parameters.

The part of the analog system obtained through funds from the present contract forms the back bone of the whole system, and is, in a limited way, self sufficient. It is shown in Fig. 22. It permits the following operations:

1. To produce a permanent record of laboratory data;
2. To determine cross correlations between two different signals;
3. To determine root-mean-square values of random signals;
4. To determine spectra of energies contained in random signals;
5. To plot out the data listed under points 1 to 4 against time or position on 8-1/2 x 11 paper.

In detail, the system consists of the following components.

The tape recorder will be an AMPEX model FR 1100. This recorder was chosen because it meets all the requirements and permits addition of a time-delay head stack on the tape transport panel. This advantage was judged of such an importance that it overruled the consideration that the FR 1100 is the oldest recorder offered (on the market since 1957). The recorder has not yet been acquired, and another SC-contract will make its acquisition possible.

The product of two random signals is obtained by a Philbrick Model SK5M analog multiplier. The power supply for the multiplier is a Philbrick R300. It was chosen of sufficient size to drive another SK5M multiplier.

Since in many applications the average signal has to be determined with utmost accuracy (for example products of turbulence signals obtained with crossed-wire probes, for extracting shear stress data), a precision integrator became necessary. The Technical Products Type 633 integrator was considered the most satisfactory. This integrator is also to be used in conjunction with the wave analyzer.

The signal coming from the multiplier or directly from either transducer or recorder will be analyzed for its harmonic content by the spectrum analyser. Of the analyzers on which bids were received the accuracy of the Technical Product Type 627, with oscillator Type 627 was highest. This analyzer offers the greatest versatility of spectrum analysis. It permits changes in the bandwidth by exchanging plug-in filters, it permits plotting of the output on either linear or logarithmic scale with log converter A-9835 added, and it gives a low frequency cutoff of 2 cps.

Another feature of the system is a rms-meter for which the B and K Type 2409 was chosen. This meter serves for determining intensities of turbulence, and other rms quantities.

The data analyzed by the above instrument shall be recorded on an X-Y-recorder. The model 300 TRA of the Electro Instrument Company was chosen.

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1. J. E. Cermak: "Wind tunnel for the study of turbulence in the atmospheric surface layer". Final report on Contract AF19 (604)-1706. Colorado State University, Department of Civil Engineering Report No. CER58JEC42. November 1958.

2. E. J. Plate and J. E. Cermak: "A study of design and operation of a low speed precision wind instrument test facility". Interim Report on Contract DA-29-040-ORD-2346. Colorado State University, Department of Civil Engineering, Report No. CER60EJP58. November 1960.

3. E. J. Plate: "Operation and maintenance of the low speed precision wind instrument test facility". Final Report on Contract DA-29-040-ORD-2346. Colorado State University, Department of Civil Engineering, Report No. CER62EJP10. February 1962.

4. A. C. Spengos and J. E. Cermak: "Turbulent diffusion of momentum and heat from a smooth, plane boundary with zero pressure gradient". Final Report on Contract AF19(604)-421. Part I: Experimental equipment. Colorado Agricultural and Mechanical College Department of Civil Engineering, Report No. CER56ACS12. August 1956.

5. J. E. Cermak and A. C. Spengos: "Turbulent diffusion of momentum and heat from a smooth, plane boundary with zero pressure gradient". Part II: Presentation of data and analysis. Final Report on Contract AF19(604)-421, AFCRC-TN-56-273. 1956.

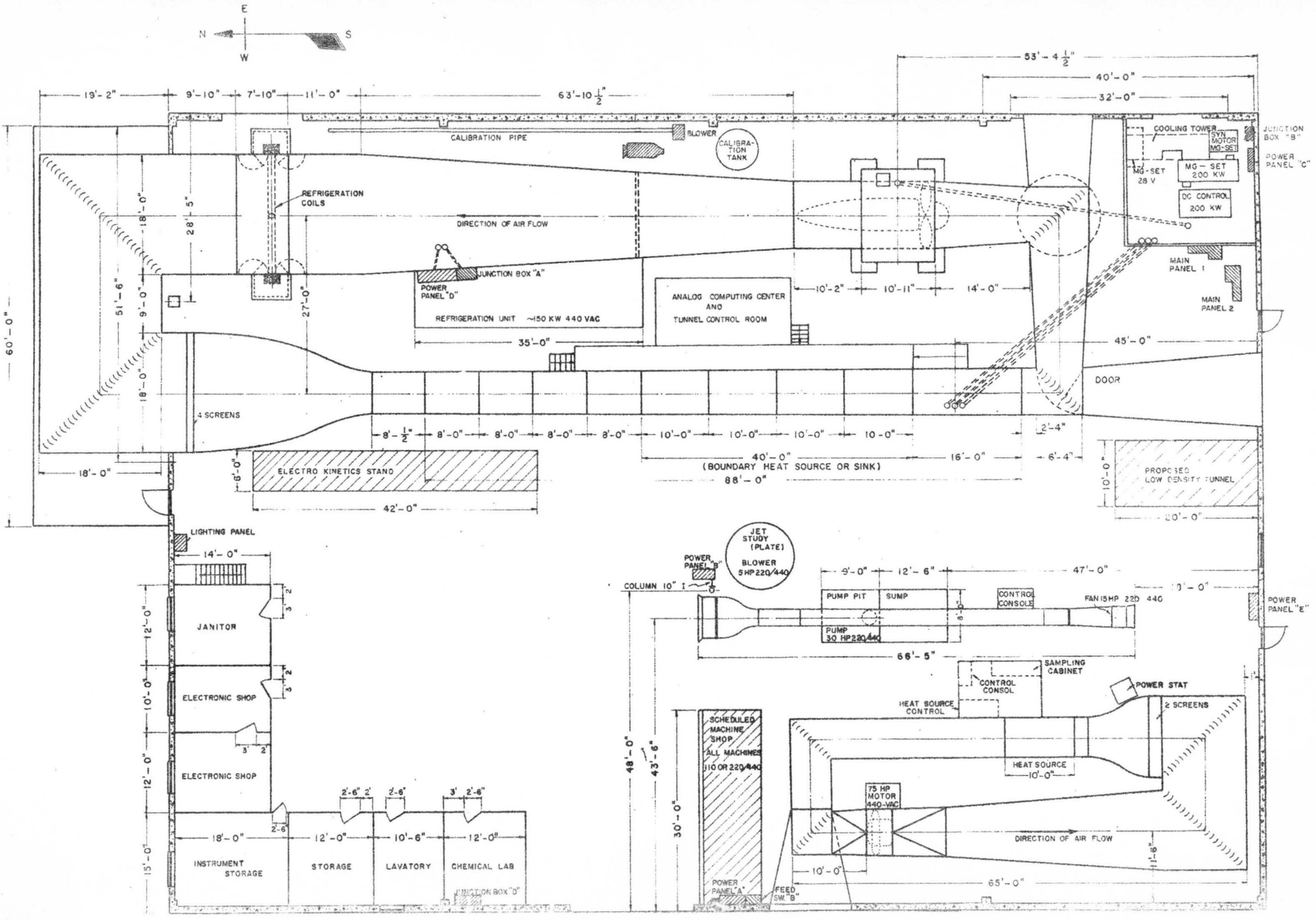


FIG. 1 FLUID DYNAMICS AND DIFFUSION LABORATORY FLOOR PLAN

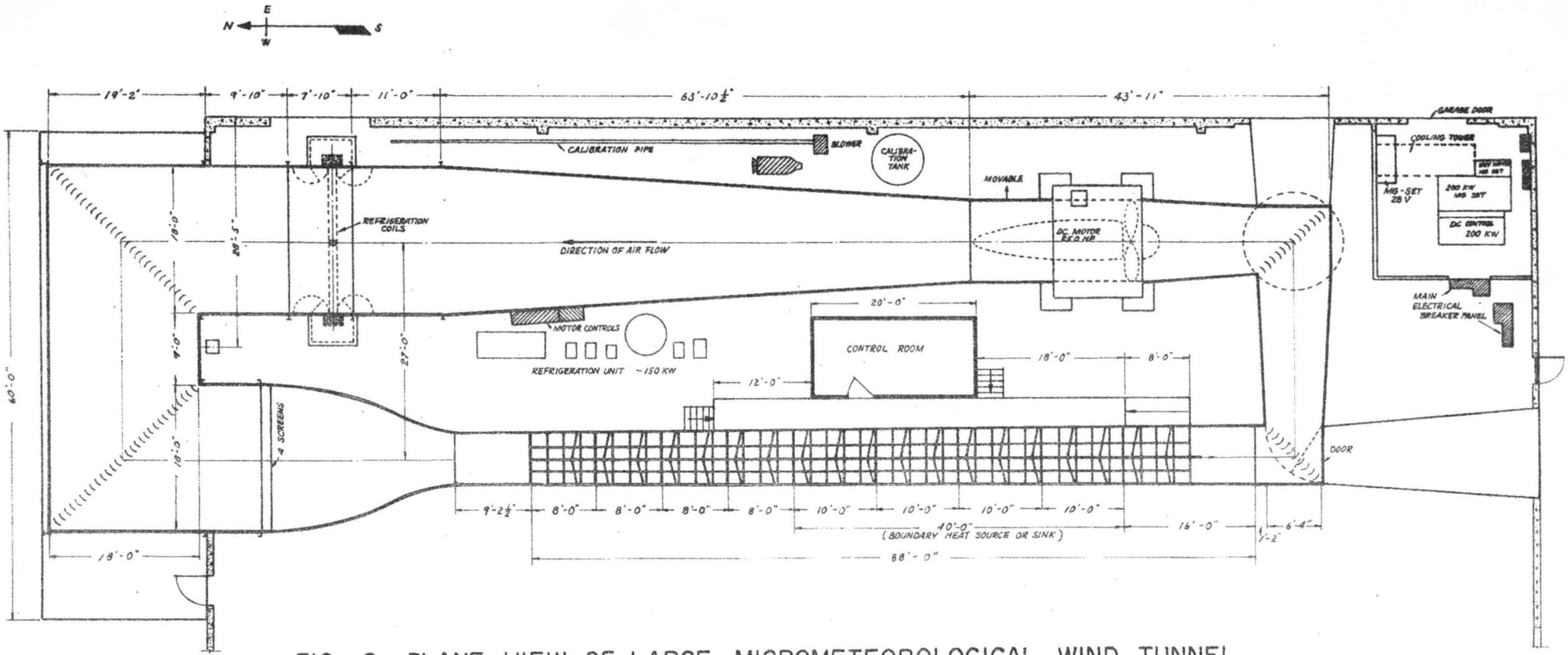


FIG. 2 PLANE VIEW OF LARGE MICROMETEOROLOGICAL WIND TUNNEL

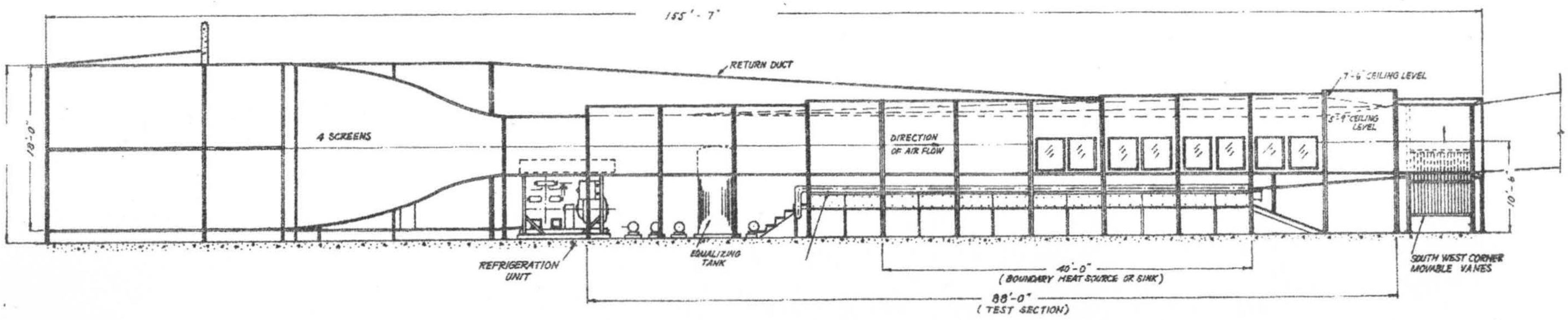
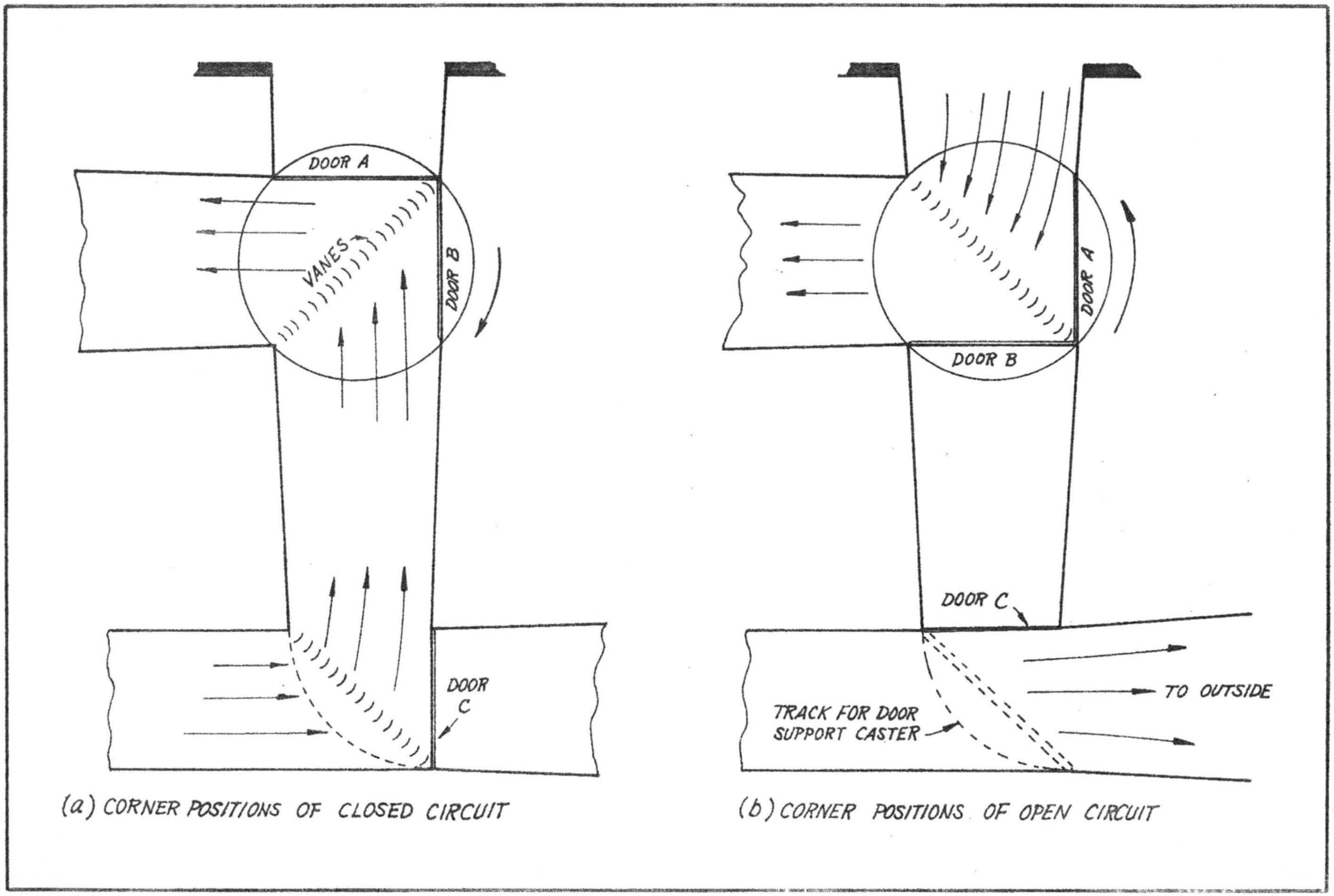


FIG. 3 SIDE VIEW OF LARGE MICROMETEOROLOGICAL WIND TUNNEL



(a) CORNER POSITIONS OF CLOSED CIRCUIT

(b) CORNER POSITIONS OF OPEN CIRCUIT

FIG. 4 CONVERSION FROM CLOSED TO OPEN CIRCUIT OPERATION

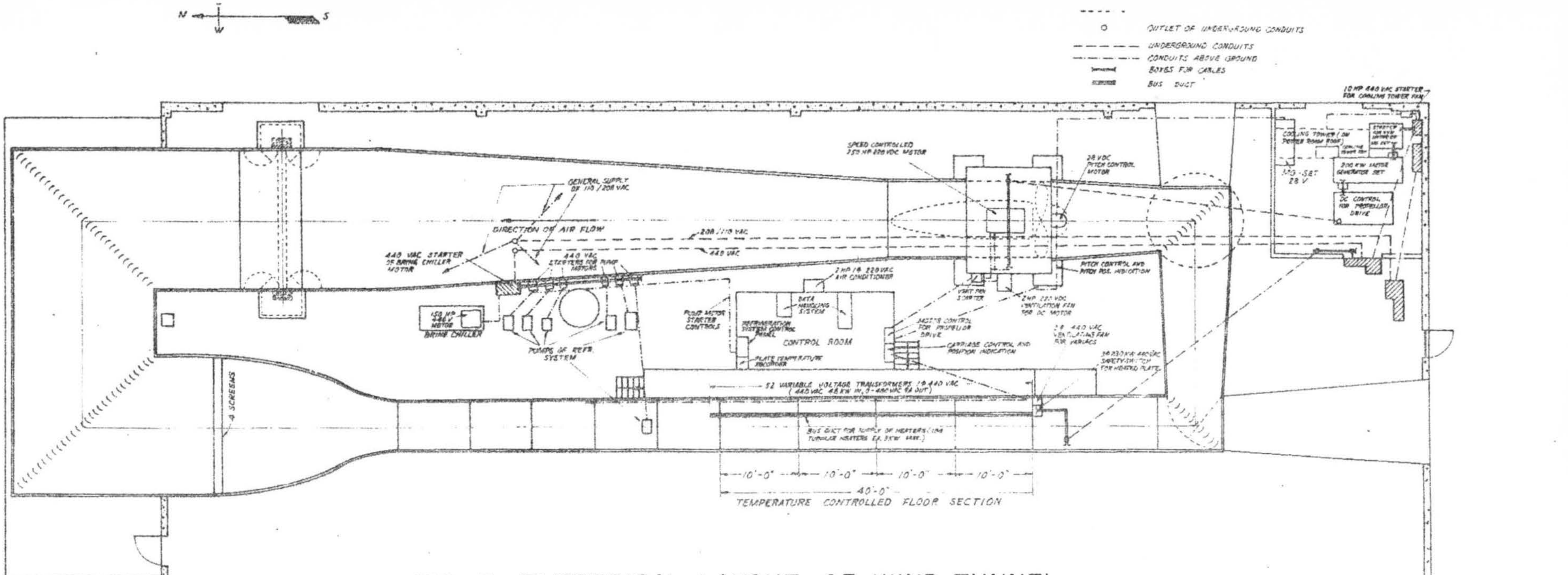


FIG. 5 ELECTRICAL LAYOUT OF WIND TUNNEL

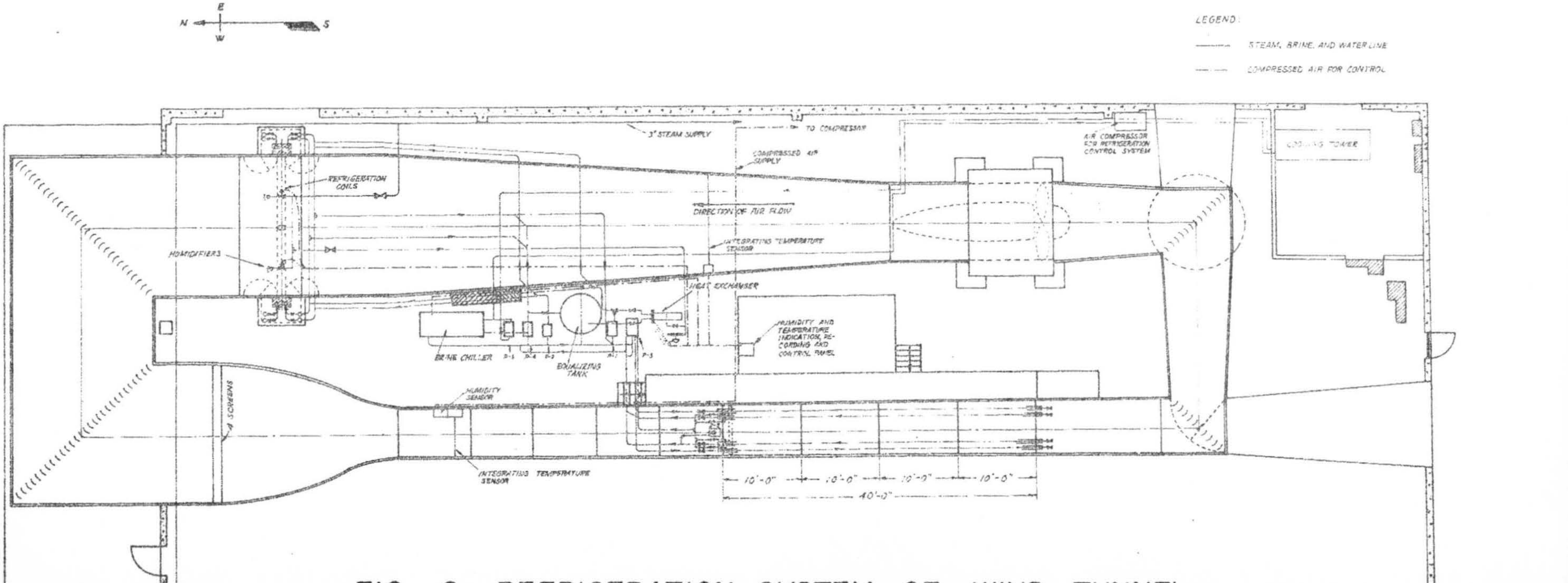
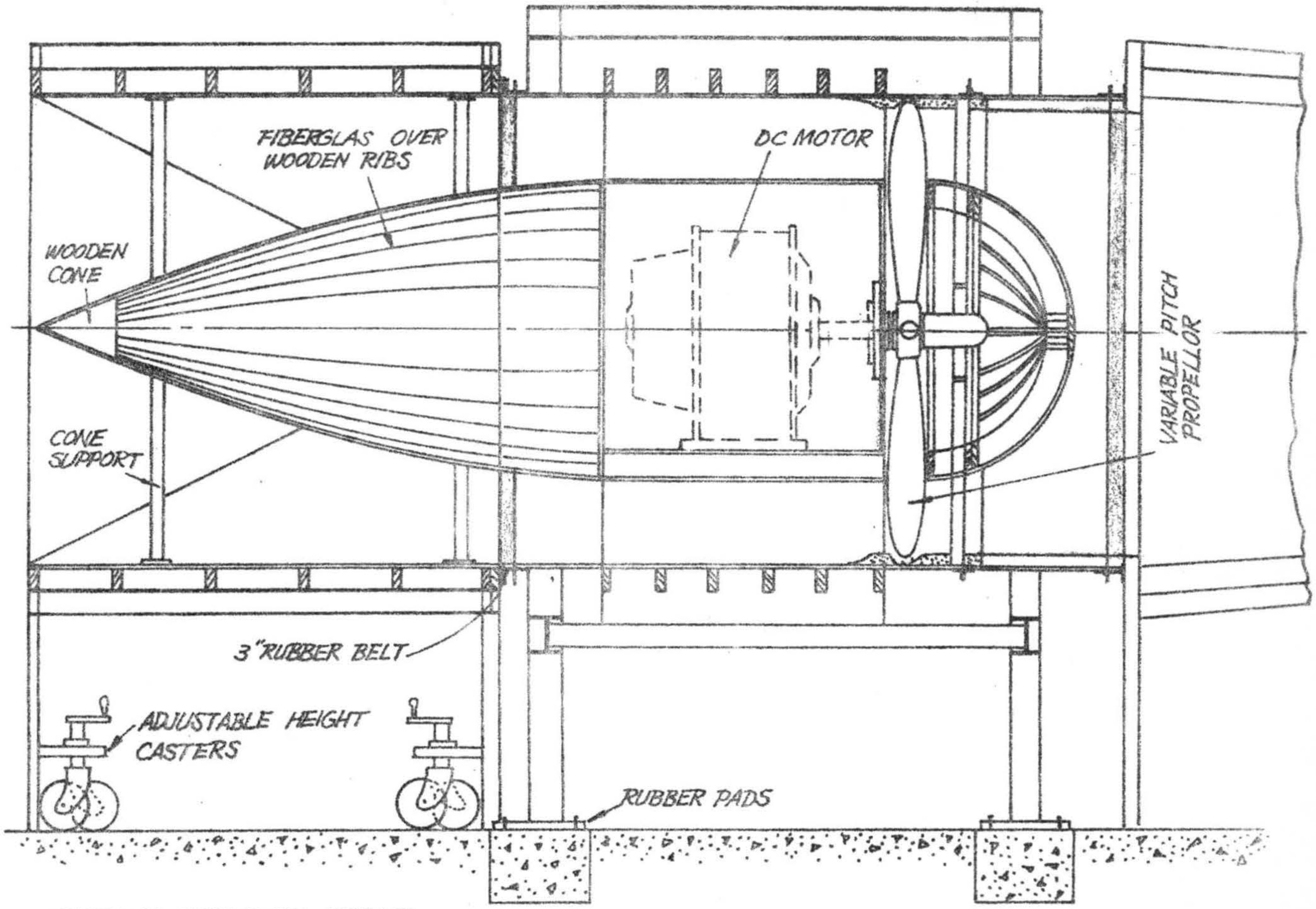
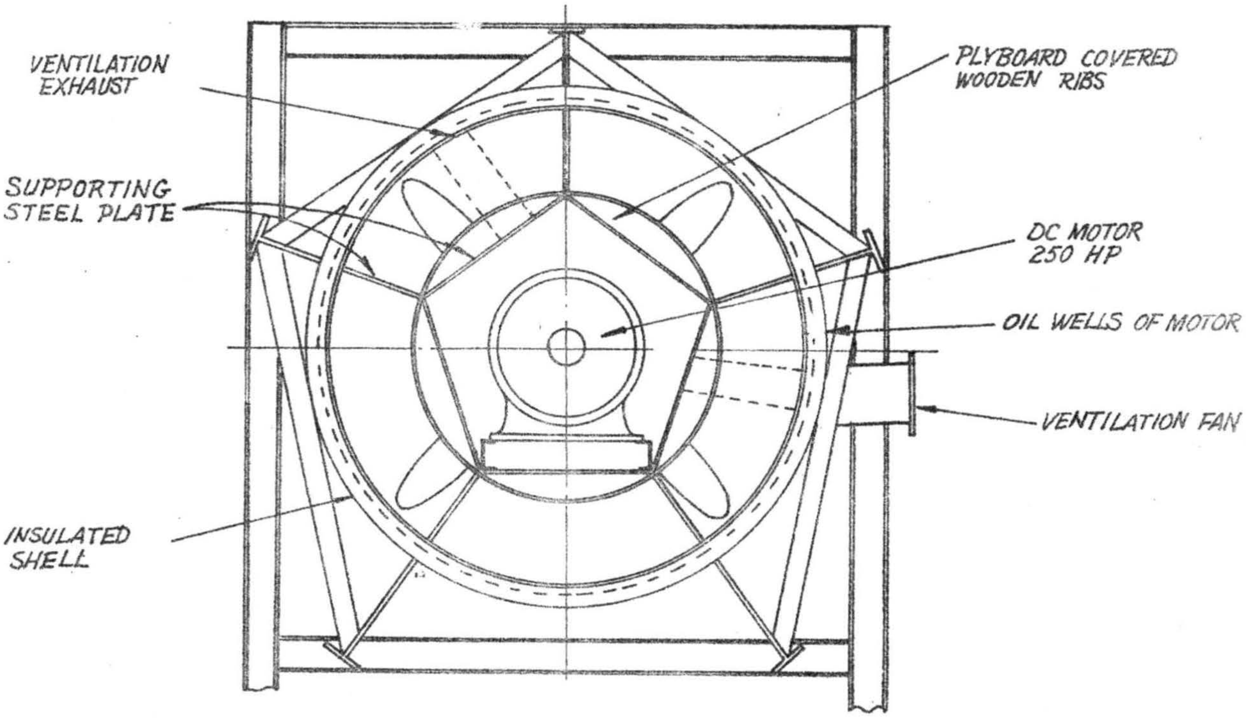


FIG. 6 REFRIGERATION SYSTEM OF WIND TUNNEL



SECTION THROUGH DRIVE



CROSS SECTION OF DRIVE

FIG. 7 DRIVE SECTION

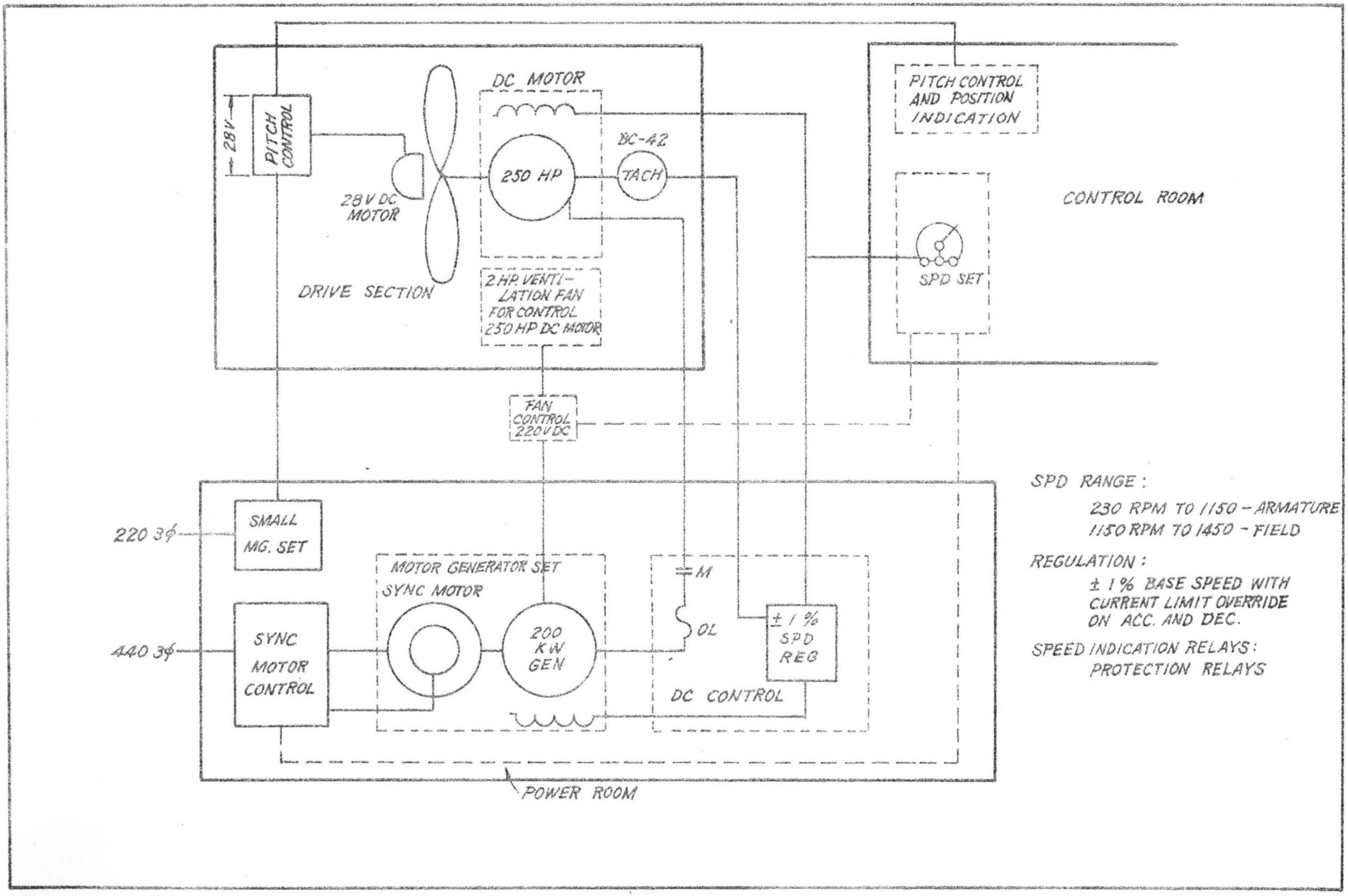


FIG. 8 LARGE WIND TUNNEL — ELECTRIC DRIVE

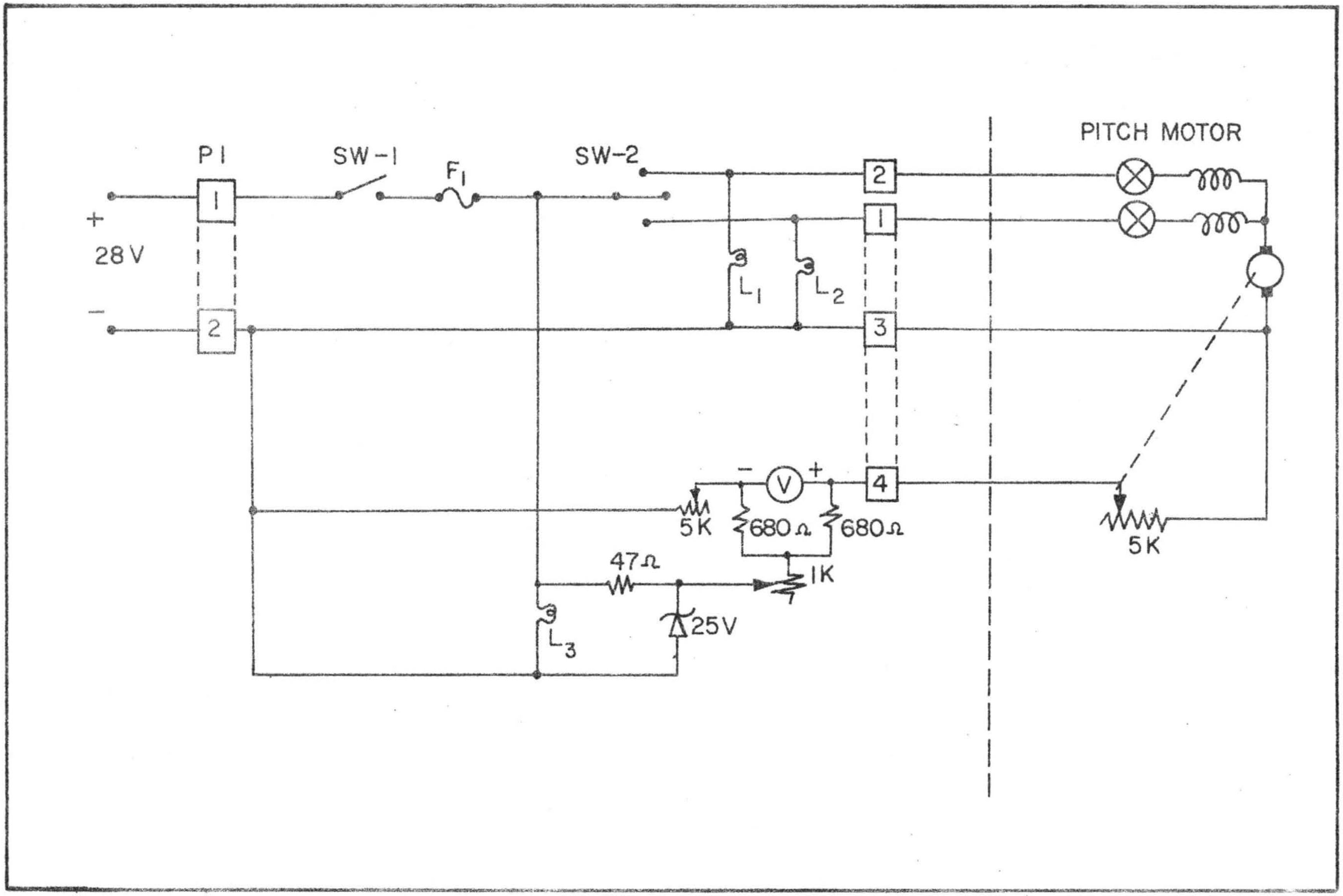
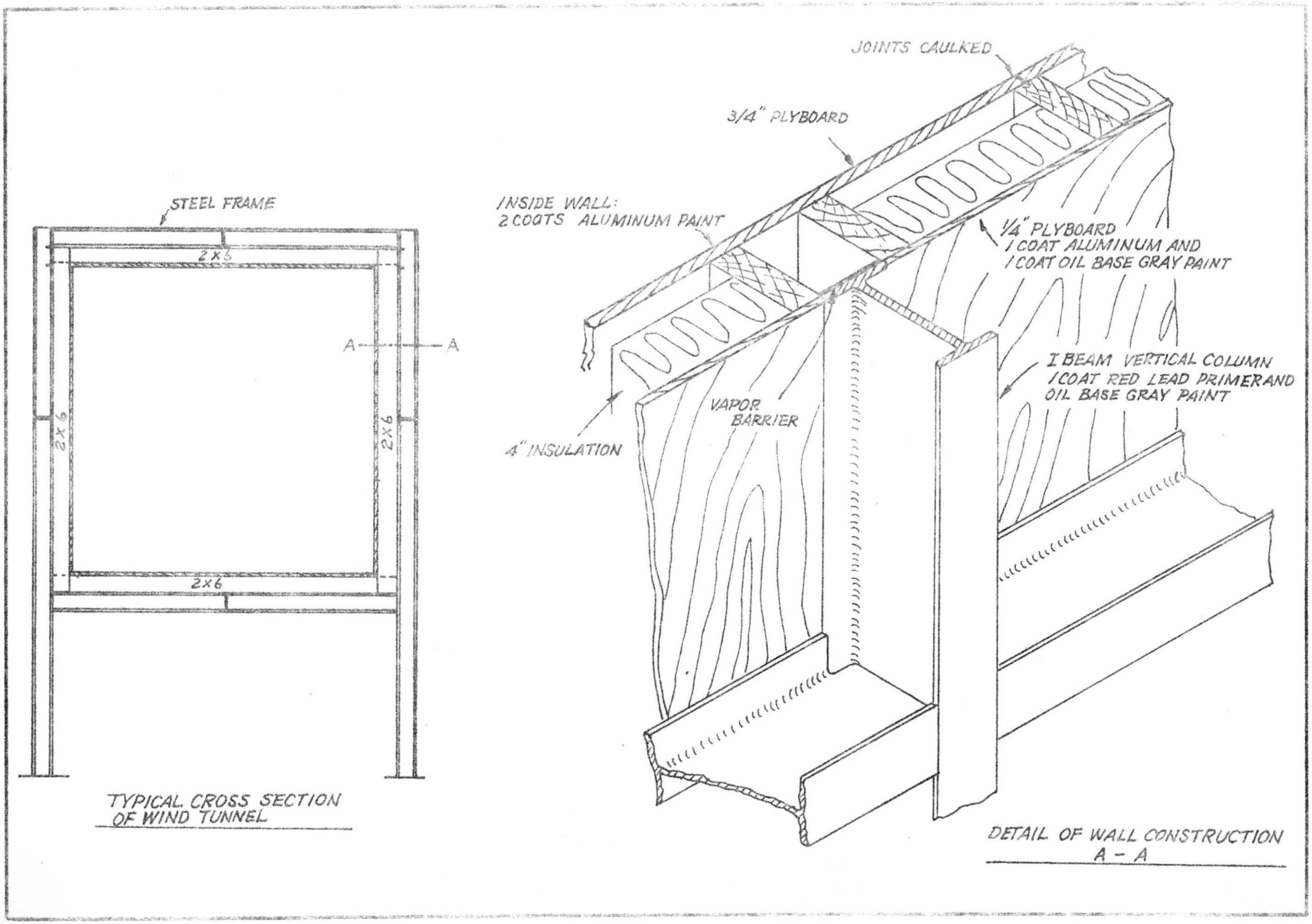


FIG. 9 LARGE WIND TUNNEL: PITCH CONTROL CIRCUIT



TYPICAL CROSS SECTION OF WIND TUNNEL

DETAIL OF WALL CONSTRUCTION A - A

FIG. 10 LARGE WIND TUNNEL CONSTRUCTION

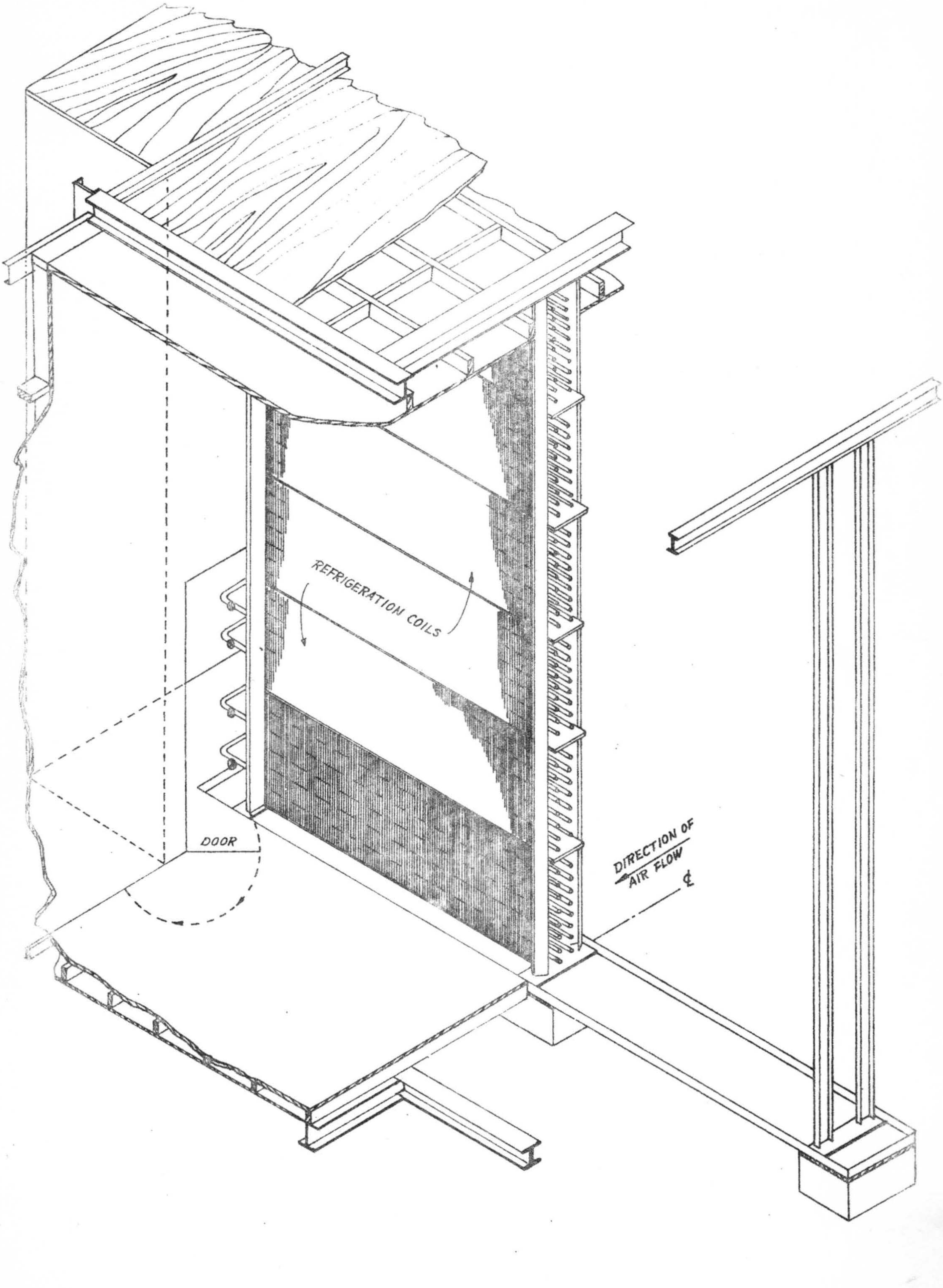


FIG. 11 RETURN DUCT: REFRIGERATION COIL SECTION

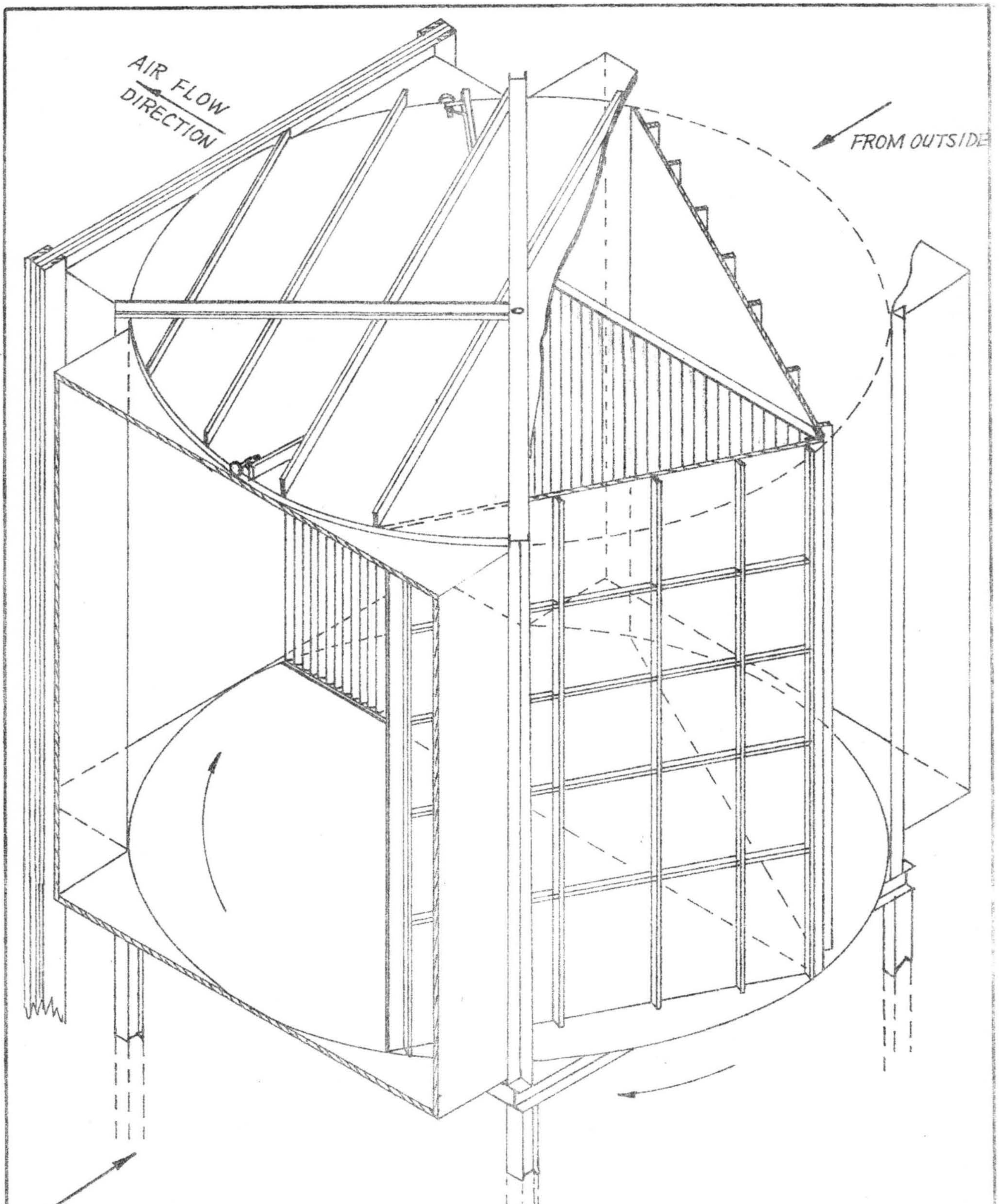


FIG. 12 CONSTRUCTION OF ROTATING CORNER

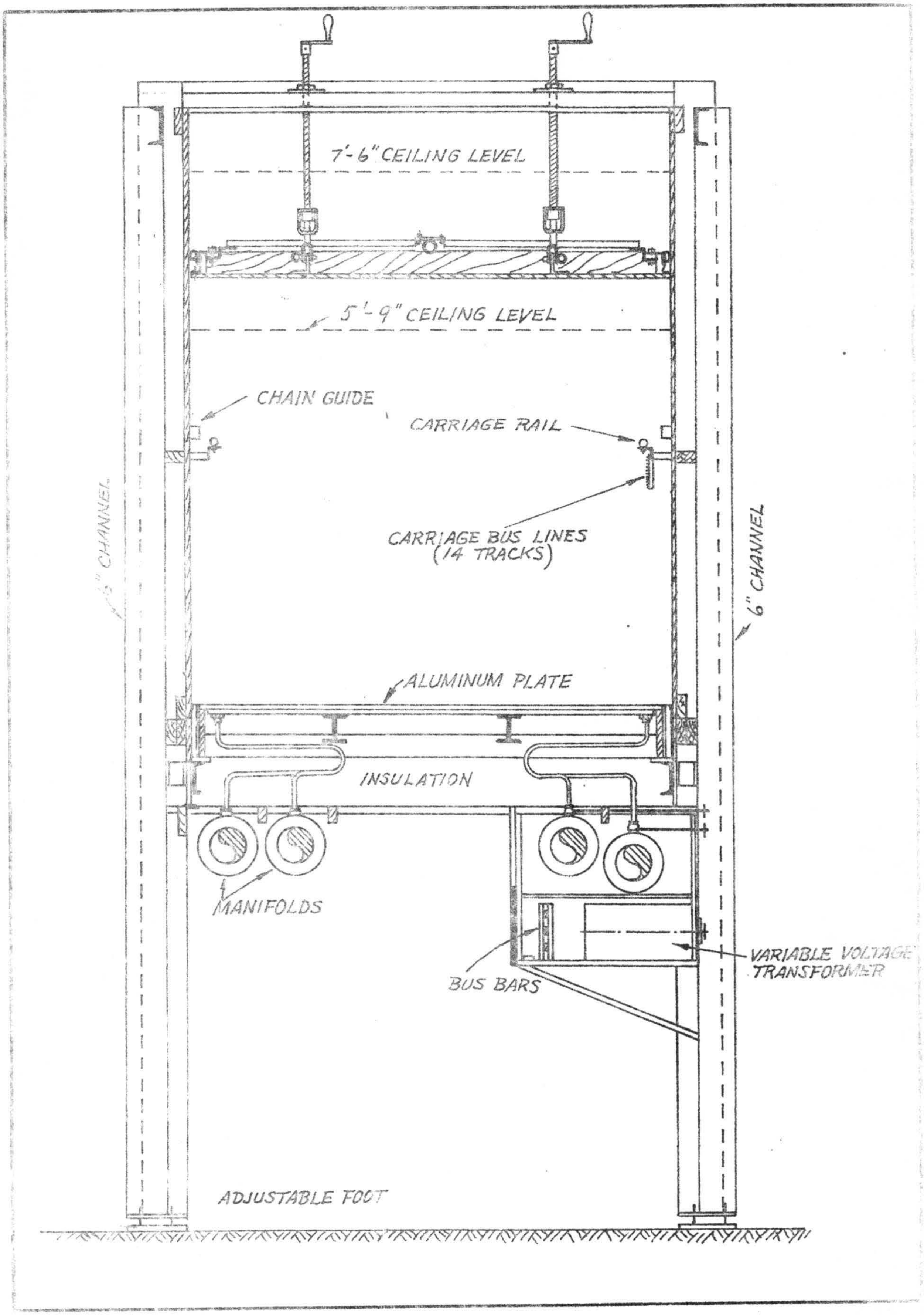
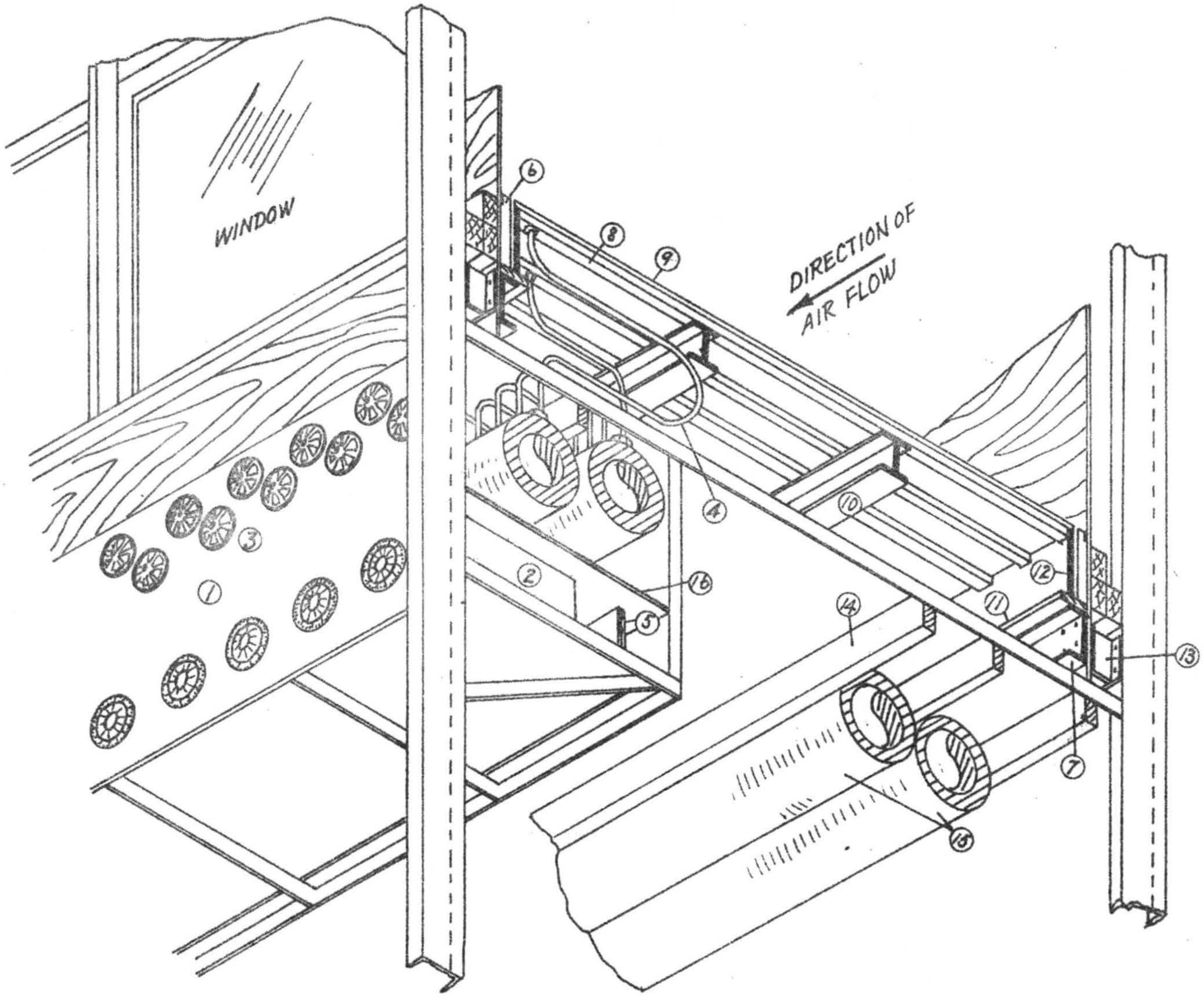


FIG. 13 TYPICAL TEST-SECTION CROSS SECTION



1	CONTROL PANEL
2	VARIABLE TRANSFORMER
3	VALVE WHEELS
4	COPPER TUBING
5	BUS BARS
6	7"×1" SOLID INSULATION
7	6" CHANNEL
8	CONDUIT
9	ALUMINUM PLATE
10	4" I BEAM
11	3" SOLID INSULATION
12	½"×6" STEEL
13	3" I BEAM
14	2×4
15	MANIFOLDS
16	DRIP PAN

FIG. 15 DETAIL OF TEST SECTION PLATE

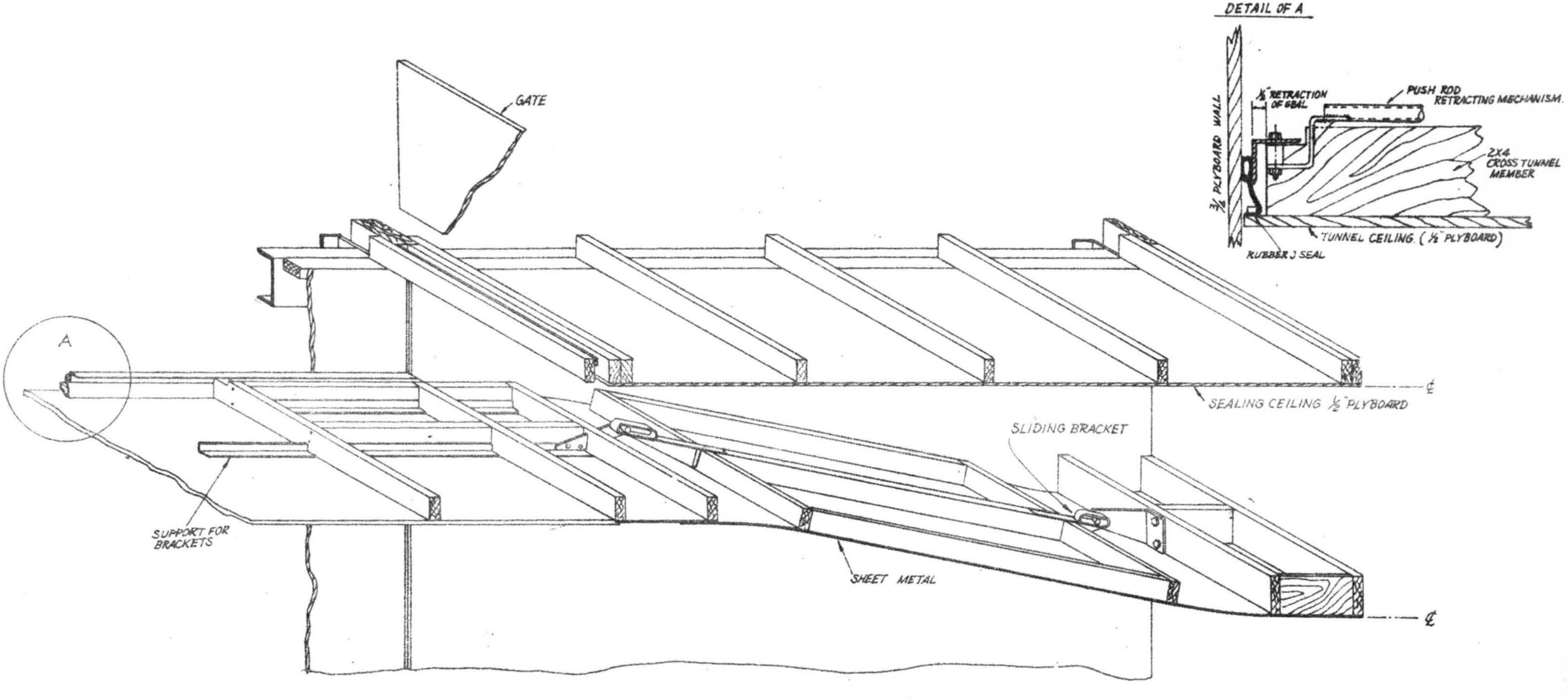


FIG. 14 DOWNSTREAM SECTION OF ADJUSTABLE CEILING

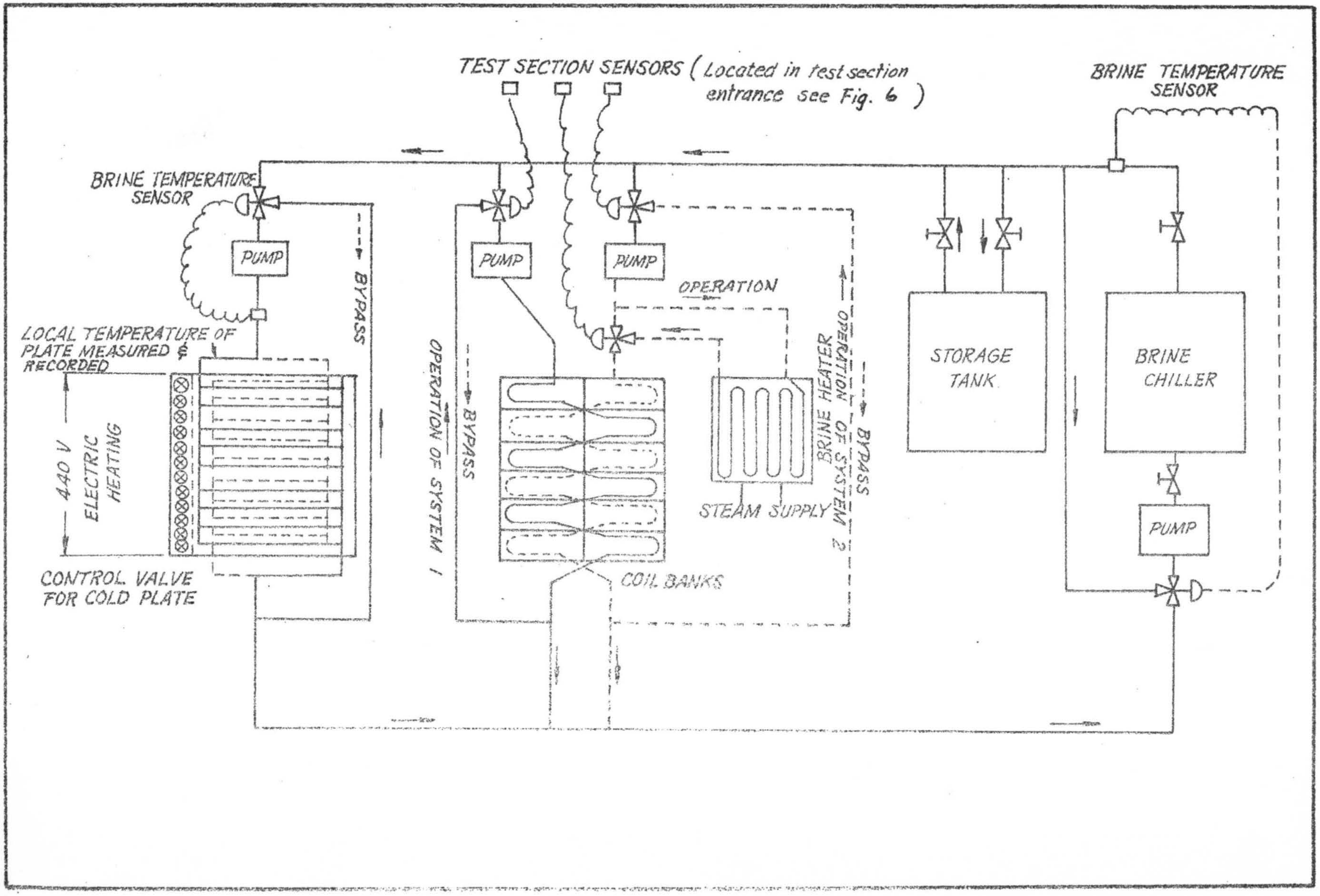


FIG. 16 LARGE WIND TUNNEL — TEMPERATURE CONTROL SYSTEM

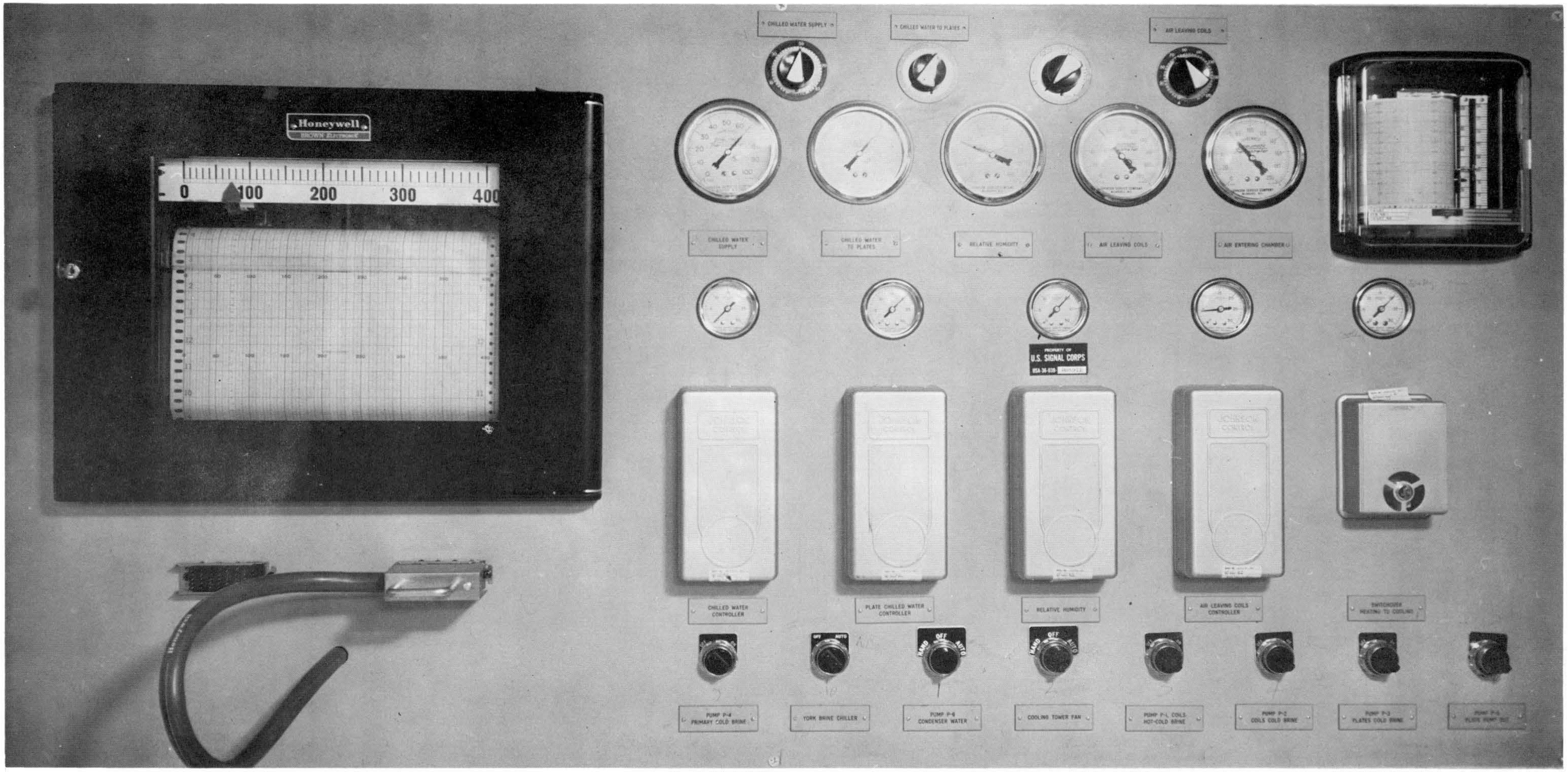


FIG. 17 LARGE WIND TUNNEL-TEMPERATURE CONTROL SYSTEM
CONTROL PANEL

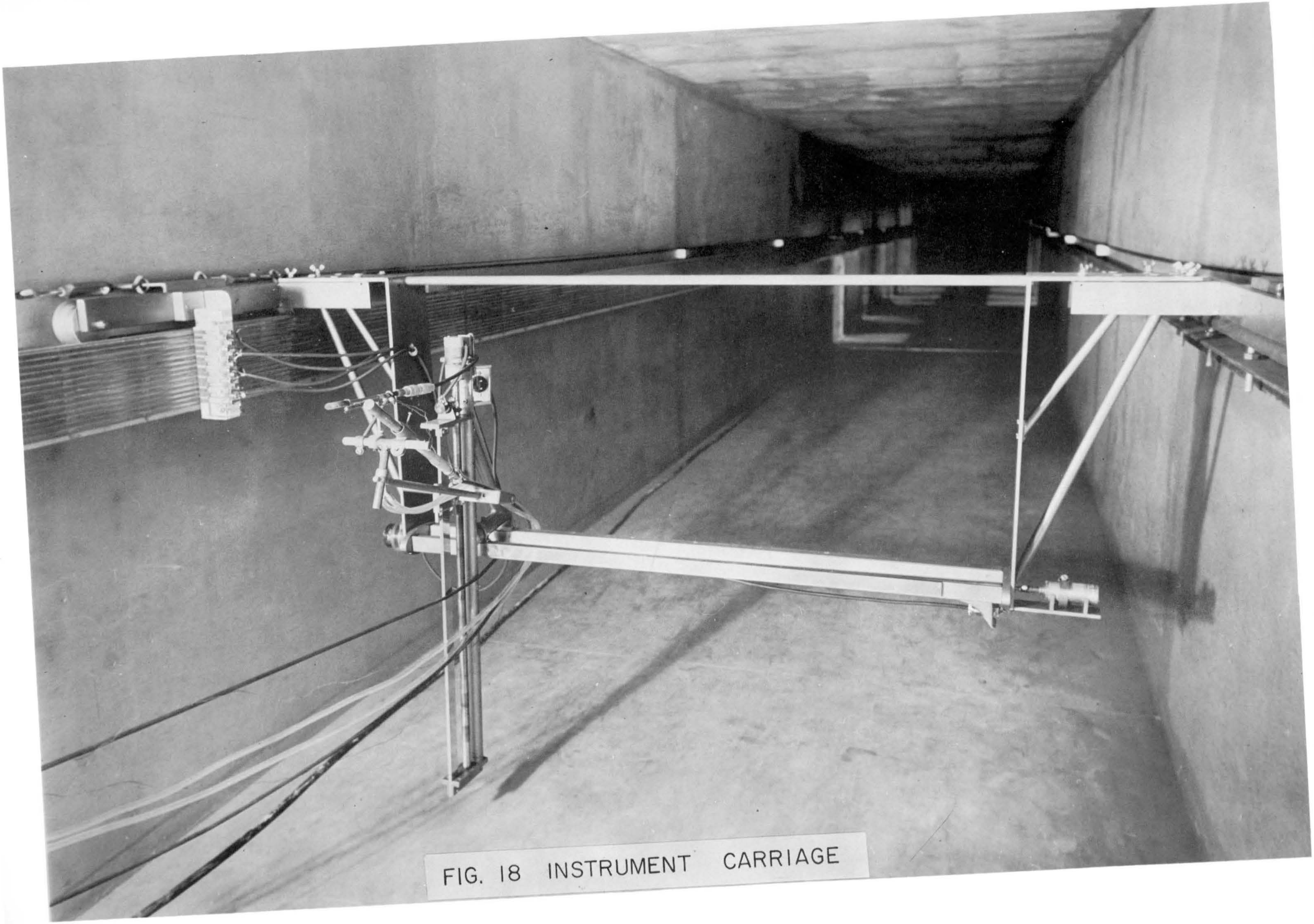


FIG. 18 INSTRUMENT CARRIAGE

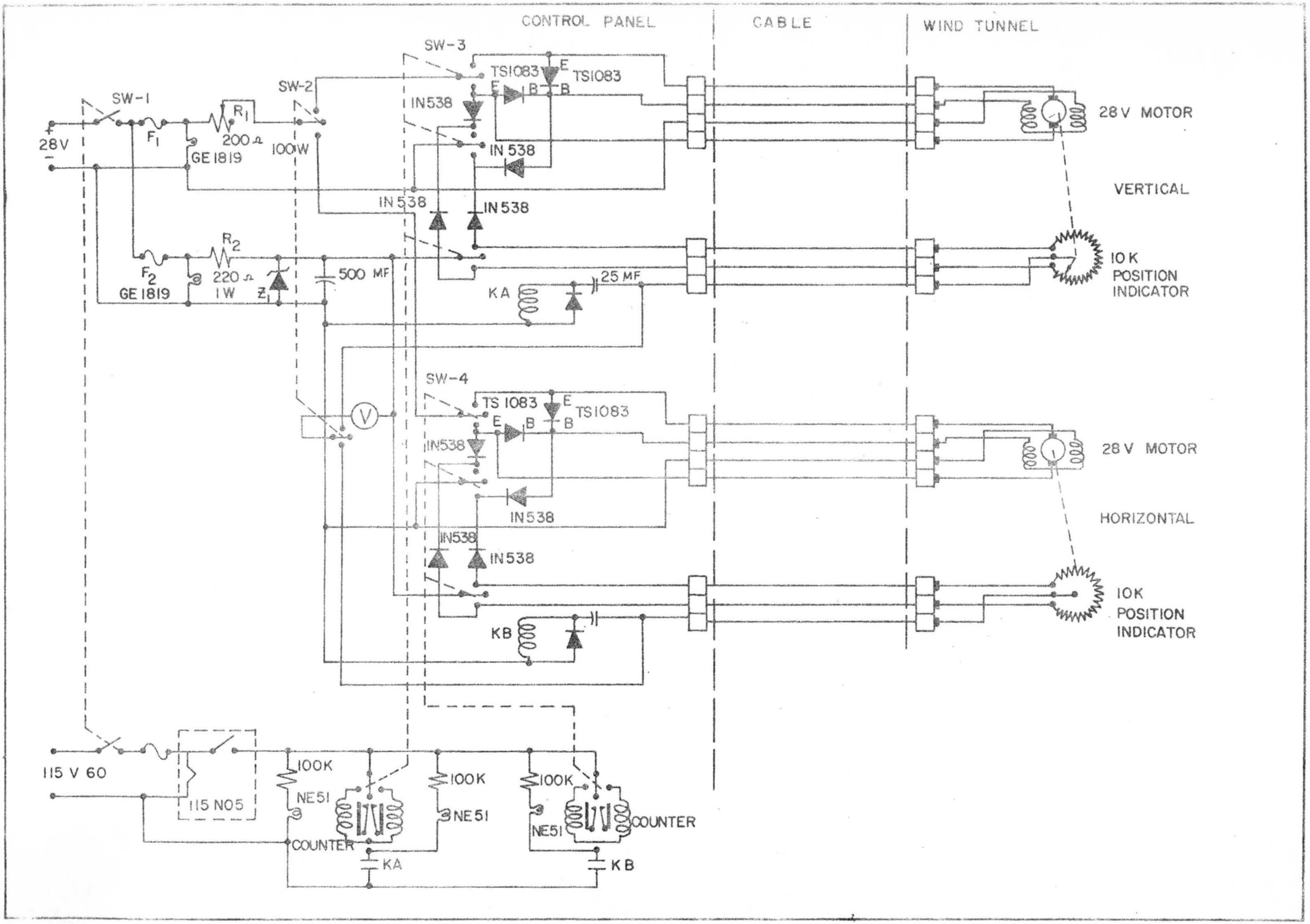


FIG. 19 CARRIAGE CONTROL

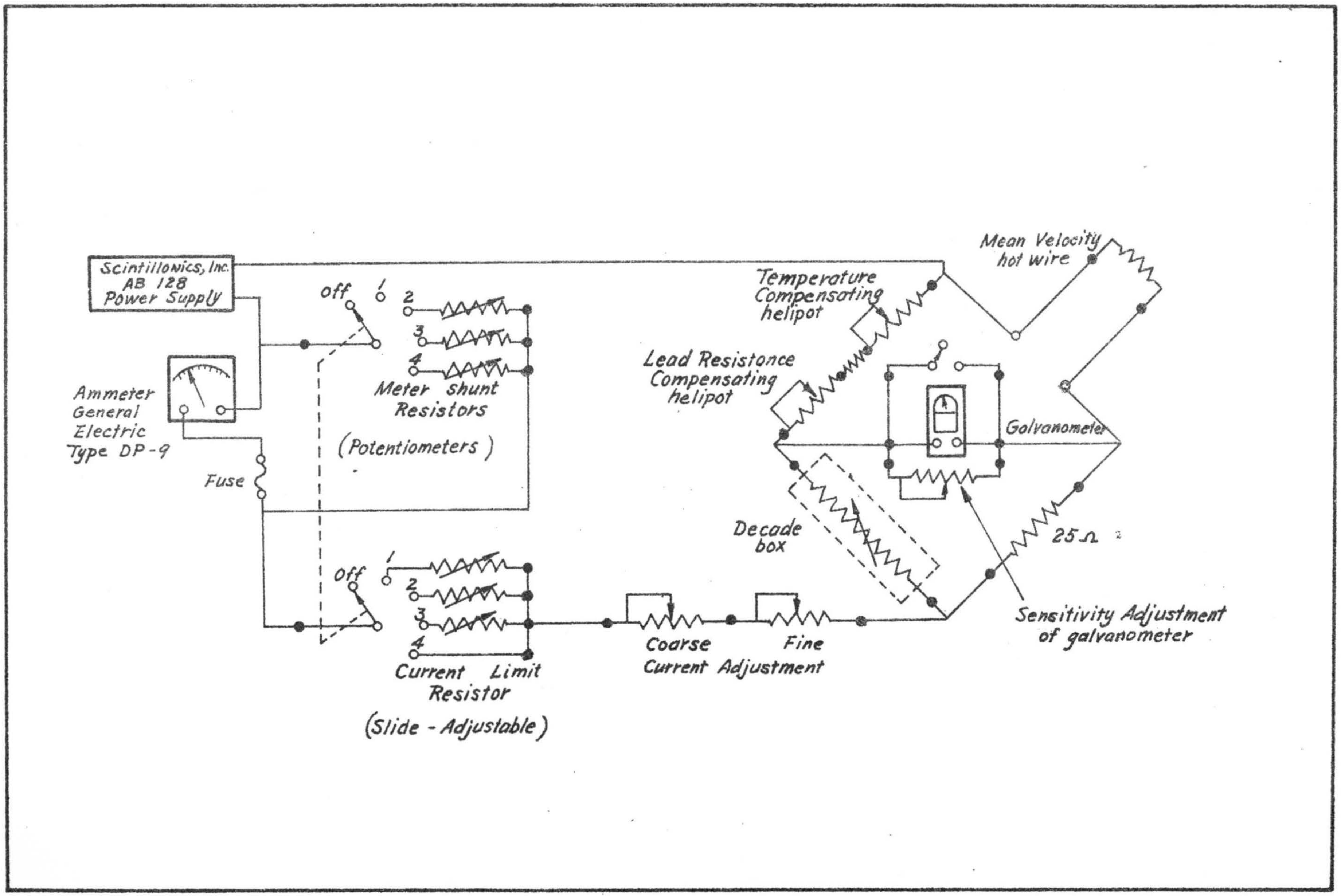


FIG. 20 MEAN VELOCITY HOT WIRE CIRCUIT

FIG. 21 FLUID DYNAMICS AND DIFFUSION LABORATORY: COMPUTING CENTER

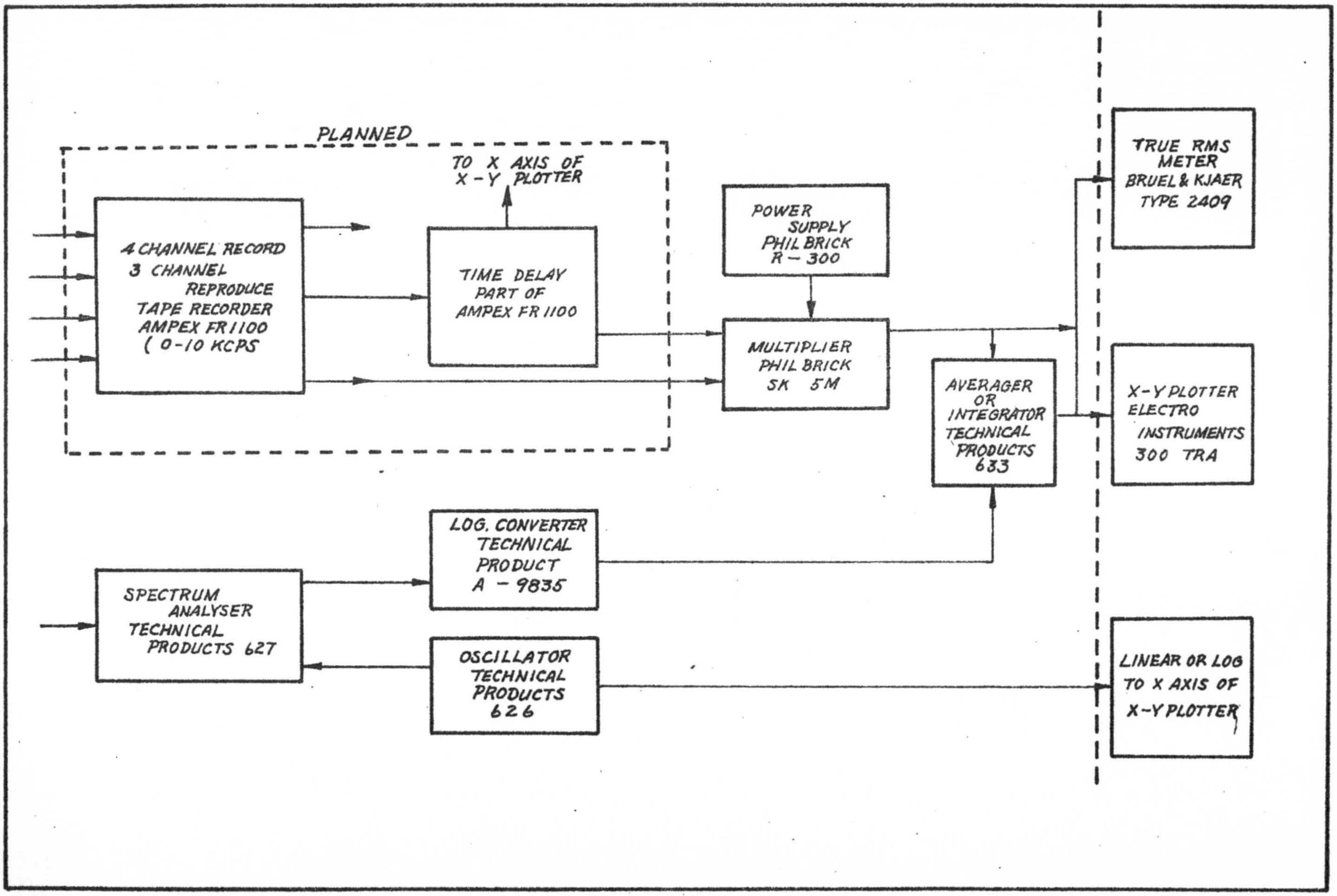


FIG. 22 DATA-ANALYSIS SYSTEM