The corners of the tunnel contain turning vanes for efficiently turning the air (see *Figs. 5 and 6*). These are mounted in an elliptical section about three feet long, which is inserted between the ends of the cylindrical shells. The forces acting on the elliptical ring are the following:

(a). Dynamic air forces on the vanes.
(b). Air pressure on inside of elliptical ring.
(c). Loads due to stresses in shell plate wherever it is intersected by the elliptical ring.

Loads (a) and (b) are fixed and do not depend on the elastic properties of the elliptical ring. Loads (c) are known if the elastic properties of the elliptical ring correspond to those of the cylinder which has been cut away. This relationship, however, is very difficult to establish.

Two types of construction were considered:

1. The ends of the vanes to be fastened to the elliptical ring so as to act as stay bolts.
2. The ends of the vanes to be fastened through slip joints so that no axial loads could be transmitted to the vanes.

Both types of construction had been used previously for wind tunnels, but no data were available on which a choice could be based. The staff of the Cooperative Tunnel selected method (1) above, because in their opinion it saved considerable material, eliminated a lot of "dirty" expansion joints and provided a much more rigid elliptical ring, thus being much more satisfactory so far as carrying loads (c) above. A typical corner may be seen at the right of *Fig. 4*.

A design of the elliptical ring was made on the basis of statics, neglecting bending stresses in the ring and assuming that the loads due to stresses in the shell were not changed because of the elastic properties of the ring. These assumptions seemed reasonable, but it was felt that some further substantiation was necessary; so a scale model was constructed (six feet in diameter—approximately one-fifth scale). Because of the materials available, the dimensions of the model were such that a pressure of 53 pounds per square inch on the model caused the same unit stresses as would a pressure of 47 pounds per square inch in the tunnel. The model is shown in *Fig. 7*.

The stresses in the model were measured by using Huggenberger strain gages on the elliptical rings and shell, and dial gages on the vanes. The results showed that the model had not been built with sufficient accuracy to secure the results ultimately desired, but nevertheless they showed that the design assumptions were satisfactory. After the stress measuring program had been completed, the model was proof-tested as this practice is defined in the A.P.I.-A.S.M.E. code. This test consisted of painting the surface of the model with whitewash and then gradually raising the pressure until flaking of the whitewash indicated yielding of the material. The pressure in the model reached 175 pounds per square inch before any flaking of the whitewash was detected. The pressure was then gradually increased to 225 pounds per square inch. At this pressure the distortion was large over the entire model and there seemed to be no reason for carrying the pressure higher.

The decompression sphere was designed on somewhat the same basis as the corner structures. A model of this section was also built and tested in a similar manner. In general the model test results indicated satisfactory behavior.

The fan for the 10 foot *Galcit** tunnel until quite recently has been equipped with wooden blades. During approximately 15 years of operation a number of wooden fan blades have been wrecked and on one occasion the loose blades broke through the comparatively thin concrete shell surrounding the fan. The fan blades for the cooperative tunnel are aluminum alloy, so that there is every reason to believe that the danger of losing a fan blade is negligible; nevertheless an attempt has been made to provide for that contingency. The fan shaft and bearing supports are strong enough to resist the unbalanced certrifugal force occasioned by the loss of one-half of the blades—all on one side of the hub. The shell surrounding the fan section is twice as thick as required by pressure considerations. It is further reinforced by a steel cone, filled with concrete, surrounding the shell at each fan.

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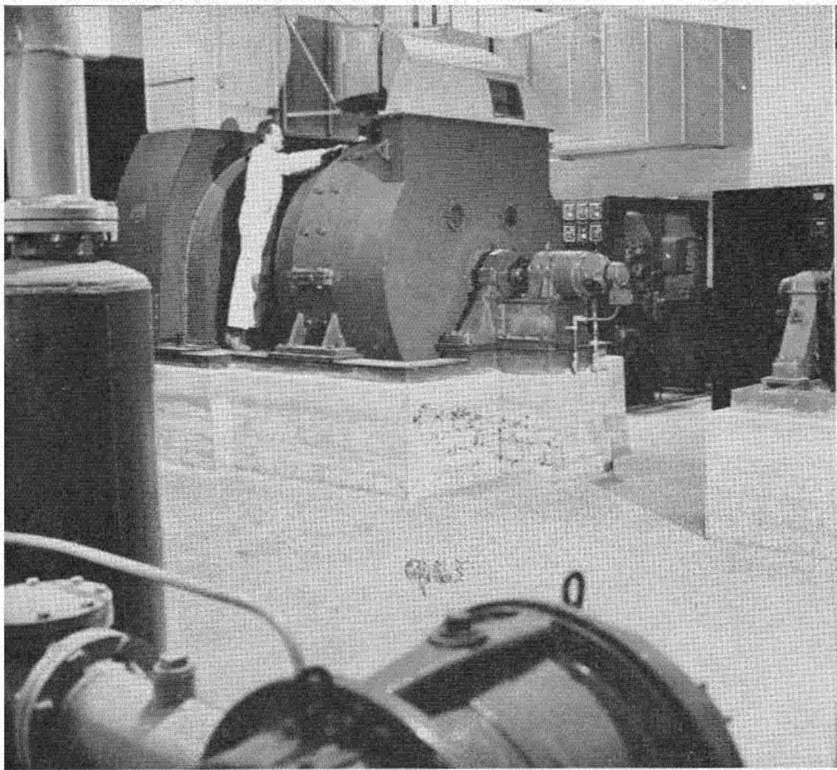
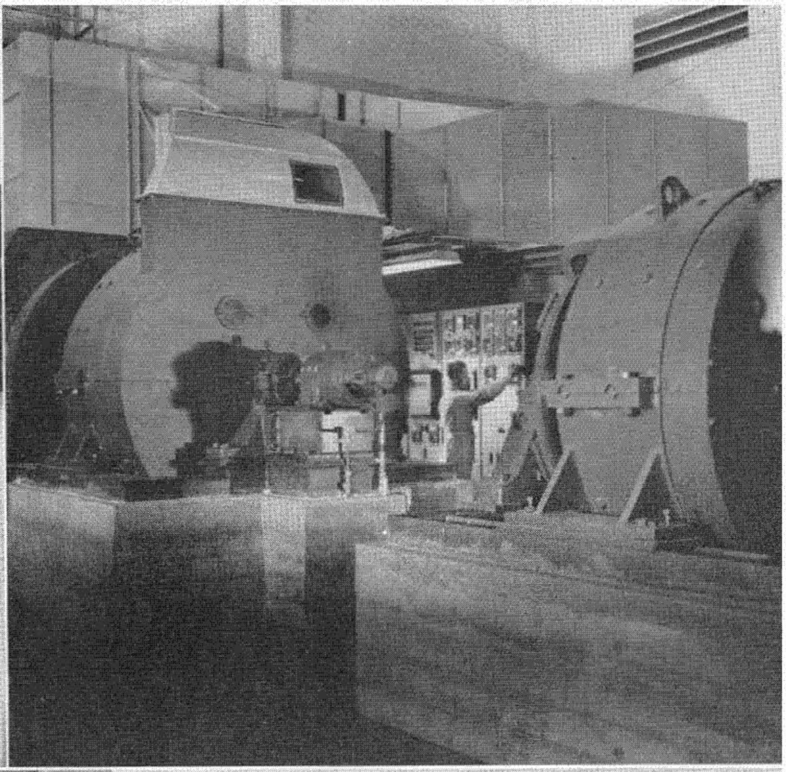
The shell and the reinforcement of openings, etc., conform to the A.P.I.-A.S.M.E. code. The stiffening rings, which prevent the shell from collapsing because of external pressure, were designed so as to buckle under an external pressure of 60 pounds per square inch. The design formulae can be found in Timoshenko's *Strength of Materials* or *Theory of Elastic Stability*.

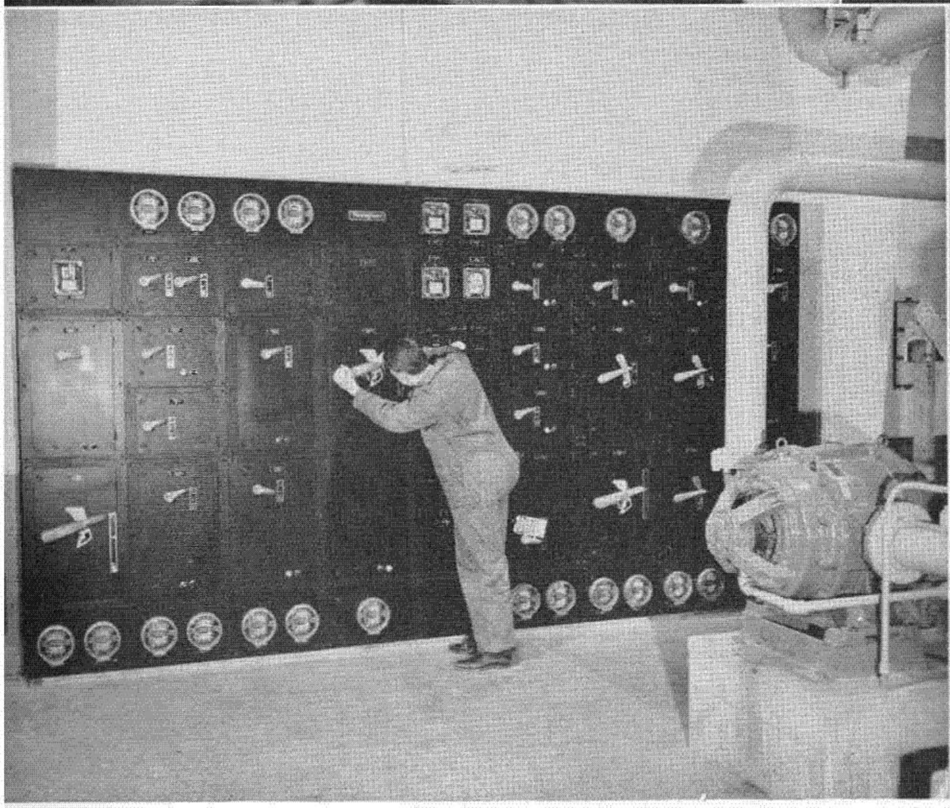
MAIN DRIVE POWER PLANT AND CONTROLS

THE fan system in the Cooperative Wind Tunnel is driven by a two-element electric motor set with a peak rating of 12,000 *hp*. The basic unit of this set is a variable speed direct current motor supplied through a separate motor-generator, which is made up of a variable voltage direct current generator directly coupled to and driven by an alternating current motor of the synchronous type. These three machines, comprising the direct-current system, have a top rating of approximately 2,000 *hp* at from 300 to 570 *rpm*. Power requirements beyond the capacity of the direct current system are supplied by an alternating current, adjustable speed, induction motor provided with a wound rotor and slip rings and carrying a short time rating of 10,000 *hp*. The speed and torque of this alternating current machine are controllable by means of a slip regulator of the liquid rheostat type, involving movable electrodes immersed in an electrolyte solution. Both motors are separately forced air cooled and are assembled as a three-bearing set, driving the fan propeller shaft directly through flexible couplings. A portion of the power room is shown in *Figs. 8 and 9*. One of the power panels is shown in *Fig. 10*.

This split system of drive motors was devised to take advantage of standard developed machines in a combination providing flexibility and reliability at moderate cost. The particular combination selected, in conjunction with a controllable pitch propeller fan system, is calculated to permit comparatively high efficiency operation over the complete speed and power range and at the various air densities attainable. This is possible since a substantial portion of the high air speed region may be operated at approximately full shaft speed, thus effecting low slip losses in the induction motor secondary resistive device. The reader is reminded that appreciable losses are inherent in the operation of such an induction motor substantially below its designed top speed. Full advantage is taken of the wind tunnel characteristic that power requirements at various speeds are essentially proportional to the cube function of the comparative speeds, so that at one-half the maximum air speed only one-eighth, or roughly 1500 *hp*, is required to drive the fan.







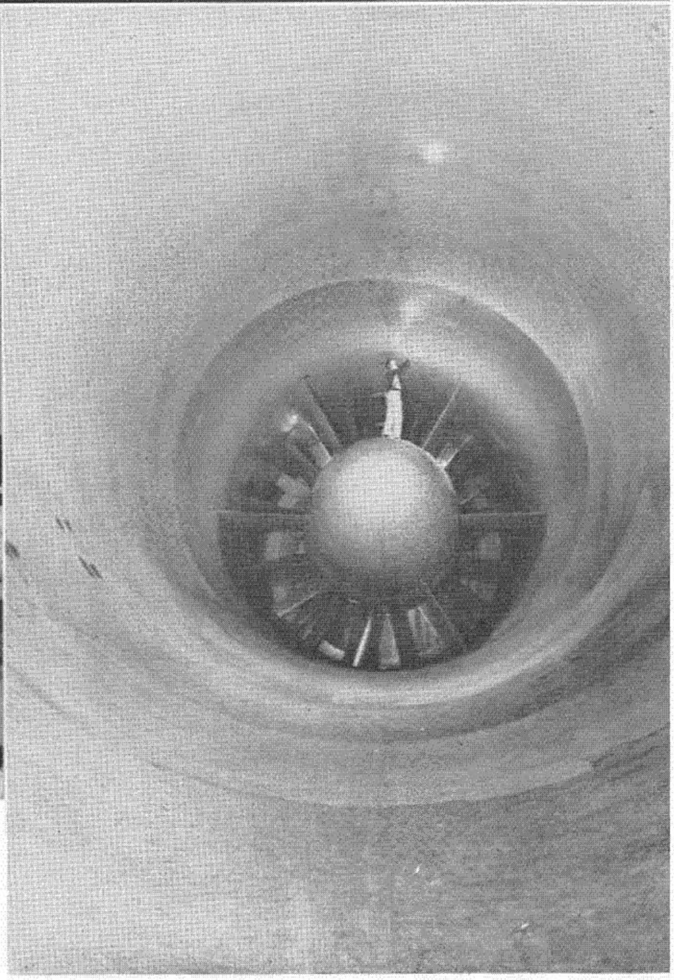


FIG. 8 *(upper left)*: Main power drive. FIG. 9 *(upper right)*: Main power drive, portion of panel, and generator. FIG. 10 *(lower left)*: One of the power panels in power house. FIG. 11 *(lower right)*: Upstream view of the fan system. Diameter of the tunnel in that region is 12 feet 10 inches.

One of the functions of the direct-current component in this system is to enable a quick slow-down of the air in motion in the tunnel by means of absorbing power back into the electrical system through provisions for regenerative braking feed-back. Regenerative braking occurs when the fan is driven at a speed substantially below that corresponding to the combination of air velocity and propeller screw pitch. Under such conditions the fan operates as a turbine to absorb power, which then drives the direct-current motor as a generator to pump electrical energy back into the supply system. This is desirable especially at high air densities, since comparatively large amounts of energy are stored in the high speed recirculating wind stream, which must be stopped before the procedure of quick change of a model rigging cart may be effected.

Thus it may be understood that the direct-current system covers the lower half of the speed range independently, does its share in the upper end of the loading, and regulates to stabilize and maintain precise speed at any setting, besides operating as a brake on emergency slow-downs. The duty of the induction motor is to

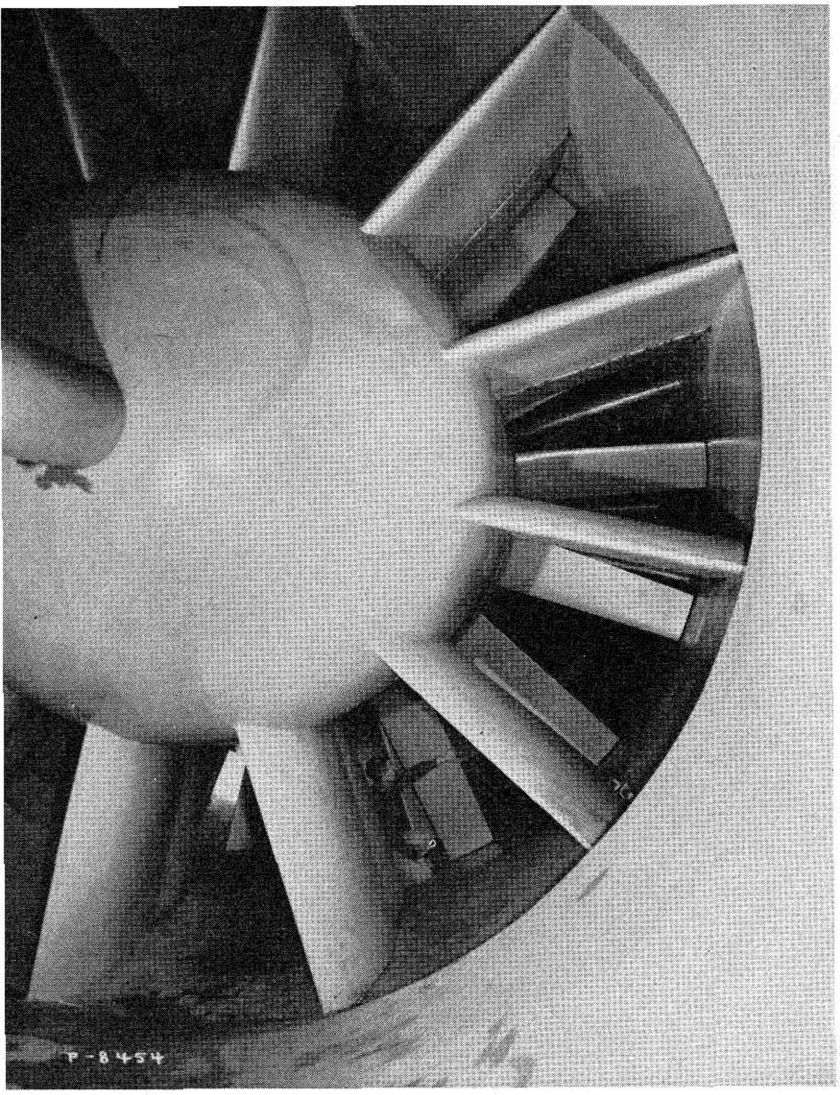


FIG. 12. Downstream view of fan installation showing blades behind prerotation vanes.

carry the major load over the upper half of the speed scale.

Another important requirement for precision testing is met by the adaptability of the direct-current machines to a modern electronic speed regulator with which this drive is equipped.

Electricity is purchased wholesale from the Pasadena Municipal Light Plant. Service is brought to the laboratory underground through a 17,000 volt cable. At the wind tunnel substation the voltage is stepped down to 2300 volts for use in the main machinery and in a separate transformer bank in the same station where it is reduced to 440 volts for auxiliaries and for supplying local transformers for small power and light circuits.

The system of control installed provides for centralized operation at a master control console *(Fig. 2)* by means of remote control and indication circuits. With the exception of selection of type of operation and required speed, all functions are automatic. This involves the extensive use of interlocking and interpretive relays and contactors to initiate such operations as forced draft cooling of the main drive units, circulation and cooling of the slip regulator electrolyte, starting sequences, the allocation of power requirements between the direct-current machine and the alternating-current machine, and the condition of regenerative braking. Among the numerous automatic features is a regulator for maintaining a favorable power factor of the system. This device interprets the phase relationship of incoming current and voltage and adjusts the excitation of the main drive synchronous motor to maintain a preset power factor within the limits of the equipment capacity. Direct control of starting and operation of the main machines is effected through metal clad switchgear, utilizing air-break circuit breakers carrying a fault interrupting rating of 150,000 kilovolt-amperes.

Since this power machinery is used for experimental purposes it is susceptible to unusual load conditions and is therefore provided with an extensive system of interlocks and automatic protective devices. This includes a multi-point strip chart temperature recorder-controller which indicates and records temperature of various machine windings, transformers, tunnel air and slip regulator electrolyte. This device is arranged to transmit warning signals to the console operator on approach of excessive temperatures and to initiate automatic shutdown prior to dangerous conditions.

Excitation and control of the main drive equipment and also for the auxiliaries, such as model power motor generators and compressor drive, is supplied by a separate five unit 125 *hp* set having four exciter generators. Protection of major machines is insured by the use of a storage battery for tripping circuits.

Preliminary tests of the equipment under actual load conditions indicate that satisfactory operation may be expected.

FAN SYSTEM

THE wind tunnel air drive installation comprises the electrical power system described above, directly connected to two tandem mounted fans by means of shafting and flexible coupling.

The requirements that the fan of the Cooperative Wind Tunnel must meet are usually severe: Operating at highest possible efficiency over the entire range of tunnel pressure, it should be able to absorb the entire power input of the 12,000 *hp* drive. The pressure rise across the fan should be reasonably uniform over the cross section of the tunnel and the flow leaving the fan should at all times be purely axial in direction.

The design resulting from these requirements is an unusually flexible fan arrangement, operating at a maximum of 595 *rpm* and consisting of two identical stages and a set of flow straightening vanes, located downstream of the second corner of the wind tunnel. The diameter of the tunnel in that region is 21 feet 10 inches and the hub diameter of the fan is 12 feet. See *Fig. 11.*

Each fan stage consists of a set of 12 stationary prerotation vanes and a set of 16 fan blades with detachable coupling located between the two fan hubs, making it possible to use either the first stage alone or both stages. The prerotation vanes are equipped with adjustable 30 per cent trailing edge flaps. Pitch of the fan blades can also be adjusted. Both of these adjustments can be made by remote control. This control is arranged in such a manner that it is possible to change all of the flap angles and blade angles simultaneously by means of a master push button, or to carry out the change separately for each of the following five groups: prerotation flaps of first stage, blades 1-8 of first stage, blades 9-16 of first stage, prerotation flaps of second stage, blades 1-16 of second stage. It is envisaged that the master push button will be used for all adjustments during a run, while the separate controls will be needed whenever the tunnel pressure or speed is appreciably changed. In the region of high pressures (about one and one-half to four atmospheres) only one-half, *i. e.*, eight of the blades of the first stage will be used. The other half of the blades of that stage and all the blades of the declutched second stage will be set to give no thrust. In the intermediate pressure range (about one and one-half to three-fourths