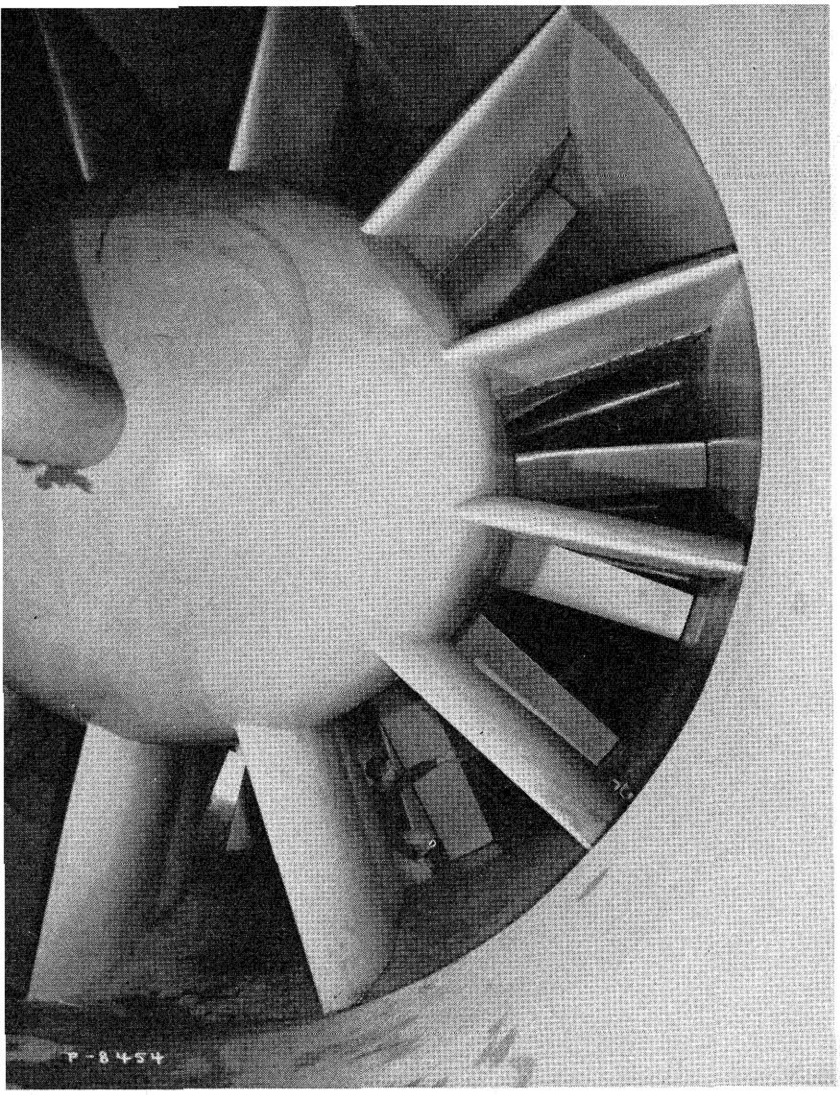


FIG. 12. Downstream view of fan installation showing blades behind prerotation vanes.

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 atmospheres) all blades of the first stage will be used, while both stages will have to operate at the lowest tunnel pressures. At the proper combination of blade pitch and flap angles the flow will leave the fan with approximately axial direction, *i. e.*, without appreciable rotation. Any small rotation left in the flow is removed by means of a set of six straightening vanes located just downstream of the second fan stage.

The fans are coaxially mounted in the east run of the tunnel near the corner adjacent to the power house. They are 21 feet nine and one-half inches in diameter, with one-quarter inch nominal clearance between blade tip and tunnel shell. See *Fig. 12.* Each fan carries 16 forged aluminum alloy blades held in socket assemblies, which are bolted to flats on the periphery of a seven foot diameter hub. The blade socket in which the inner end of the blade is held is a forged alloy steel hollow cylinder, flanged at the hub attaching end. The blade enters and is rotatably mounted in the socket near its outer end on three angular contact ball bearings. The outer pair of bearings carry the centrifugal force load of about 100 tons.

In addition to the function already mentioned, the blade socket houses a series arrangement of two bevel gear units and a planetary gear unit connecting the end of the blade with the pitch control shaft, which enters the socket through the flange. About 2600 turns of the latter are required for one turn of the blade. Chevron seals are provided where blade and pitch control shafts enter the socket, to prevent loss of lubricant.

The fan hub is a steel weldment consisting of an outer forged ring, 16 inches wide by three and one-half inches thick, joined to a sleeve 20 inches long by 29 inches in diameter by two web plates two and one-half inches thick. The 16 flats on the outer periphery are machined to give the blade axis an upstream angular inclination of one degree 18 minutes from the plane of rotation. Under these circumstances centrifugal force imposes a moment on the blade which counteracts a portion of the moment due to air thrust. The fan hub is pressed on and keyed to a forged alloy steel solid shaft which is 14 inches in diameter where it passes through the hub, and 10 feet long. The fan shaft is supported near the end by two spherical self-aligning roller bearings. The downstream bearing mount contains, in addition to the radial bearing, a thrust bearing to carry the full load air thrust of 18 tons.

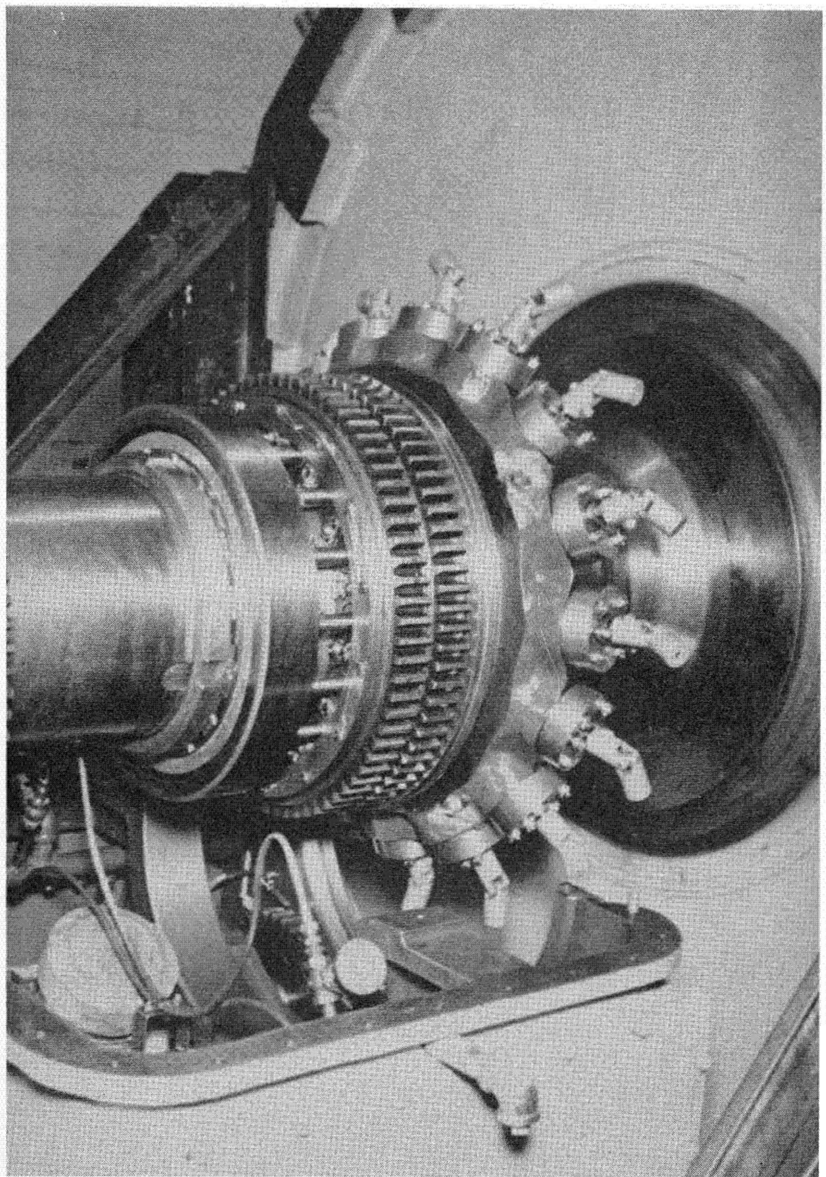
A declutchable flexible coupling connects the two fan shafts and provides for operation of the upstream fan singly or the two fans as a unit. When the tunnel is operating with the upstream fan alone, the blades of the downstream fan will be set at full feather pitch to keep the fan slowly windmilling and prevent Brinnelling of the roller bearing races. A 16-inch diameter hollow steel drum shaft 30 feet long supplies the connection between the upstream fan shaft and the motor in the power house. A plain seal bearing supports the motor end of the drive shaft and a spherical roller bearing the fan end. The drive shaft is connected to the upstream fan shaft by a flexible coupling which is identical to the one connecting the two fan shafts. Motor and drive shaft are connected by an extended type flexible coupling which will permit an offset of one-fourth inch between the shafts and a change of two and one-half inches in the gap between them. These allowances are necessary because of expansion and a strain in the tunnel structure.

The 22-inch long babbitted bearing is swivel mounted on the tunnel shell and carries the 10-inch diameter drive shaft journal. In addition to its function as a support, the bearing provides a seal against loss of air to or from the tunnel. Hub oil is fed to a circumferential cavity at the center of the bearing from an overhead supply tank and flows through the clearance space around the journal toward both ends of the bearing. Flow of oil from the atmospheric end is collected in a drain tank vented to the atmosphere, and the flow from the tunnel end in a drain tank vented to the tunnel. Float-controlled pumps return the oil from the drain tank through a filter to the overhead supply tank. The oil supply tank is vented in such a manner that the air pressure above the oil is either atmospheric or tunnel pressure, whichever is the higher.

The drive shaft is completely enclosed in a steel tube 22 feet long, one end of which is welded to the tunnel shell and the other to the upstream nose of the nacelle. All parts of the fan installation, including fan shafts, bearing mounts, hubs, sockets, etc., are enclosed in a 12-foot diameter by 50-foot long nacelle.

The flow of air through the fan section takes place in the annular space between the nacelle and the tunnel shell. See *Fig. 12.* The nacelle is supported by means of three sets of vanes which extend radially between the nacelle and the tunnel shell. A set of 12 equally spaced prerotation vanes is located just upstream of each fan, and a set of six straightening vanes a short distance downstream of the fans. The trailing third of each prerotation vane is attached to a shaft located at the forward end of the flap. The shaft is carried on ball-bearing mounts, one just inside the wall of the nacelle and

FIG. 13. Pitch control gear box, showing connection to control rods.



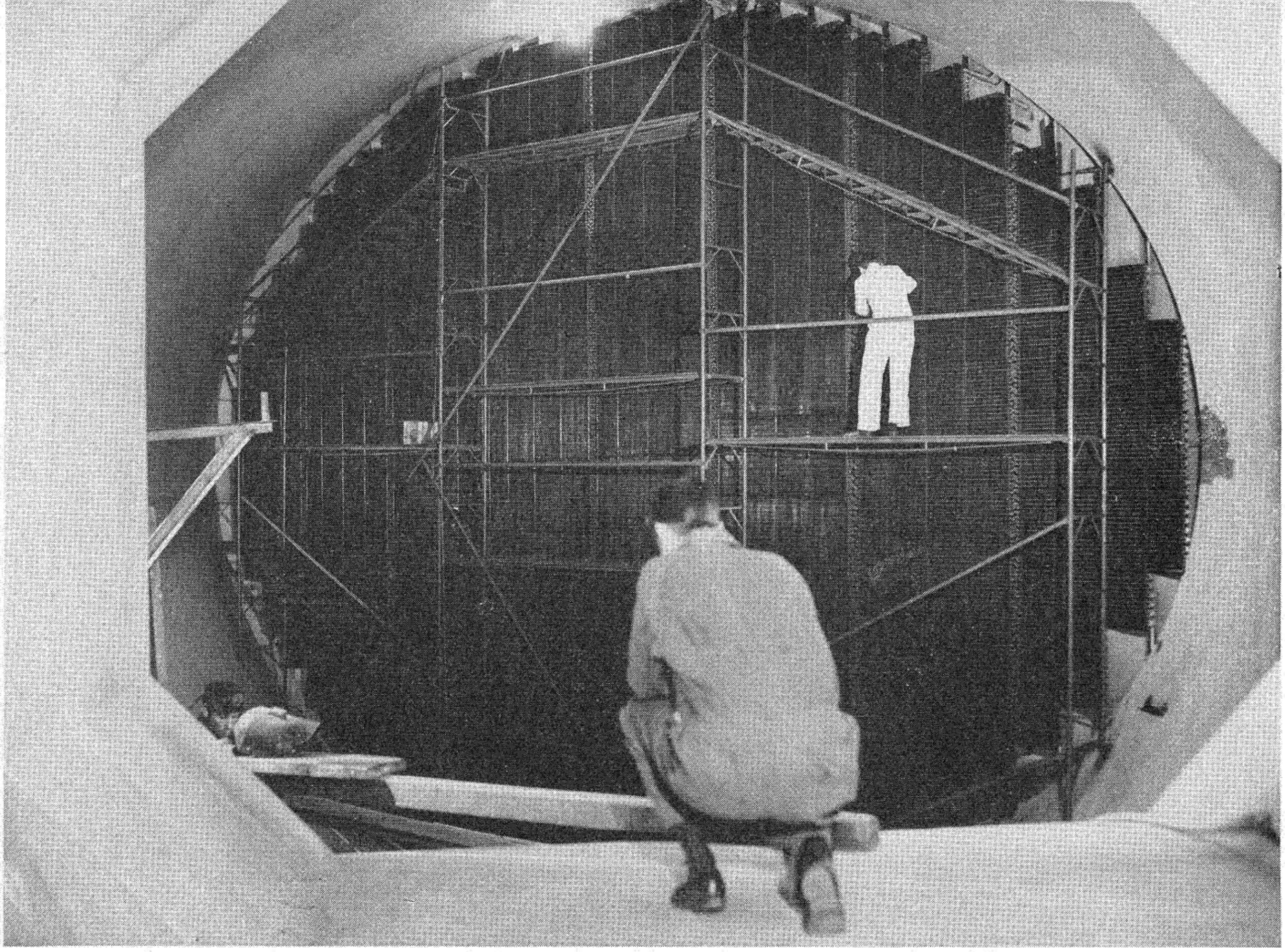


FIG. 14. The cooling radiator at corner upstream of working section consists of 80 units of finned copper coils.

one just outside the tunnel shell. The shaft is sealed at the shell by means of a chevron-packed stuffing box.

The flap shaft is rotatable by means of a lever, nut, and lead screw mechanism. The lead screws controlling the flaps on each set of prerotation vanes are connected together by means of universal joint assemblies so that the 12 flaps of a set can be rotated as one. There is a 25¾-inch wide continuous slot in the nacelle at each fan, through which the blades project into the air stream.

A continuous fairing structure which is attached to the hub fills the nacelle slot except for a three-eighths-inch clearance gap at each side. The 22-inch diameter blade access holes in the fairing are filled by cuffs which are attached to the blades. Seal plates extending between the hub and the fairing structure on both sides of the fan completely blank off the blade socket pockets and minimize windage losses. A differential gear box is mounted on each fan shaft on the upstream side of the fan. This gear box, shown in *Fig. 13*, gathers the 16-blade socket pitch-control shafts and provides a mechanical connection between control shafts attached to rotating and non-rotating structure.

Two group-control shafts project from the upstream gear box and a single one projects from the downstream box. The blades on the upstream fan may be connected to either of two pitch-control groups by means of a manual adjustment within the differential gear box. The two group-control shafts on the box provide separate pitch control for the two-blade group. The 16 blades on the downstream fan are controlled in a single group. Extensions of the three-blade pitch control shafts from the differential gear box pass through stuffing boxes at the tunnel shell and connect to worm gear reducer nuts mounted on concrete blocks on the floor. The two-flap pitch control extension shafts connect to identical floor units. Universal joint assemblies are incorporated in all five control lines to provide for the relative motion of tunnel and ground.

Actuating power, control, and indication for flap and blade pitch change are supplied by an external pitch control system. This is an assemblage of electric motors, miter gear units, magnetic clutches and special gear boxes, mounted on a concrete foundation on the floor near the fan section.

Each of the two-flap and three-blade pitch-control shafts continues on from the worm gear reducer and couples into the output shaft of a special gear box. These gear boxes serve several purposes. They contain dials from which the pitch can be read, and fine and coarse autosyn generators which transfer pitch indication to the console in the control room. They also mount the limit switches which control travel limits of blade and flap. In addition the boxes provide facilities for changing the gear ratio between the input and output shafts if it becomes desirable to alter the rate of pitch change. The motors and auxiliary elements of the system are arranged and electrical controls are set up so that the special gear boxes may be driven simultaneously by the master motor or independently by the individual motors.

The main drive lubricating system provides a continuous flow of cooled and filtered lubricating oil through the nacelle roller bearings and differential gear boxes. In the system are a storage tank, filter, filter circulating pump, two supply pumps, oil cooler, distributing manifold with pressure relief line back to the storage tank, orifice plates, control valves, distributing piping, teleflow meters, temperature indicators, thermoswitches, and collection piping. The 200-gallon storage tank is hung from the east side of the tunnel near the large hatch. The pump, filter, cooler, and distributing manifold are grouped on the floor near by.

In operation, oil is supplied at the rate of 12 gallons per minute to the distributing manifold, from which it flows into the supply lines and to the various nacelle units. After flowing through the units it drains into the collection piping and is returned to the storage tank. The latter is vented to the tunnel so that flow conditions are independent of tunnel pressure. In each supply line near the nacelle unit a teleflow meter is installed. This is a device which prevents operation of the main drive motor whenever oil flow is not established.

A temperature indicator and thermoswitch are mounted in the case of each roller bearing at a point where they are in contact with the outflowing oil. The temperature indicator gives a remote reading at the console in the control room. The thermoswitch stops the main drive motor if the oil temperature exceeds 190 degrees *F*.

COOLING AND DEHYDRATING

THE cooling specifications of the Cooperative Wind Tunnel call for continuous operation of the equipment at a power input of 12,000 *hp*, with the temperature of the air inside the tunnel limited to about 125 degrees *F*. The radiator, which removes the corresponding amount of heat, *i.e.*, about 500,000 *B.t.u.* per minute, shown in *Fig. 14*, is located in the fourth wind tunnel corner just upstream of the contraction. It consists of 80 units of finned copper coils, each coil having three rows of tubes in depth.

In order to insure the smallest possible pressure drop across this radiator, it was placed with the tubes running parallel to the plane of the corner ellipse. The corner vanes, similar to those shown in *Fig. 6*, turn the air by only 45 degrees; thus the air arrives normal to the radiator face and is turned by an additional 45 degrees, completing the full 90 degree turn, on leaving the radiator. This final turn is achieved by means of small turning vanes that are integral parts of the radiator fins. The radiator coils are provided with water circulation entering and leaving through the tunnel corner vanes. The water is cooled by circulation over a cooling tower. About 3,600 gallons per minute of cooling water can be circulated in this system.

Recently it has become known that the relative humidity of the air is one of the important parameters of high speed flow. Furthermore, any appreciable accumulation of moisture would cause considerable inconvenience and complications. Therefore, it became advisable to control the humidity of the air inside the tunnel. This is done by means of a so-called dehydrator, an air

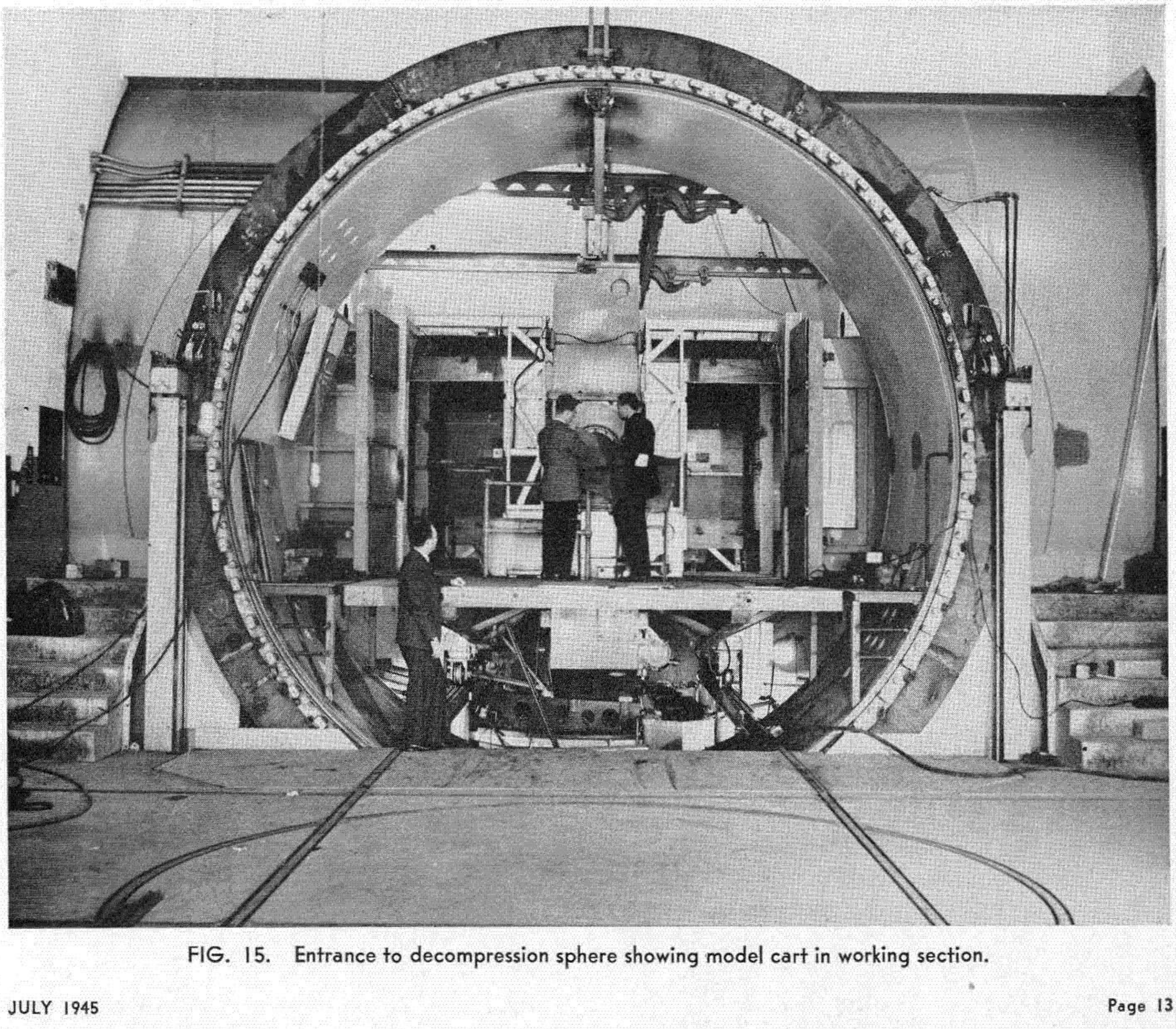


FIG. 15. Entrance to decompression sphere showing model cart in working section.