DESIGN AND DEVELOPMENT OF A PRECISION SPEED CONTROL ELECTRIC DRIVE FOR THE GUGGENHEIM AERONAUTICS WIND TUNNEL.

Thesis by

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SUMMARY.

The problem and solution described in this report is that of designing and building a suitable electric drive for the propeller which drives the air in the wind tunnel of the Guggenheim Aeronautics Laboratory. Specifications were written for a suitable direct current motor and a motor-generator set for furnishing the direct current, and a complete control system was designed and installed. The control system is arranged so that a minimum number of operations is required to start and stop the equipment and to adjust the speed of the propeller. All intermediate processes are automatically controlled and the equipment is interlocked so that operations can not occur out of proper sequence. Adequate protective features prevent serious injury to the equipment, even though the equipment is neither visible nor audible from the point of control. Two types of speed control are provided, one known as hand control and the other as regulated control. When under regulated control the speed of the propeller is regulated to a constant value with a high degree of precision for equipment of this size, and the value of the regulated speed can be adjusted at the will of the operator over a wide range. Speed control of both kinds may be obtained at conveniently located stations by operation of a transfer switch.

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I. INTRODUCTION. Under the terms of a grant from the Daniel Guggenheim Fund for the Promotion of Aeronautics, a department of aeronautics was recently established at the Institute. One of the principal features of the laboratory built for the purpose of carrying on the experimental work in this department was a high speed wind tunnel with a working section ten feet in diameter. The problem and solution described in this report is that of designing and building a suitable electric drive for the propeller in this wind tunnel.

Before proceeding to a discussion of the drive, a general description of the tunnel itself and its use would be desirable. The tunnel is of the Gottingen closed-circuit type, the air being continuously recirculated. A cross section of the tunnel is shown in Fig. 1. As can be seen from the notations in the figure, the tunnel occupies the height of nearly four floors, the overall vertical dimension being about 45 feet, and has a length of nearly 100 feet. The greatest internal diameter is 20 feet.

The tunnel is composed of sections of circular cylinders and cones, connected end to end to form the closed circuit shown in the figure. The four sections in the observation room are made of redwood staves held together by hoops of steel rod and angleiron on the outside. The remainder of the tunnel is made of reinforced concrete, the supporting structure and parts of the end cylindrical sections being cast in the usual manner, and the remainder formed by the "gunnite" spraying process. In order to minimize the transmission of vibration the entire tunnel structure is supported free of the building. The mouth of the right-hand upper concrete section before the installation of the wood sections is shown in Fig. 2.

A series of deflecting vanes is mounted in each of the elliptical sections, formed by the intersection of a horizontal and a vertical section, in order to change the direction of the wind with minimum energy loss. These vanes have the standard Gottingen vane profile, the sets in the upper left and two lower corners having a chord of 3 feet and the remaining set a chord of 2 feet with 6 inch tails. Fig. 3 shows the vanes in the lower right hand corner after the installation was completed. Three of the vanes may also be seen, before installation, in the left foreground of Fig. 2.

The propeller which drives the air through the tunnel is composed of four detachable blades, each of Clark Y section, mounted in a central cast hub. The diameter of the propeller is 14 feet 11 inches and of the tunnel at the section where the propeller is located approximately 15 feet, so that clearance between propeller and tunnel wall is very small. Two methods of mounting the propeller motor were possible, one to mount the motor inside the tunnel and connect it directly to the propeller, and the other to mount the

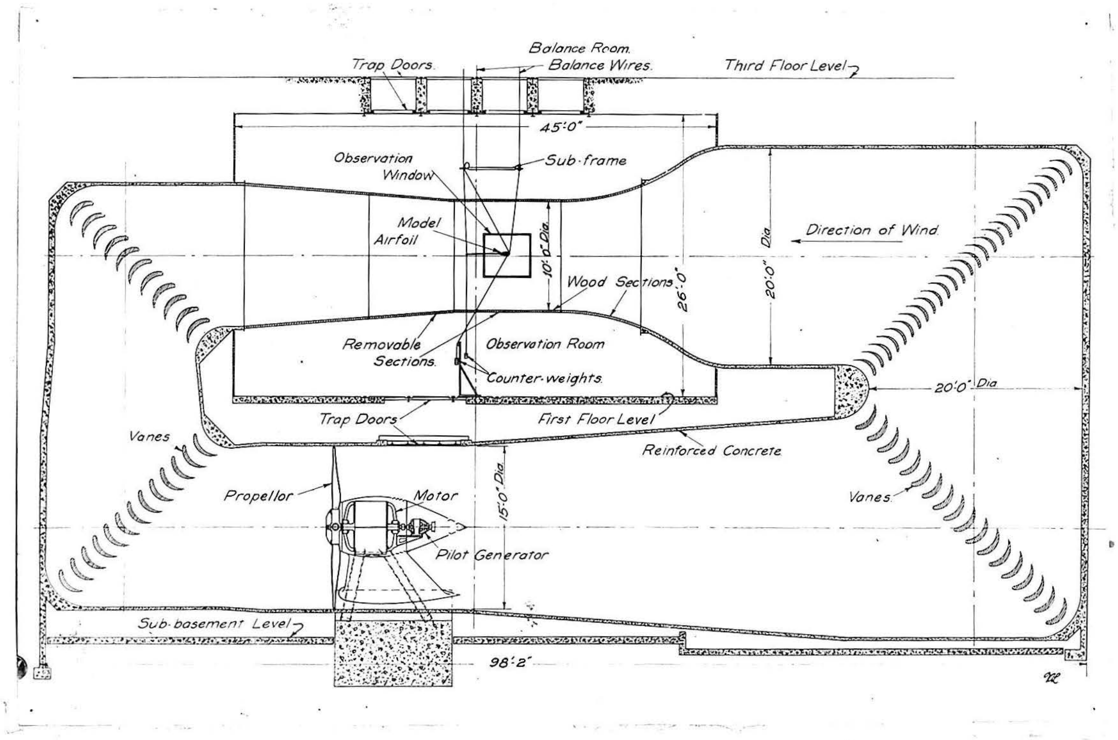


Fig. 1.

CROSS-SECTION OF WIND TUNNEL.

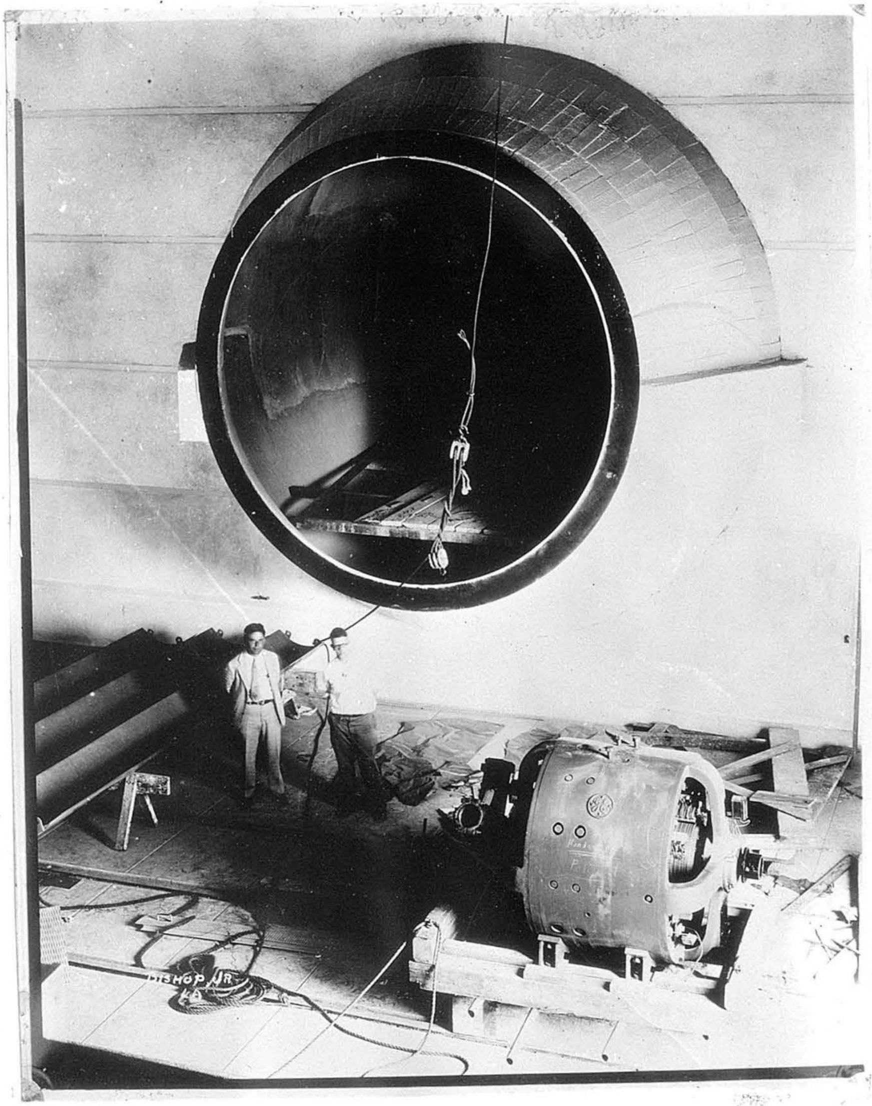


Fig. 2.

CONSTRUCTION VIEW, SHOWING MOUTH OF CONCRETE SECTION. DEFLECTING VANES AND PROPELLER MOTOR IN FOREGROUND.

motor outside, connecting it to the propeller by means of a long shaft. After consideration of all features the former method was chosen. This method eliminated the difficulties that would be introduced by the numerous bearings and the stuffing box required for the long shaft, and the problem of supporting the propeller became that of supporting the motor itself. Also the obstruction introduced by the motor was not serious, since aerodynamical considerations required that the wind stream be contracted just back of the propeller.

In the operation of the tunnel the model to be tested is mounted, usually inverted, in the upper or working section of the tunnel, and supported, by means of wires attached at three points, from a sub-frame above the tunnel, as shown in Fig. 1. A series of counterweights assists in holding the model in position. The sub-frame is supported by means of the balance wires from three balances, located in the balance room located on the third floor of the building. A series of trap doors is so arranged that the balance wires may be led through the floor with a minimum of difficulty.

Two observation windows, one on each side of the tunnel, are provided so that the action of the model may be noted. In case it is desired, however, one or more of the wooden sections may be removed, and the tunnel operated with "open throat". In this case the tunnel circuit is closed by the observation room itself, and to minimize the disturbance so caused, all unnecessary projections in the observation room floor, walls, doors and ceiling have been eliminated. One of the principal advantages of the closed-circuit tunnel is that the working section and hence the observation room may be operated at atmospheric pressure.

When the propeller is started, a stream of wind is driven past the model in the direction shown by the arrow in Fig. 1. The nozzle-like contraction in the tunnel just before the working section and model are reached causes the wind stream to be quite straight and uniform and to reach its maximum velocity as it passes the model. The reactions of the model due to its relative motion with respect to the air are reflected in a drag, or force downstream, and a lift or upward force. Since the model is mounted inverted, this upward force with respect to the model is downward with respect to the balances. The two forces cause changes in the tensions in the balance wires and can be immediately detected by the change in balance readings for equilibrium. Small motors driving cable drums attached to the supporting wires make possible easy and convenient adjustment of the position of the model in the tunnel.

For all accurate testing, the performance will be determined entirely from balance readings, and therefore the operator must be stationed near the balances on the third floor of the building. In order that tests may be made conveniently and rapidly, it is essential that the operator have complete control over the velocity of the wind and therefore over the speed of the propellor. Since many variable factors, such as position of the model, temperature and pressure of the air, wind velocity, etc. are present, engineering accuracy requires that the variations in each of these quantitites be restricted to as small a value as possible. Even with absolutely constant propellor speed, slight variations in air velocity are unavoidable, and in order to keep these variations minute, it is important to have the propellor speed as precise as possible. At the same time, in order to obtain complete series of tests, it is necessary that the propeller speed, at the will of the operator, be varied over a wide range, from practically zero up to full speed, and yet after the speed has once been set, it must be maintained with a high accuracy over a considerable period of time.

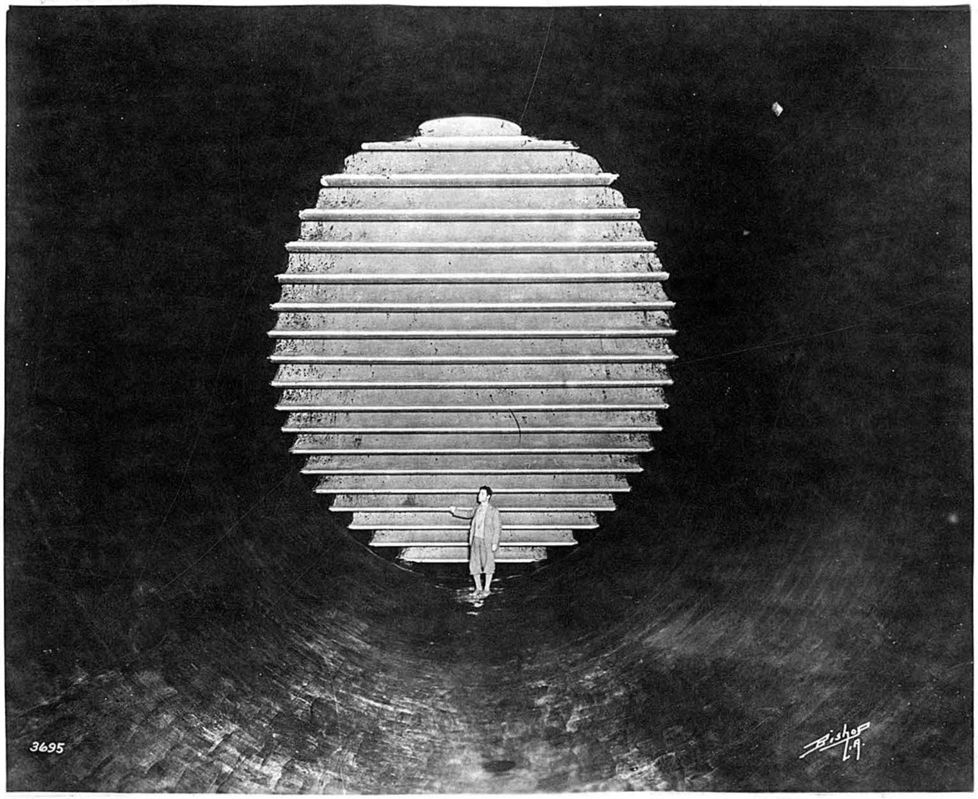


Fig. 3.

INTERIOR OF TUNNEL SHOWING DEFLECTING

VANES AT THE LOWER TWENTY FOOT

INTERSECTION.

II. DESCRIPTION OF MAIN ELECTRICAL APPARATUS.

From data furnished by the Aeronautics Department it was determined that the output of the propeller motor must have a value of at least 500 H.P. at 700 r.p.m. At the same time, in order not to restrict the flow of air past the motor, the overall diameter had to be less than 6 feet. The wide speed range desired indicated that a direct current drive would be essential.

Preliminary investigation showed that the standard direct current motor of this size would be mounted on a bed-plate and would be furnished with pedestal bearings supported from the bed-plate. It was also found that an enclosing shell within the maximum diameter of 6 feet would be difficult, if not impossible, to obtain with the standard motor design. Special designs with bearings mounted in end brackets supported directly from the motor frame, developed for submarine and other transportation purposes, solved the problem, and specifications were written to call for this type of motor. Notwithstanding the fact that a 40 per cent overload rating for a one-half hour period, and an ambient temperature of 45 degrees C. were specified, the motor purchased has an overall diameter of only 4 feet 8 inches.

In order to locate the motor at the center-line of the tunnel without reducing the effective tunnel cross-section, a fabricated-steel supporting structure for the motor was necessary. It was found that a smaller overall diameter for the motor and framework would result if the motor feet were eliminated and the framework made to fit the cylindrical motor frame. Therefore a structure was designed which terminated in a semi-circular steel-plate cradle having the same internal diameter as the external diameter of the motor. This was supported by four steel legs extending out through the tunnel wall into a heavy concrete foundation. Vibration of the propeller motor and of the pilot generator, a small generator supported from the motor and described below, was expected to be a serious source of inaccuracy in the regulated speed. Hence it was necessary to make the motor supporting-framework so rigid that its natural frequency of vibration would be far beyond any introduced by the fundamental frequency of the propeller, although the sections required for this purpose were much larger than any required for strength alone. The cradle was made of 2 inch rolled steel plate and the legs of 10 inch, 136.5 lb. per foot H column-section. The connections of the legs to the cradle were heavily reinforced and riveted in place. A view of the framework during assembly is shown in Fig. 4. The two rear U-shaped troughs in the rear H-column legs were covered by steel plates, as shown, and were used for wiring gutters to convey the connections to the motor terminals. The details of this are shown clearly in Figs. 6 and 7.

The concrete foundation was made very heavy in order to absorb as much vibration as possible and was

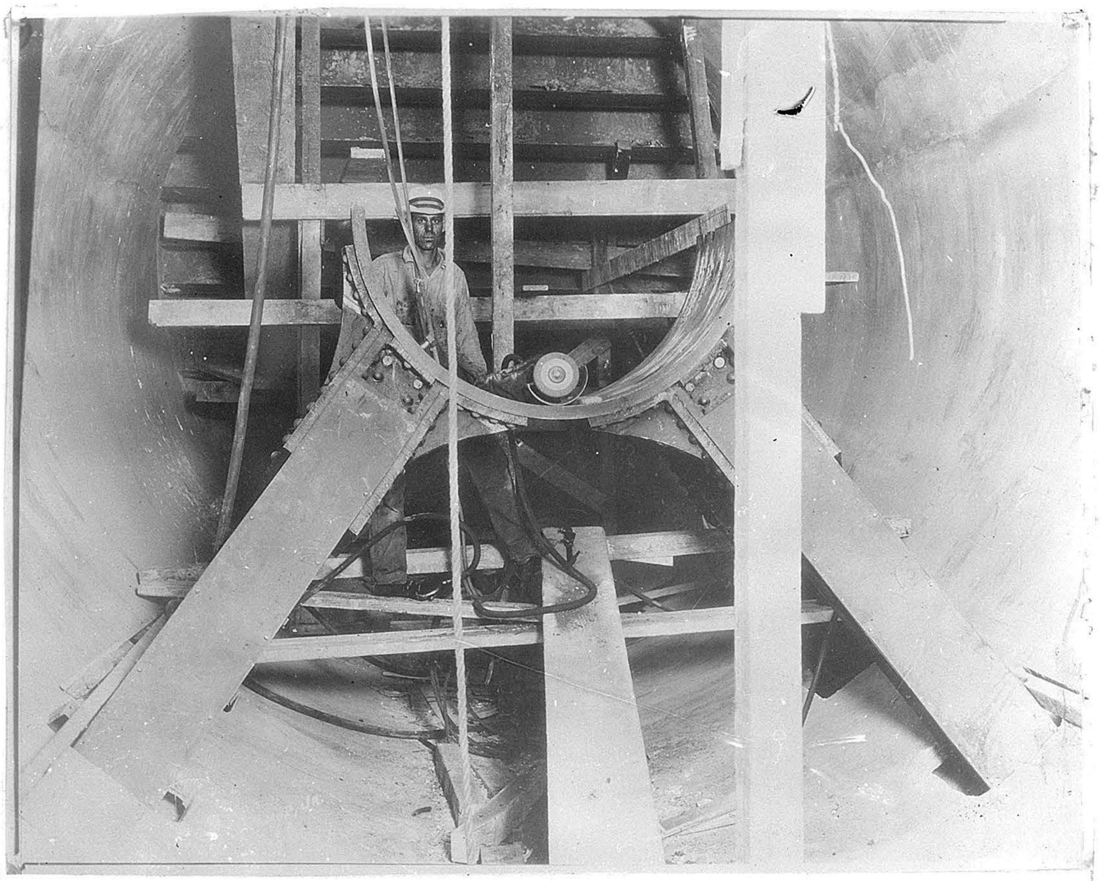


Fig. 4.

CONSTRUCTION VIEW OF PROPELLER MOTOR

SUPPORTING FRAMEWORK.

heavily reinforced. It was also entirely isolated from the tunnel and the remainder of the builing and completely poured with the exception of four pockets for the legs of the framework before the framework was installed. Mounting bolts, for supporting and adjusting the framework, and heavy reinforcing bars around the leg pockets were cast into the foundation. The framework was then assembled, the motor mounted in the framework, the two aligned as a unit, and then the leg pockets were filled with concrete, uniting the entire structure into a rigid and continuous whole. Cored ducts in the foundation continued the wiring gutters to accesible locations.

In order to permit this type of motor mounting, it was necessary to countersink the heads of the bolts holding the field poles into the motor frame, but wherever possible openings were cut in the cradle to give access to these bolts. The motor was secured to the cradle by cap screws, passing through openings in the cradle into holes tapped in the motor frame.

The motor is of General Electric manufacture, rated at 500 H.P. continuous, with an overload rating of 50 per cent for two hours, based on 40 degree C. ambient temperature. This is adequate to meet the specified requirement of 40 per cent overload for one-half hour with a 45 degree ambient temperature, mentioned above. The normal voltage, current and speed ratings are: 230 volts, 1760 amperes, 700 r.p.m. The speed, however, is variable over a wide range, from 30 to over 800 r.p.m., with corresponding changes in input, the method of speed control being described below. A view of the motor before it was lowered into place is shown in the right foreground of Fig. 2, and a closer view, with the propeller hub casting in place, is shown in Fig. 5. It may be noted from the latter figure that the motor is of the interpole type and has six main field poles. The main field is excited from a 125 volt D.C. source, described later. The net weight of the motor is approximately 15,000 lbs.

One serious problem, introduced by mounting the motor inside the tunnel, is that of securing adequate ventilation and cooling. The entire output of the propeller is eventually converted into heat, by friction of the air, and since the air is recirculated, this heat together with the losses in the motor will be taken up by the air and walls of the tunnel. As data for determining the heat transfer from the air to the tunnel walls was meagre and inaccurate, it was impossible to predict the temperature to which the air would rise or the time for equilibrium. If the air temperature remained within reasonable limits, it would be an easy matter to deflect part of the tunnel air through the motor, cooling it directly. On the other hand, if the air temperature should exceed approximately 50 degrees C., a forced draft of air from outside the motor would be required for cooling. Because of the absence of definite figures, the expense of external cooling, and the difficulty of carrying on work in the observation room with

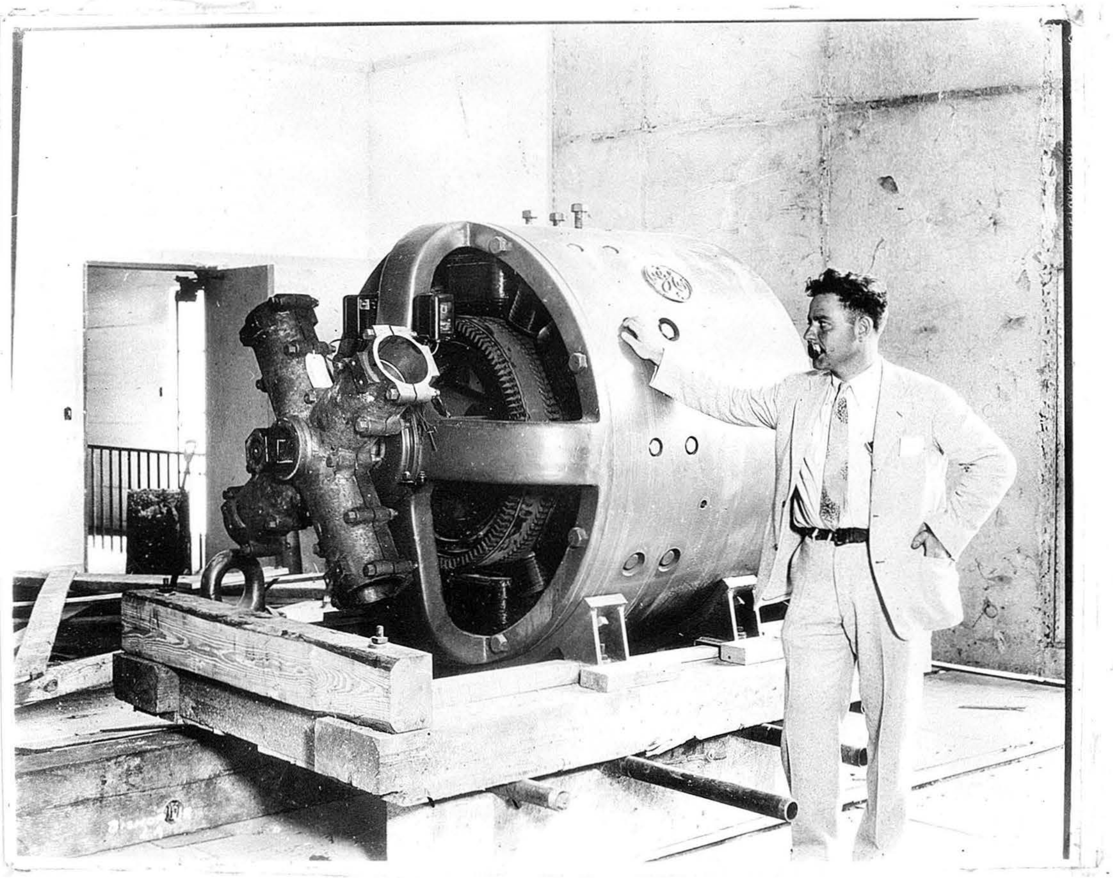


Fig. 5.

PROPELLER MOTOR AND

PROPELLER HUB CASTING

BEFORE BEING PLACED IN THE TUNNEL.

the temperature of the air in the tunnel exceeding 50 degrees C., especially during open throat work, the decision was reached to use the air in the tunnel for motor ventilation. In order to cool the tunnel itself as much as possible, provision was made for a good natural draft circulation of air about the tunnel, air from the outside of the building being fed in at the bottom, rising as it was heated and being exhausted through vents in the roof of the building. As a further precaution, the deflecting vanes in the two left-hand corners of the tunnel, Fig. 1, were arranged for water cooling. A mean of several estimates placed the average air temperature at 45 degrees C. and the specifications called for the motor to deliver its specified output at this ambient temperature. Experience has indicated that equilibrium temperature will considerably exceed 50 degrees C., although this value is not reached until after several hours of operation at high speed. As a consequence it has been decided not to complete the water cooling installation, for the present at least, and to allow the tunnel to run until excessive air temperature is reached, at which time the tunnel will be shut down, the air changed and the motor cooled by circulation of the new air.

In order to keep the friction loss, caused by the air passing the motor, a minimum, it was necessary to enclose the motor and its support in a streamline fairing (#), broad nosed at the propeller end and tapering-off to a point

(#) Fairing is an aeronautical term indicating a streamline covering.

at the tail. To allow ventilating air from the tunnel to pass through the motor, an opening was left in the nose and louvres were provided in the sides. As it was desirable to maintain the pilot generator, attached to the motor shaft, at as constant a temperature as possible, arrangements were made to ventilate it separately, by placing a baffle between it and the propeller motor. The air entering through the nose is deflected out through louvres ahead of the baffle, and fresh air drawn in through louvres behind the baffle cools the pilot generator and passes out through the tail. The two sets of louvres are staggered around the periphery to avoid passing the same air through the two circuits. The fairing is made up of a skeleton framework attached directly to the motor and its support, covered with steel plates screwed in place. The section covering the propeller hub revolves with the propeller, but the remainder is stationary. A view of the framework showing the assembly is given in Fig. 6. Another view looking toward the tail is shown in Fig. 7. In the former figure the baffle is hidden by its supporting angles, but it is plainly visible in the latter view. To obtain access to any part of the motor it is necessary to remove the adjacent plates. An ingeneous assembly of the skeleton frame allows a large section of the fairing to be removed as a unit in case of major repairs.

After the fairing of the motor itself had been completed, the legs on each side of the shaft were enclosed in additional fairings. Views of the completed installation

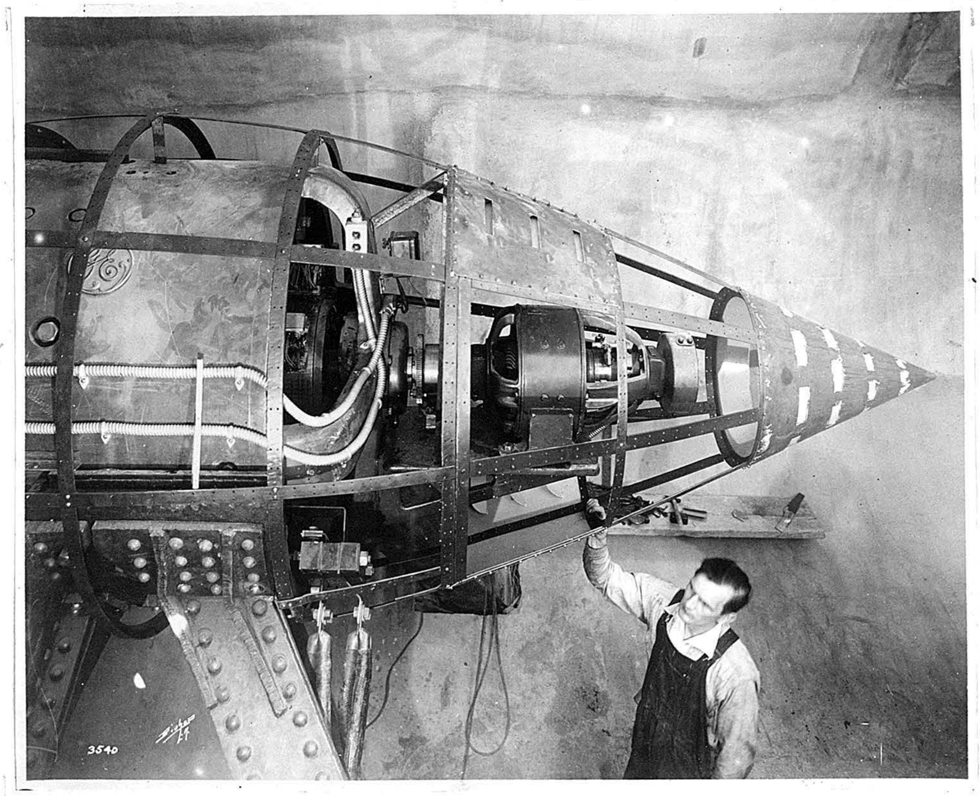


Fig. 6.

PROPELLER MOTOR AND PILOT GENERATOR
IN PLACE, SHOWING FRAMEWORK
FOR FAIRING.

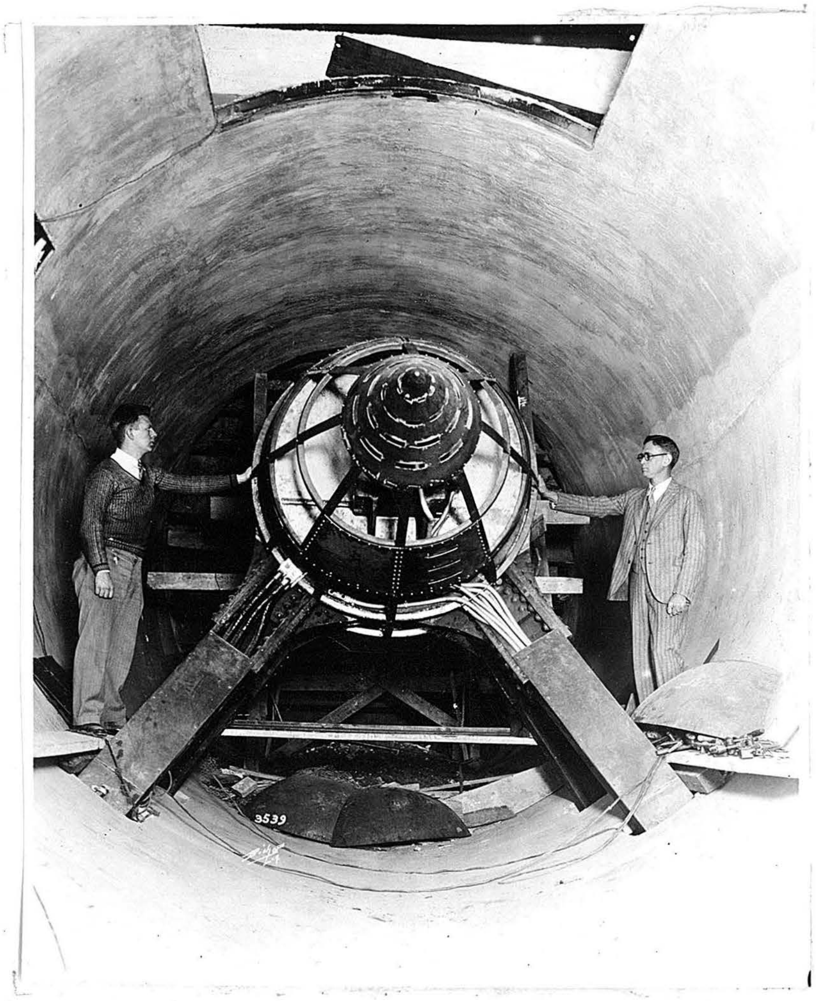


Fig. 7.

CONSTRUCTION VIEW OF PROPELLER MOTOR FRAMEWORK AND FAIRING.

are shown in Figs. 8 and 9, from the propeller and tail ends respectively.

For furnishing the direct current necessary for the propeller motor, a motor-generator set is required. A general view of the set, after installation, is shown in Fig. 10. To a large extent this equipment is standard and requires no special comment. The direct current generator is rated at 430 KW. continuous, with a 50 per cent overload for 2 hours, 230 volts, 1870 amperes. The synchronous driving-motor is rated 540 KVA. 612 H.P. .9 P.F., continuous, with of course a 50 per cent overload rating, 2300 volts, 136 amperes, 3 phase, 50 cycle, 1000 r.p.m.

In order to operate satisfactorily with the speed controlling equipment, the D.C. generator is separately excited by a 5 KW. 125 volt D.C. exciter, direct-connected to the generator. This exciter and the overspeed device are shown in the foreground of the figure. In order to make possible future automatic power-factor control of the synchronous motor, in case it should be desired, to simplify the starting sequence, and to eliminate the losses of the synchronous motor field rheostat, an individual exciter is provided for the synchronous motor. This is direct-connected and mounted on the opposite end of the set. Variations in synchronous motor field current are made by adjusting the exciter field rheostat. This exciter has a rating of 4 KW. at 125 volts.

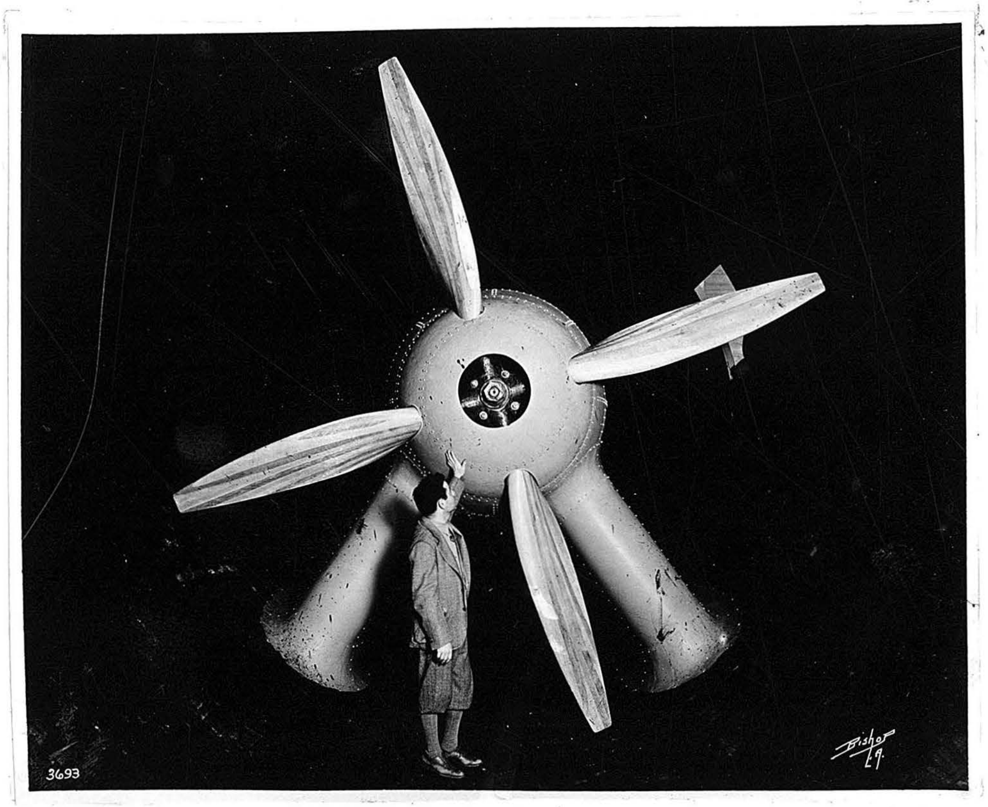


Fig. 8.

COMPLETED INSTALLATION

SHOWING PROPELLER AND FAIRING,

FACING PROPELLER END.

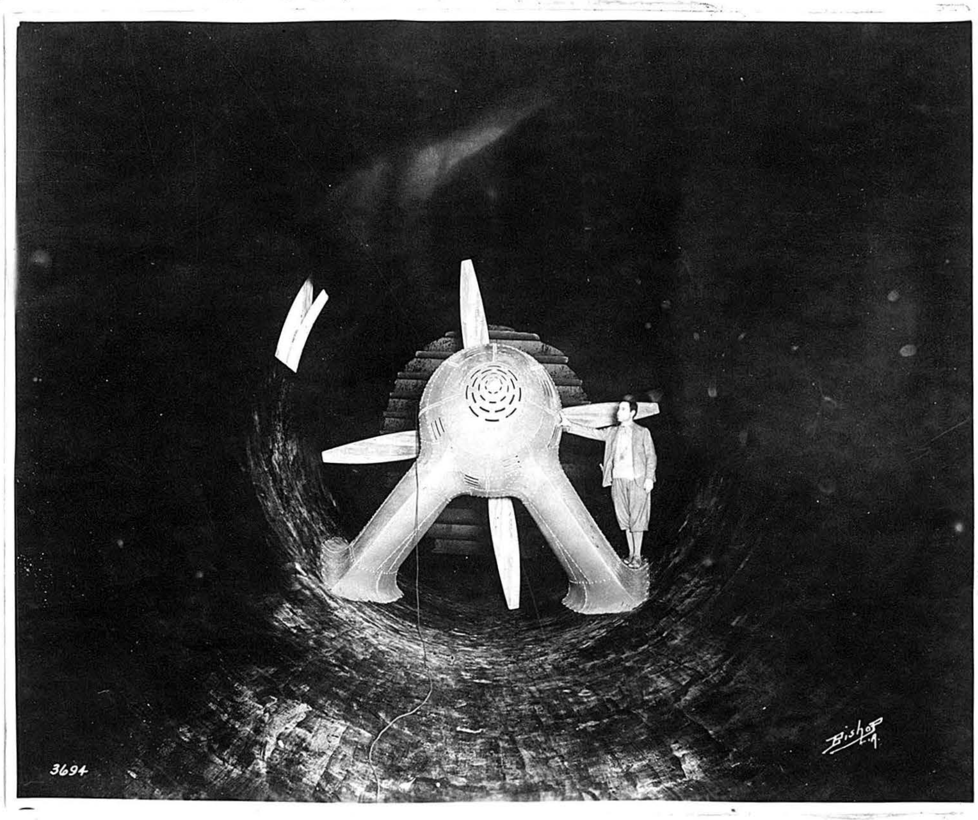


Fig. 9.

COMPLETED INSTALLATION

SHOWING TUNNEL INTERIOR AND MOTOR FAIRING,

FACING TAIL END.

Ventilation for this set is furnished by natural draft, air from outside the building being furnished under the base of the set, driven through the machines and discharged into the room. Part of this air is exhausted into ducts leading direct to the roof and the remainder is passed into the space around the tunnel, helping to cool the tunnel as described above. The pit under the machine for the ventilating air forms an admirable chamber for connections, as it permits all main leads to be taken out at the bottom and run into conduits extending into the pit. The foundation for this set is also isolated from the building and all conduits which pass through the walls of the pit are insulated so that no vibration is transmitted through them.

As the equipment is to date the largest source of direct current on the campus, it was considered desirable to make some provision for utilizing it in other types of work, and double throw switches, as described below, have been provided for transferring connections easily from the tunnel to another experimental set-up. As the type of experiments anticipated will probably require a current of large magnitude at relatively low voltage, it was deemed advisable to keep the generator voltage at 230 volts, thus making available a current of nearly 2000 amperes continuous at any voltage up to 230 volts. To provide for stable operation at low voltage the generator is provided with a differential series field.

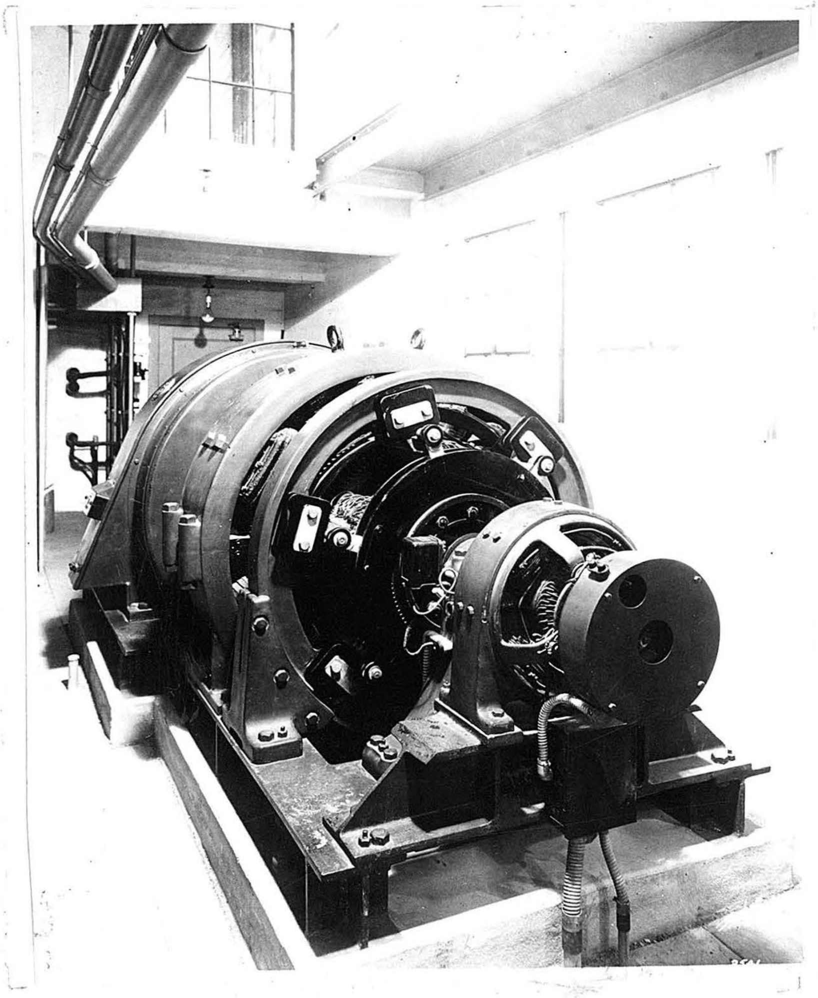


Fig. 10.

COMPLETED INSTALLATION.

MAIN MOTOR-GENERATOR SET.

III. METHOD OF CONTROL.

As previously indicated it is essential for the operator in the balance room on the third floor to have complete control of the propeller speed. For the remaining control functions, namely, starting and putting the motor-generator set on the line and starting the propeller motor, two alternatives were possible. One was to have direct control of the necessary switching devices in their desirable locations near the machines, and the other was to employ remote control, locating the control station at a point most convenient for the operator and locating the switching devices near the machines controlled. Any other possibility, such as locating the main switching devices at a point convenient for the operator and running the main leads there , was economically out of the question because of the large conductors required for the D. C. leads and the high voltage of the A. C. leads. Of the two possible arrangements, remote control was obviously the best from the operator's standpoint, although probably more expensive. On the other hand, concentrsted direct control was not easy to obtain, since the large size cables necessary for the D. C. leads would require the control station to be located quite close to the motor-generator set and the propeller motor. Any such location was found to be unfavorable with respect to the alternating current switching apparatus, making remote control of some sort, either mechanical or electrical, almost a necessity for the alternating current switching equipment. Every location desirable from an electrical point of view would have to be either at the basement or sub-basement levels, four or five floors from the normal location of the operator, and therefore very undesirable from an operating viewpoint. Also because the men operating the equipment would be non-electrical men, the protective interlocks and simplifications in operation possible with remote control were very desirable. An estimate of the cost under the two schemes showed that remote control was very little more expensive than direct control because of the more economical arrangement of main switching equipment possible. It was therefore decided to locate the control station near the operator on the third floor and employ remote control. Because of the great distance from that point to the apparatus, mechanical control was impossible and electrical control was therefore adopted.

With the selection of remote control some source of control power was necessary. In general, direct current is preferable to alternating current because of less expensive operating devices, smaller current requirements and greater reliability, but in this case alternating current was the easiest to obtain. A storage battery was out of the question because of the enormous expense it would entail and the undesirability of the extra equipment required for charging.

However, no source of direct current for supplying the field of the propeller motor had yet been provided. Further it was undesirable or impossible to supply this field from the main D.C. generator or either exciter. The main generator could not be used because the wide speed range of the motor required a voltage varying over too wide limits. The exciter for the D.C. generator could not be used because of variable voltage required of it in order to work with the speed regulator. It was undesirable to use the synchronous motor exciter because such operation precluded the application of a power-factor regulator and also because it would prevent the use of the exciter rheostat for synchronous motor field control, thus entailing the use of a main rheostat in the synchronous motor field circuit.

It was therefore decided to add an additional small generator for supplying the field of the propeller motor and to use this machine for control and other miscellaneous.power. The increase in size necessary to supply control power was almost negligible, since field for the propeller motor is not required until nearly all operations requiring large amounts of control power have been completed. However, this generator could not be driven by the main synchronous motor because the former has to furnish power for operating the starting devices for the latter. A 9½ KW. 125 volt D.C. generator, driven by a 220 volt 3 phase induction motor, was therefore added to the equipment. A standard automatic starter for this motor-generator, using A.C. control power, made remote control of this equipment simple. In order to start the equipment it is necessary to first start the control motor-generator, thus making available control power for all the other switching operations.

The apparatus for performing the necessary switching functions consists of oil circuit breakers and a field contactor for the synchronous motor, a motor operated rheostat for the synchronous motor exciter, air circuit breakers for energizing the propeller motor field and armature circuits, speed regulating equipment, together with miscellaneous contactors and relays necessary to secure proper operation of the above. In addition to the equipment just listed which is all electrically operated, certain hand operated equipment, such as knife switches, hand operated rheostats, etc. is required. These are set in prearranged positions and are not changed during normal operation. In purchasing it was considered desirable to divide the apparatus into related groups, obtaining separate quotations on each group. Thus the A.C. switching equipment, with necessary current and voltage transformers, composed one group, the D.C. circuit breakers and knife switches a second group, control and instrument switches, push buttons, etc. a third group, meters, instruments and relays a fourth group, etc.

This arrangement was justified when quotations showed that appreciable savings could be obtained by purchasing certain groups from one manufacturer and the others from another. Quotations in these groups dictated that the rotating machinery and speed regulating equipment be General Electric, the remainder being nearly all Westinghouse.

The general scheme of connections is shown diagrammatically in Fig. 11, the main leads being shown by the heavy lines, and the field and main control leads by lighter lines. The 2300 volt switching operation for the synchronous motor is practically standard, requiring no comment here, as it is explained completely later on when the switching sequence is given in detail. It is therefore omitted from this diagram. The main direct current connection may be followed through from the armature of the generator, starting with the upper or positive lead, over and down through the circuit breaker, 172, through the lower throw of the right-hand main knife switch, 189, the armature of the propeller motor, its commutating field, the lower throw of the center main knife switch, 189, the differential series and commutating fields and thus back to the negative terminal of the generator. The field connections for the main generator may be traced from the exciter to the right of the generator through the motor-operated field rheostat, the generator field and back to the exciter. The field circuit for the propeller motor may be followed from the positive control bus through the circuit breaker, 141, the hand-operated rheostat, the field and back to the negative control bus.

In operation, the speed of the propeller motor may be adjusted by two means, namely, varying the field and varying the armature voltage. The former is known as field control and the latter as the Ward-Leonard system. In this case the entire operating adjustment is obtained by the Ward-Leon-

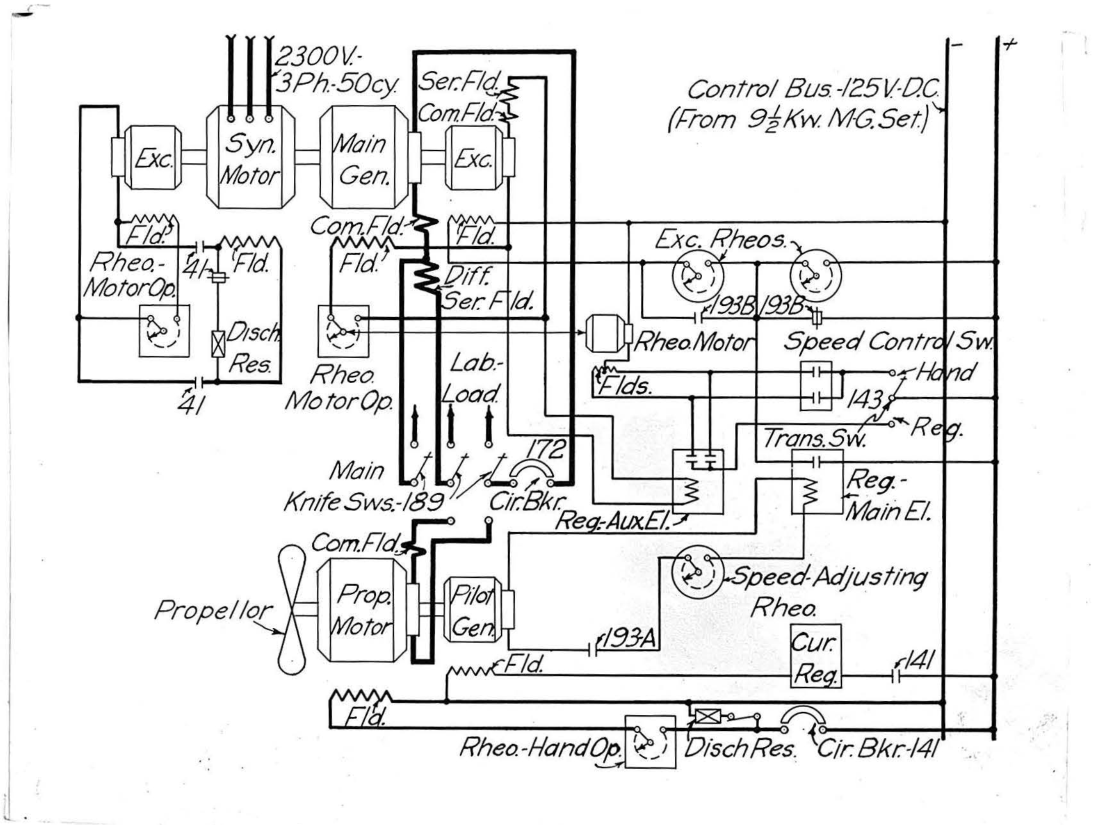


Fig. 11.

SCHEMATIC CONNECTION DIAGRAM.

ard system, the adjustment of the field being used only to obtain the best operating point for the particular setting on the propeller, and once obtained is not varied. This method is used because field control alone is insufficient to obtain the required range and a combination of the two, although quite possible, renders the control much more complicated. As sufficient range can be obtained with armature voltage control alone, the additional complications are unnecessary. For certain kinds of work the precision speed control mentioned above is unnecessary, and some simpler form of speed adjustment is desirable. With the system shown in the diagram this is easily obtained by control of the motor-operated rheostat in the field circuit of the main generator. In this discussion this type of speed control will be called hand control, and the operating circuit can be easily traced from the figure. The motor for operating the rheostat is provided with two series fields wound in opposite directions so that a circuit through the armature and one field will cause rotation in one direction and a circuit through the armature and the other field will cause rotation in the opposite direction. With the transfer switch, 143, closed in the upper or "hand" position, the circuit starts from the positive control bus through the transfer switch, 143, one or the other of the contacts in the speed control switch, then through one of the series fields, the armature of the rheostat motor and thus back to the negative control bus, the contact chosen in the speed control switch determining the direction of rotation and therefore whether the resistance is increasing or decreasing. The amount of resistance in the field circuit determines the voltage of the main generator and therefore the speed of the propeller motor. For this type of control, of course, constant voltage at the exciter is required. In order to accomplish this without interfering with the action of the regulator, when it is used, two rheostats are employed in the field circuit of the exciter, the left-hand rheostat being used during hand control and the right-hand one during regulator control. It will be noticed that the right hand rheostat is shown short-circuited by a contact of relay 193-B in its de-energized position and therefore the left-hand rheostat determines the voltage of the exciter, independently of the other rheostat.

It may be noticed that no starting resistance is used in the circuit to the propeller motor armature. Starting is accomplished by reducing the generator voltage to a sufficiently small value before closing circuit breaker 172. To insure this condition, interlock connections, not shown in the figure, prevent the closing of the circuit breaker until the generator field rheostat is entirely cut in, and also set up the circuit to run the rheostat to this position as soon as the circuit breaker opens.

It is also essential that the field of the propeller motor be energized whenever the armature circuit is energized in order to keep the motor from trying to run away. This is accomplished by so interlocking the circuit breakers 141 and

172 that 141 must be closed before 172 can be closed and causing 172 to open immediately after 141 has opened from any cause whatever. Both circuit breakers are closed and tripped in the proper order by one control switch, at the control station.

When the main generator is being used for supplying some laboratory load, and the propeller motor is disconnected, the interlocking system described above between the position of the rheostat and the closing of the circuit breaker may or may not be desirable, depending upon the type of load. To accomodate this condition, a double throw switch has been arranged so that in one position the same interlocking prevails as when the propeller motor is in operation, and in the other all interlocking between the two is eliminated, whenever the main switches are closed in the position for the laboratory load. The energizing of the field of the propeller motor is also undesirable when the main generator is feeding a laboratory load, and suitable interlocks prevent the field circuit breaker, 141, closing when the knife switches, 189, are thrown to the laboratory load position. In this case the same control switch which previously closed both circuit breakers now closes only the main circuit breaker, 172.

IV. PRECISION SPEED CONTROL.

One of the principal difficulties in the construction of this wind tunnel equipment has been the obtaining of a suitable precision speed control which would regulate the speed within very narrow limits and at the same time allow the speed maintained by the regulator to be adjusted at the will of the operator. Several different types of speed regulation were considered but the majority had to be discarded because they would not fill all the requirements. One of the schemes which seemed most promising at first sight was that of balancing the speed of the propeller motor against an accurate speed of reference, any deviations causing corrective impulses until the speeds were exactly matched. A small synchronous motor with speed controlled by a tuning fork, a system known as the Benioff drive, was available as a speed of reference, with accuracy close to 1 part in a million. A system of speed regulation had been developed for individual paper machine plants, where highest accuracy in relative speeds is required, which would match the speed of the propeller motor against that of the speed of reference with far greater accuracy than required for our purposes. However, no means could be found by which the regulated speed could be adjusted without destroying its accuracy. The speed of reference was inherently fixed, and the system of matching allowed variations of approximately 10 per cent either way from mean speed. This variation was obtained by adjusting the position of a belt connecting two parallel cone pulleys, tapering in opposite directions, one pulley being directly connected to the apparatus being regulated and the speed of the other being matched against the reference speed. To increase the length and diameter of these pulleys to the point where the desired range of variation, approximately 10 to 1, could be obtained, was in itself not feasible mechanically, to say nothing of the cost and difficulty of developing a device for shifting the position of the belt from one point to another easily, accurately and within a reasonable time. No other scheme was found by which the variation could be accomplished and so the method had to be discarded.

Another method, used by the Westinghouse Elec. and Mfg. Co. in building a small wind tunnel for the government at Langley Field consisted essentially in balancing the pull of a coil, connected to a voltage proportional to the speed of the propeller motor, against the weight of the coil plunger. This system worked very satisfactorily in the case in which it was used, one report indicating that a speed variation of not more than one-tenth of 1 per cent was obtained with this equipment, although some doubt as to the accuracy of this figure has arisen. However, the speed range covered by this equipment was small, being approximately 2 to 1, and it could not therefore be used in our case.

The working of this scheme is essentially as follows. A small generator, called the pilot generator, is directly connected to the propeller motor, and when its field is constant it will generate a voltage proportional to the speed of the propeller. This voltage is then impressed on the main element of a direct-current vibrating voltage regulator. This regulator varies the voltage obtained from the main generator until the speed of the propeller is just sufficient to cause the voltage from the pilot generator to balance the regulator. In this case, in order to reduce the current handled by the regulator and to reduce the tendency for hunting, the regulator, instead of operating directly on the main generator, controls the voltage of the exciter for the main generator, thereby indirectly controlling the voltage of the latter and maintaining it at the proper value. The similarity between this operation and that of an alternating current vibrating generator voltage regulator is apparent. Any means by which the voltage impressed on the main element of the regulator is varied without the speed of the propeller motor being changed will cause a change in the regulated speed, since the voltage necessary to balance the regulator will occur at a different speed. In this case a rheostat was inserted in the field circuit of the pilot generator, causing the voltage generated for a given speed to vary with the position of the rheostat. As the range of voltage possible to obtain from the exciter under stable regulator control is only about 2 to 1, the speed range possible is limited to about the same figure.

Several other ideas were considered but no essentially different methods were evolved. In the mean time two schemes, really modifications of the above in principle, although somewhat different in operation, were developed.

One was suggested by the General Electric Co. in a preliminary quotation and the other developed by us.

Both methods employ the pilot generator as was done in the scheme outlined above, but the adjusting rheostats are now placed in the armature and regulator circuit of the pilot generator, instead of the field circuit. In order that its field current could be maintained constant, the pilot generator was excited from the control bus described above, and it was planned to regulate the voltage of the control generator to a constant value. The increase in possible speed range is obtained by the addition of a motor operated rheostat in series with the field of the main generator, the position of which is under control of an additional element of the regulator. If the voltage required at the field and rheostat terminals of the main generator and which the main part of the regulator is trying to produce, is above or below certain fixed limits between which the response of the regulator is sufficiently rapid and the action stable, the additional or auxiliary element of the regulator changes the position of the rheostat until the excitation voltage required has been brought within the necessary limits. The detailed description below will make the operation clearer.

The difference between the two methods lies in the way in which the excitation voltage furnished by the main part of the regulator is produced. In the General Electric scheme the source, instead of being an exciter with a variable voltage under control of theregulator, is some constant potential, 125 volt D.C. supply. However, inserted in series with the field circuit is a direct current "counter-E. M. F." motor, the voltage drop of which is under control of the regulator, the latter acting on the field of this motor. The counter-E. M. F. and therefore the equivalent resistance drop of this motor can be varied only through definite limits. The rheostat, also in series, provides an additional drop and if the latter drop is not at a suitable value so that the motor can remain within its prescribed limits, the regulator auxiliary element, connected across the counter-E. M. F. motor terminals and operating on the rheostat motor, changes the position of the rheostat to a satisfactory point. In other words, the pure resistance, which would be used under hand control to vary the generator voltage, is split up into a motor operated rheostat and an artificial equivalent resistance produced by the counter-E. M. F. motor. The small fluctuations are taken by the motor, which responds rapidly, and the big gradual changes are taken by the rheostat. Since the total resistance of the rheostat can be made very large in comparison with the variation in equivalent resistance of the motor, it is obvious that the range can be greatly increased.

In our system, instead of using a constant potential source and inserting a motor armature in series to reduce the voltage to the proper value, the two functions are re-combined into a single exciter, the voltage of which is the same as the above combination and likewise under the control of the regulator. The auxiliary element which controls the position of the rheostat is now connected across the armature of the exciter and adjusts the rheostat resistance until the voltage maintained at the terminals of the field and rheostat by the main part of the regulator is within the limits of quick response for the exciter. If the exciter is separately excited, just as the counter-E.M.F. motor is in the General Electric scheme, the speed of response will be essentially the same for both schemes. Although this scheme is simpler than the General Electric and closer to the original Westinghouse model on which it is based, it is more difficult to observe at first sight that it will work satisfactorily. The latter scheme also has a higher efficiency than the former because the loss in the counter-E.M.F. motor, connected in opposition to the constant potential source, is eliminated.

The largest source of error in both schemes, as originally designed, is the change of field current of the pilot generator as its windings change temperature. We were able to overcome this to a very large extent by regulating the current in the pilot generator field instead of the voltage across it. Assuming perfect current regulation, the only effect on the voltage, produced by temperature changes, is that due to change in permeability and in dimensions of the magnetic circuit. Both of these effects are small and very gradual within the temperature range encountered. Both schemes, after this change had been made, appeared to be satisfactory from a regulation point of view, and the specifications were written in such a manner that the bidder could choose the one he preferred. It is interesting to note that the General Electric Co., the successful bidder on this part of the equipment, in their final proposal discarded their scheme, which they had urged upon us quite strongly, and adopted ours.

We are now in a position to trace out the details of the final scheme on the elementary diagram, Fig. 11. The field circuit for the pilot generator may be traced from the positive control bus through the auxiliary contact on circuit breaker 141, the current regulator, the field and back to the negative bus. The current regulator maintains the field current and hence the field flux constant and the voltage of the pilot generator is therefore accurately proportional to the speed of the propeller motor, since the pilot generator is directly connected. When the regulator is in use, the transfer switch, 143, is changed to the "Regulator" position,thus disconnecting the speed control switch and supplying positive control power to the contacts of the regulator auxiliary element. As soon after this is done as satisfactory conditions are established, relay circuits not shown in the diagram close relays 193-B and 193-A. The latter completes the circuit from the pilot generator armature through 193-A, the speed-adjusting rheostat, the main operating coil of the regulator main element, and back to the armature. If the voltage drop across the regulator coil, or more strictly the current through the coil, is below the correct value, the contacts of the regulator immediately close. Since relay 193-B is now energized, the left-hand exciter rheostat is short-circuited and the right-hand one inserted in the circuit. However, as soon as the regulator contacts are closed, the latter rheostat is also short-circuited, causing the exciter voltage to rise. This in turn increases the voltage of the generator, the speed of the propeller motor, and the voltage of the pilot generator. As soon as the voltage of the pilot generator has increased sufficiently, the regulator contacts open, inserting the rheostat in circuit again. This reduces the exciter voltage and in turn the voltage of the generator, the speed of the propeller motor and the voltage of the pilot generator until the contacts again close, and the cycle is repeated. Thus the speed of the motor is not maintained steady but is caused to oscillate about a mean speed. An auxiliary or anti-hunting coil in the main element of the regulator, connected in parallel with the auxiliary element, across the exciter armature, but for simplicity not shown in the diagram, causes the contacts to open sooner and close sooner than they otherwise would. This has the effect of reducing the oscillations in propeller speed until they are of negligible amplitude, and the regulator becomes in effect a direct-current voltage regulator varying the voltage of the exciter above and below a mean value which depends upon the desired correct speed of the propeller motor. It may happen, however, that the mean voltage of the exciter which corresponds to the desired speed of the propeller motor is so low, for a given position of the generator field rheostat, that the regulator contacts remain open continuously, and the regulator is no longer able to control the speed. This condition is overcome by the regulator auxiliary element, the operating coil of which is connected across the exciter armature. If the voltage of the exciter becomes less than a specified value, one of the contacts of the auxiliary element will close, energizing the rheostat motor and increasing the resistance. This will reduce the speed of the propeller motor, and after a sufficient reduction, the contacts of the main element will close, causing the exciter voltage to rise. When the increase is sufficient, the auxiliary element will open its contacts, stopping the rheostat,but the value of the exciter voltage now corresponding to the desired propeller speed is within the required operating range and the main element of the regulator again has control.

If the condition is reversed and the regulator contacts remain closed, the exciter voltage will rise sufficiently to close the other contact of the auxiliary element, reducing the resistance until the regulator contacts again vibrate. Thus the two elements, operating in conjunction, are able to regulate the speed over a wide range.

It is obvious that the speed maintained by the regulator is a function of the position of the speed adjusting rheostat, and any change in the position of the rheostat will change the regulated speed. For balance the voltage drop across the regulator coil is a constant. This voltage plus the drop across the rheostat must equal the voltage of the pilot generator, and the latter is proportional to speed.

Changing the rheostat will cause the voltage drop across the regulator to change, but this unbalances the regulator and the speed will change until the proper drop is restored. By adjusting this rheostat, the speed of the propeller motor may be varied, with the present calibration, from about 120 to 850 r.p.m. Although no precision speed measuring device has yet been installed, the magneto speed indicator used shows fluctuations above and below normal speed of considerably less than ½ of 1 per cent and no observable deviation in the mean speed indicated is noted over a considerable period of time.

The pilot generator has been mentioned previously under the description of the propeller motor. It is rated at 1½ KW. 600 volts at 700 r.p.m. The rating is, however, quite conservative for the frame size in order to reduce the effects of temperature on the speed regulation. The high voltage rating is necessary in order to supply sufficient energy for operating the regulator at the low speeds, approximately 45 volts being necessary to balance the regulator with no resistance cut in from the speed adjusting rheostat, and proportionally higher voltages required at the higher speeds. The pilot generator is supported from a bracket mounted on the end-bell of the propeller motor and is direct connected to the propeller motor shaft by means of a flexible coupling. The pilot generator and its mounting may be quite clearly seen in Fig. 6.

V. DETAILED DESCRIPTION OF CONTROL EQUIPMENT AND METHOD OF OPERATION.

As mentioned above in this discussion no single location was a convenient and economical place for all the major switching devices. With remote control, centralizing of equipment of different classes presented few if any advantages, and so the high-tension switching equipment, consisting of the three oil circuit breakers, namely, magnetizing, starting and running, the necessary disconnecting switches, current and potential transformers, was located in a separate chamber on the basement level, known as the primary vault. In this same vault were also placed the hand operated oil circuit breakers for the building transfromers and the building motor-generator set, and the automatic starter for the building set. The building power and light transformers and the starting auto-transformer were placed in the transformer vault immediately below. As the equipment in the primary vault was well adapted to structural mounting, it was all erected on a framework of 1¼ inch iron pipe. Since the incoming power leads entered the building at the end of the primary vault opposite the machinery, a very satisfactory arrangement of connections and bus work was possible.

The D.C, air circuit breakers requiring panel mounting, some form of switchboard was necessary where they were located. This point being quite central with respect to the machines and the conduit route for the third floor control station, this switchboard was extended and made large enough to accomodate all the field and control contactors, and the control, miscellaneous, and part of the protective relays, with the exception of the control relays for the oil circuit breakers, which had to be located with the circuit breaker operating mechanisms in the primary vault. The three large field rheostats, namely, the synchronous motor exciter field, the main generator field and the propeller motor field rheostats were located nearby on a structural framework. Fig. 12 shows this switchboard, partially completed, in the foreground, and the rheostats and the automatic starter for the control motor-generator beyond and to the left. The left-hand panel of the switchboard is used in connection with the building motor-generator, and the remaining three panels contain the equipment for the wind tunnel. On panel three is located the propeller motor field circuit breaker, 141, and on panel 4 the main circuit breaker,172, and the three knife switches are observed. This switchboard is called the relay or "B" switchboard.

The main control switchboard at which all switching operations are performed is located on the third floor. This switchboard also consists of four panels, on the first of which are mounted the regulator elements and accesories. The second contains the control switch, rheostat, and instruments for the control motor-generator and in addition two protective relays for the main motor-generator set for which there is no room on panel 3. The third panel contains the control

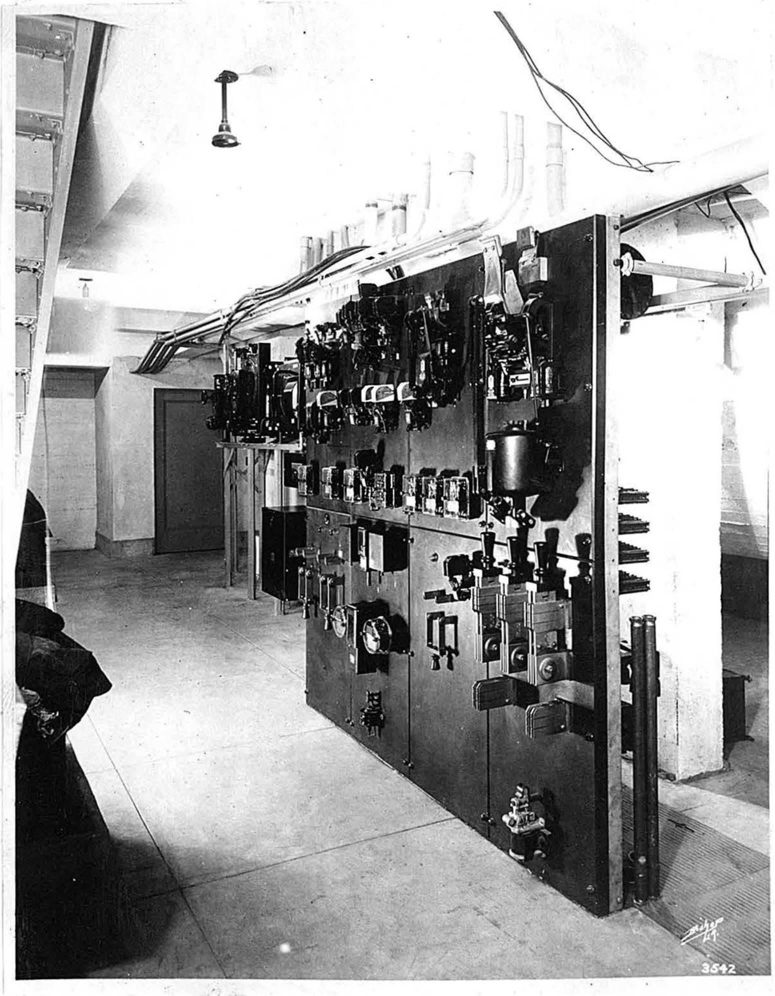


Fig. 12.

RELAY OR "B" SWITCHBOARD.

switches, meters, instruments and overload relays for the main synchronous motor, and the fourth panel the control switches and instruments for the main generator and propeller motor, and also the exciter rheostat which is used during regulated speed control. This switchboard is called the control or "C" switchboard.

In addition there are four small auxiliary panels for various purposes, as follows. For convenience in testing and in the use of the main generator for experimental purposes other than the wind tunnel, a small control panel was provided, containing four control switches and an ammeter and voltmeter for the main generator. With the automatic features and interlocking provided, these four control switches will perform all the necessary switching operations for running the tunnel under hand speed control, or for using the main generator for other purposes, except that of starting the control generator. The control motor-generator set must first be started by means of a push button located near the "B" switchboard or the control switch at the "C" switchboard. This panel is normally located a few feet to the right of the "B" switchboard, but if desired, may be removed to any location within reasonable distance and placed in service by connecting its terminals to a set of terminal blocks at the normal location. This panel is consequently called the "semi-portable control panel".

A second panel called the "set-up panel" is located in an enclosing steel cabinet under lock and key just to the right of the "B" switchboard. On this panel are mounted transfer switches for transferring control of the equipment from the main control switchboard to the semi-portable control panel and for connecting or removing the interlock between the main generator rheostat and the main circuit breaker, as described previously.

The remaining two panels are auxiliary speed control stations which may be used for controlling the speed of the propeller motor. These speed control stations as well as the speed control switch at the "C" switchboard are mutually exclusive and control must be transferred from one to the other by means of a transfer switch, 143, located at the "C" switchboard. Hand speed control only is available at the "C" switchboard, but either hand or regulated speed control is available at either of the auxiliary stations. One of these stations is located immediately adjacent to the balances on the third floor and the other is located in the observation room on the first floor.

Extensive electrical protection of the rotating equipment was considered desirable, because of the large investment involved and because, under normal operation, the machinery is neither visible nor audible from the point of control. Although this considerably increases the complications of the equipment, the additional cost was only a small proportion of the total cost and any dangers which might arise due to operation by men not thoroughly familiar with the electrical equipment are reduced to a minimum. This protection may be divided into three general classes, the first of which prevents the normal operations progressing until the preceding operations have been successfully completed, or until satisfactory conditions prevail, the second, which causes operations to occur which will perfect unsatisfactory conditions in order to allow normal sequence to follow, and the third which will shut down the equipment in case of serious abnormal condition. In the first class may be mentioned the conditions which will prevent the starting of the motor-generator set, which are:

1. Low A.C. voltage.
2. Unbalanced or reverse phase A.C. voltage.
3. Low or reversed control voltage.

The remaining features of the first class and those of the second are, in general, obtained by interlock or auxiliary switch connections and will be mentioned as they arise during the discussion of the operating sequence. The third class may be sub-divided into two groups, one which causes a shut-down and prevents the equipment being restarted until the trouble has been investigated, and the second which causes shut-down but allows the equipment to be immediately restarted in case the trouble has disappeared. With two exceptions all the devices operating in the first group obtain their operation by actuating a lock-out relay and an annunciator which indicates the cause of the shut-down. The lock-out relay is hand reset and when operated causes immediate shut-down of the propeller motor and the main motor-generator, and neither can be restarted until the lockout relay has been reset. The two exceptions are the overspeed devices on the motor-generator set and the propeller motor. These devices are circuit opening and are therefore unable to operate the annunciator and lock-out. The overspeed device for the motor-generator set shuts down the motor-generator and propeller motor, and the device for the motor shuts down the motor only. The equipment shut down can not be restarted until the proper overspeed device has been reset.

The features included in the first group are:

1. Unbalanced A.C. line current during starting period of the motor-generator set. (46).

2. Failure of the motor-generator set to complete starting sequence in a predetermined time. (48).

3. Continued overload (Thermal protection).(49).

4. Overheated bearings on the motor-generator set. (38).

5. Field failure in synchronous motor. (40).

6. Overspeed of motor-generator set. Can occur only in case of power feed back into motor-generator upon loss of A.C. supply. (12).

7. Overheating of propeller motor. (168).

8. Overheating of bearings on propeller motor. (138).

9. Overspeed of propeller motor. Shuts down

propeller motor only. (112).

The features included in the second group are:

1. Low control voltage. (80).

2. Low, unbalanced or reverse phase A.C. line voltage.(47).

3. Unbalanced A.C. line current during running period. (46).

4. Severe momentary A.C. overload. (51).

5. Direct current overload.

6. Opening of propeller motor field breaker. Shuts down propeller motor only.

The distinctions between features of one group and those of another are in some cases not very marked, as a single device may perform functions in more than one group depending upon the circumstances.

Comparison of the first feature of the first group in class three with the third feature of the second group shows that both depend upon unbalanced A.C. line current for operation. This condition may be caused either by internal machine conditions or unbalanced voltage. However, unbalanced voltage, if not too great, will not be detected by the voltage relay, since the machine itself acts as a phase converter and holds up the voltage on the low phase. The first cause is a serious fault and the machine should be locked-out. The second is an external condition which is not due to any machine trouble and a lock-out is not desired.

If the unbalanced current first occurs while in the running position, the above arrangement separates the two causes. In either case the machine is shut down as soon as the unbalance reaches serious proportions. If the fault is internal, there is nothing to prevent the machine being restarted, but if the trouble persists, the machine is immediately locked-out. If the shut-down was caused by unbalanced line voltage, the phase converter action of the motor will cease as soon as the machine stops and the voltage relay will prevent restart until balanced voltage is restored to the line. In this case no lock-out occurs.

In any system of control, faults may occur, and in a system as complicated as this one has become, locating the trouble may be more difficult than correcting it. To render fault detection as easy as possible, the wiring was carefully organized. Each wire in the entire system bears a wire designation which is indicative, as far as possible, of its function and the machine with which it is primarily used. This designation appears on all the diagrams and at the terminal blocks where the wire leaves a panel. The "B" switchboard is a distributing point for all control wiring except that to the two speed control panels which are subsidiary to the "C" switchboard. All wiring at the "B" switchboard is terminated at a series of terminal blocks at the rear of the panels and is grouped as far as conveniently possible according to the location of the other end of the run. All instrument and control wiring leaving the primary vault runs through a terminal board cabinet where a series of terminal blocks renders similar identification. All small wiring entering or leaving any switchboard panel passes through a terminal block, so that any wire may be readily located. Wires leaving the "B" and "C" switchboards are maintained in small related groups, run through floor plates into an underfloor distributing gutter, and are there sorted out and led into the appropriate conduit. The system has already proven its value in the simplicity with which the initial sequence tests were conducted and individual devices operated under test conditions, and in the ease with which such circuit troubles as have arisen have been located. Changes may also be made much more easily when each wire can be almost instantly located at both ends.

The first step in laying out a system of wiring of this type is the construction of a schematic wiring diagram in which every device is placed with reference to its electrical rather than its physical location. Before this diagram can be completed the entire sequence of operations must be known from beginning to end, and every relay, contactor, switch or other device must be completely specified with regard to its method of operation, operating voltage, number and type of contacts, etc. The remaining characteristics, such as voltage and current ratings, interrupting capacity, etc. must be determined at the same time from a careful analysis of every circuit and other piece of apparatus affected by the device in question. Then a check must be made to determine if the devices desired are obtainable and suitable from a commercial and economic point of view. If not, the schematic diagram must be modified until a completely satisfactory system is obtained. After the diagram itself is completed, the wire numbers are assigned, and the information is then available for making the switchboard outline drawings, which show the locations of the devices and the construction of the switchboards, and the connection diagrams, which show the actual connections, as made on the installation, and the approximate arrangement of wires, assuming, of course, that complete information on each individual device is at hand.

The schematic diagrams for this installation are shown on drawings AW-49 and AW-31, reproductions of which are appended. The diagram was divided into two parts because of insufficient room on AW-31, and also because, if the control generator, the connections of which are shown on AW-49, becomes disabled, any other source of 125 volts D.C. of 9½ KW. or more capacity, connected in its place, will allow all the functions shown on AW-31 to proceed without change. The meaning of the symbols which are not in universal use or marked may be determined from the legend shown on the drawings. Contacts indicated as "normally open" are open when the operating coil of the device is deenergized, and likewise, contacts "normally closed" are closed when the operating coil is deenergized. This point should be carefully noted in checking the operations on the diagram, as in some cases the operating coil itself may be normally and continuously energized, which causes contacts indicated as "normally open" to be closed the majority of the time and vice versa. Within each circle indicating an operating coil and adjacent to each pair of contacts, the number of the device is indicated, and the description of the device is given in the table. The complete description, with rating, catalog number, location, etc. can be obtained from the device number list on file in the records of the installation. The bills of material, the connection diagrams and the nameplates adjacent to the devices on the switchboards indicate the device numbers, so that locating a particular device is not difficult. The device designations are based as far as possible on the standard device numbers for automatic stations, adopted by the National Electrical Manufacturers Association. For this type of equipment only the numbers between 1 and 100 are authorized, but because of overlapping of functions the same numbers with the prefix 0 are used for the control generator equipment, and with the prefix 100 for the propeller motor equipment. The numbers between 1 and 100 refer to the main motor-generator. Letters alone and letters followed by a number are not standard designations and were adopted to suit conditions. The letter suffix to a number indicates an auxiliary device or one part of a device which is divided into several parts. A rectangle surrounding two or more operating coils indicates that both devices are in the same case and operate in conjunction.

As mentioned above, the wire designations, in general, indicate the function of the wire and the machine with which it is primarily used. No particular diffidulty should be experienced in distinguishing wire numbers and device numbers on the diagrams because of their location. Although certain exceptions are unavoidable, in general, the last letter of the wire designation indicates its use, according to a code, and the first number the machine with it functions, following the numbers in the machine symbols on the diagrams. The second number or lack of it designates the individual wire. The prefix B denotes a bus which may energize several devices; prefix V, instrument potential; prefix J, instrument current; and prefix L, lamp indicator. The number portions of the control bus designations, bearing the prefix B, are exceptions, and do not bear machine numbers. The code for the last letters is as follows:

A,B,C,	Main leads, usually A.C. phases A,B,C.
D,	Neutral.
E,	Equalizer.
F,	Field.
G,	Green.
L,	Lowering (voltage, etc.) or lockswitch.
N,	Negative.
O,	Ground.
P,	Positive.
Q,	A.C. control.

R, Raising (voltage, etc.) or red, with prefix L.

S, Starting.

T, Tripping of stopping.

W, White.

X, Heavy control (for solenoid mechanisms, etc.)

H,K,U, Miscellaneous control and protection not included in above.

When L indicates lockswitch the first number following is 1 instead of the machine number. A lower case letter following the usual wire designation indicates a wire of same electrical purpose as the wire without suffix, but distinguished for some non-electrical reason.

Although certain important exceptions occur, in general the main operating coil of a device, when energized, attracts a plunger or armature, which in turn mechanically closes the "normally open" and opens the "normally closed" contacts, the contacts remaining in the energized position only while the coil is energized. The principal exceptions are the circuit breakers which are latched in the energized or closed position and remain so, even after the operating coil is deenergized, until the latch is tripped. The latch may be tripped electrically in either of three ways, deenergizing a holdingncoil or low voltage release coil, energizing a shunt trip coil, and energizing a series trip coil. In all three cases the tripping devices may, in general, be made to operate within certain definite limits only, so that current below or above definite values must be present to cause operation. The holding coil, if used, must be energized before the main operating or closing coil is energized, if a satisfactory closing operation is to be obtained. The designations of these tripping coils are the same as that of the operating coil, followed by the letter H for a holding coil, and T for a tripping coil, the circuit of the coil determining whether it is a shunt or a series coil.

Certain other devices remain in the operated position, after the operating coil is deenergized, until reset by hand or other means. These devices are noted in the descriptions of apparatus on the diagrams. Several other devices have some special or unusual characteristics, and the most important ones will be described briefly below. Relays 027 and 048 operate in conjunction in such a manner that after 048 has operated it is maintained in its operated position by 027 as long as the latter is energized. 048 requires a definite time to complete its operation. The annunciator relay, 30, has no contacts, but a series of targets which drop into view when the corresponding circuit is energized. Relays 41-X and 48 require a definite time to operate after being energized, and a proportional time to reset after being deenergized. Relays 80 and 80-X operate in conjunction as a single unit, the operation of 80 causing the operation of 80-X, a rugged auxiliary relay, by the circuits shown. The regulating devices 157, 157-A and 190, 190-A, each consist of two coils, the first primarily operating the contacts and the second supplying an opposing impulse which is designed to prevent hunting. The special action of the regulator auxiliary relay, 190-X and 190-XA, is described in note 1 on AW-31. Device 158 has two contacts, which are closed at appropriate upper and lower limits of its normal voltage range, 158-L being closed when the voltage on the coil falls below a certain value and 158-R being closed when it rises above another value. The various circuit breaker control relays should also be mentioned, as they have two operating coils, the main coil bearing the designation of the circuit breaker with the suffix X and the release coil with the suffix X-R. The action is such that energizing the X coil closes the contacts and energizing the X-R coil opens them, whether the X coil remains energized or not. The contacts can not be reclosed until after both coils have been deenergized at the same time.

OPERATING SEQUENCE.

STARTING CONTROL GENERATOR.

The control devices shown in AW-49 are for the most part included in the standard magnetic automatic starter, but are shown in a diagram of this type for convenience and uniformity. The operation is as follows. If the "stop" contacts of PB 1-A, PB 1-B, and CS 1 and the back contacts of 049 are closed, closing the "start" contacts of PB 1-A or CS 1 will start the control motor-generator. The circuit may be traced from B-10 through the push buttons and control switch to 027, and in parallel with it 027-X, then through the contacts 049 to the other side of the line. 027 immediately closes its contacts, maintaining its energizing circuit after the "start" contact has been released. 06 and 048 are energized in parallel with 027, through the back contacts of 048. The former closes immediately, connecting the motor to a reduced voltage from the auto-transformer, and causing it to start. After a definite , adjustable time which allows the machine to come up to speed, 048 operates, opening its own circuit and that of 06. 048 being maintained in this position by 027, the make contacts of 048 close and energize 042 as soon as 06 has completely opened, thus placing the motor on full voltage. The contacts of 027-X, which closes with 027, energize an indicator in the main hall from a lighting circuit, as shown in the lower left of the diagram. The switchboard indicator, located at the "C" switchboard, is connected between S-12 and A-11 as shown and has the same voltage across it and its resistor as applied to the motor. As a consequence, when the motor takes full voltage, the lamp will brighten, giving a visual indication of the action.

NORMAL STOP. CONTROL GENERATOR.

To stop the set it is merely necessary to open the "stop" contacts of PB 1-A, PB 1-B, or CS 1 momentarily. This opens the circuits of all the contactors and they will remain open since the opening of 027 causes the break in the circuit to be maintained. PB 1-A is located near the "B" switchboard, CS 1 at the "C" switchboard, and PB 1-B in the primary vault. The contacts of the latter are maintained open or closed after the corresponding operation. This switch is to be left in the open position when men are working in the primary vault, so that the machines can not be started inadvertantly.

PROTECTION.

1. OVERLOAD.

In case of overload one or both coils of 049 operate, opening the contacts 049 and stopping the motor. A restart can not be made until 049 has been reset by hand, and this can not occur until 049 and presumably the motor have cooled to a safe operating temperature.

2. UNDERVOLTAGE.

In case the voltage of the A.C. supply for the control motor-generator falls below a certain value, 027 releases its contact, thus shutting down the machines.

CONTROL POWER.

As the motor comes up to speed, the generator will build up to normal voltage, if the rheostat, HR-1, has not been changed from its marked position. The voltage and current taken from this generator can be read from the instruments, and a ground on either lead will be shown by the corresponding ground detector lamp going out. Passing through switch 8, which is normally closed, the generator voltage is impressed on the control bus and the operation of securing control power is completed. Switch 8 should never be opened while the propeller motor is in operation, as this opens the field circuit of the propeller motor and no path is provided for the discharge. To insure against this the switch is held closed by means of a clamp and a wing nut.

The remainder of the connections are shown on AW-31. The arrangement of this drawing is as follows. The 2300 volt main connections are arranged vertically just to the left center of the drawing. To the left of these are located the alternating current instrument and control circuits and, above, the hall indicating lamp circuit for the main motor generator circuit. On the right of the main A.C. connections are located, at the bottom, the main direct current connections and miscellaneous and speed regulator control circuits. Above, in the first row, are located the control circuits for the main synchronous motor and in the second row for the main generator and propeller motor.

The two main control busses, positive,BP, and negative, BN, are energized as soon as the control generator, no. 2., comes up to normal voltage and switch 8 is closed. Since best interests of the equipment are served by having control power available at all times in spite of overload conditions in the control circuits, no fuses are placed in these leads, reliance being placed on the alternating current motor overload for protection. The motor field and the circuit breaker solenoids requiring large amounts of power and a few essential trip coils are connected directly to these busses. To protect the smaller control circuit leads, subsidiary busses, BP-1 and BN-1, are fed from the above through 40 ampere fuses. The circuits are so arranged that the blowing of these fuses will open all main switching devices, the power supply to the necessary trip coils not being interrupted by the fuses.

It will be seen that BP-1 is not continuous but terminates at a contact of master contactor 4. The bus beyond is called BP-2. As will be seen later, it is necessary for BP-2 to be energized, and hence for 4 to be closed, before any of the main machines can be run, and the opening of 4 immediately stops all main equipment. The busses BP-1 and BP-2 feed auxiliary busses through the various poles of the set-up switch, 95. This is the switch, mentioned above, which transfers control to the semi-portable control panel or to the "C" switchboard. In the lower or 95-1 position, control is obtained at the "C" switchboard and in the 95-2 position at the semi-portable control panel. The arrangement shown was necessary in order to avoid, under certain conditions, possible sneak circuits through a deenergized bus. It is obvious that control switches connected to busses energized in the 95-1 position would be located at the "C" switchboard or its subsidiary speed control panels, and the control switches connected to the busses energized in the 95-2 position would be located at the semi-portable control panel.

NORMAL START.

MAIN MOTOR-GENERATOR SET.

In order to operate, it is necessary to close switch 95 in one position or the other and close the appropriate lock switch 1 or 1-A at the control station selected by 95 with a key. These lock switches are provided to prevent tampering by unauthorized persons, and in the off position prevent operation of the equipment from that station. For convenience it will be assumed that 95 is closed in the 95-1 position and control is located at the "C" switchboard. The modifications for operation at the semi-portable panel will be obvious. Closing of lock switch 1 energizes low voltage relay 80 and if the control voltage exceeds a predetermined value, 80 will operate completing the circuit to 80-X which, in turn, is operated and completes its own holding circuit through its make contact.

Under normal conditions this will complete the circuit for master relay 3 up to control switch CS-3, "Start". The contacts in the circuit of 3 below the coil not only prevent starting, if open, but also stop the equipment whenever opened. The ones above, if open, prevent start, but do not cause shut down because 3, once closed, seals itself in around the contacts above the coil by means of one of its own contacts. Opening of the contacts below the coil which are hand reset, will lock out the equipment until these devices are reset. The contacts above prevent start until proper conditions are present. Contacts 47 closed insure sufficient balanced A.C. voltage and proper phase rotation. Back contacts 172 closed make sure that the main D.C. circuit breaker is open, and back contacts 19 that the transition relay has opened. Back contacts 53, the coil of which is connected across the synchronous motor exciter, will not close until the machine has slowed down sufficiently to allow all other devices time to open. If all these conditions are satisfactory, closing CS-3 will operate master relay 3, which, through a make contact, immediately closes master contactor 4. One contact of 4 energizes BP-2 and applies voltage to the devices connected thereto. A second contact of 4, through a second contact of CS-3 "start" now completes the circuit to the control relays 6-X and 6 C-X, provided the running circuit breaker, 42, is open. These relays energize the closing solenoids 6 and 6-C shown farther to the right, which close the starting and magnetizing circuit breakers 6 and 6-C, connecting the synchronous motor to the line, through the autotransformer, at reduced voltage. As soon as the circuit breakers close the release coils6-XR and 6 C-XR are energized, which, as explained previously, cause contacts 6-X and 6 C-X to open regardless of coils 6-X and 6C-X. This feature prevents holding the breakers closed under conditions which would otherwise cause them to trip. As soon as BP-2 is energized, the holding coils 6-H and 6C-H are energized through a back contact of 42, thus holding the circuit breakers closed after the solenoids are deenergized, until the trip coils 6-T and 6C-T are energized. The completion of this operation is indicated by the extinction of a green lamp on the switchboard and the illumination of a red one. The lamp circuits throughout are obvious and will therefore not be explained in detail. As soon as the red lamp has lit, the control switch may be released, allowing it to return to the normal or off position.

The synchronous motor has an auxiliary squirrel cage winding and so comes up to speed under the action of the reduced voltage. At the same time the self-excited exciter, No.6, builds up in voltage. At a predetermined voltage, corresponding normally to about 80 per cent speed, relay 53 closes, completing the circuit to the operating coil, 41, since circuit breaker 42 is open and 6 closed. In the mean time, however, the field circuit of the synchronous motor is closed through the discharge contacts of 41, the discharge resistor, DR-3, and the series operating coil 41, which is arranged to hold the back contact tightly closed as long as an appreciable current is flowing in this circuit. During starting this current is an alternating current which does not fall off sufficiently to allow the main coil to operate the contactor until about 95 per cent synchronous speed is reached. At this point the pull of the series coil becomes so weak that it is overpowered by the main coil, and the contacts are operated. This opens up the discharge circuit and connects the field to the exciter through reducing resistor, RR-3. The value of this resistance is adjusted to produce the best value of field current for transition, with normal exciter voltage.

An auxiliary contact of 41 closes the circuit of 41-X, a timing relay operated from one of the alternating-current instrument and relay potential transformers, through a back contact of 42. After a time interval which is adjusted to allow the machine to pull into step, 41-X operates and completes the circuit to the transition relay, 19, operated from BP-2. One make contact of 19 parallels the contact 41-X, thus sealing in 19, and a second contact of 19 locks in 41. A third contact completes the circuit to the trip coils 6-T and 6C-T, tripping the starting breakers, and when they are fully open, a circuit through the same contact and back contacts of 6, 6-C, and 42-Y completes the circuit to the running circuit breaker control relay, 42-X. This relay energizes the solenoid and closes the running breaker, 42, thus connecting the motor to full voltage. As soon as the breaker is closed, the closing solenoid is deenergized in the same manner as the others by the action of 42-XR. In addition, a cutoff relay, 42-Y, is energized by another auxiliary contact of 42, seals itself in, and deenergizes both 42-X and 42-XR. In short both 42-XR and 42-Y have the same function, but 42-Y is adapted for continuous duty and 42-XR is not. 42-H was energized previously by BP-2 and holds the breaker in the closed position. An auxiliary contact of 42 energizes 39, which short-circuits RF-3, and applies full field to the synchronous motor. Completion of the transition is indicated at the switchboard by the extinction of one red indicator and the lighting of a second.

FIELD ADJUSTMENT.

The field of the synchronous motor is adjusted by varying the exciter rheostat, MR-1. This is accomplished by motor, and the connections are shown at the extreme right of the first row. The "raise" contacts of CS-2 complete the circuit through the armature and one series field, causing rotation in one direction, decreasing resistance and thereby increasing the current. The "lower" contacts, completing the circuit through the other series field wound in the opposite direction, causes opposite rotation and a decrease in current. When the end of travel is reached in either direction, the corresponding limit switch operates, stopping the motor and illuminating the indicator as long as the switch contacts are held closed. An adjustable auxiliary contact designated "MR-1 Normal" is closed when the rheostat is in a preassigned normal intermediate position. Under normal circumstances the rheostat is left in this position and is not operated whie the machines are running.

NORMAL SHUT-DOWN.

MAIN MOTOR-GENERATOR.

Normal shut-down is accomplished either by turning CS-3 to the "trip" position or by turning the lockswitch,1, to the "off" position. The latter operates in exactly the same manner as failure of control voltage, described below, because the undervoltage relay is deenergized by this switch. The operation of the former is as follows. Closing the "stop" contact of CS-3 short-circuits 3, opening it. The resistor, R-3, limits the current to a reasonable value. 3 does not reclose when the control switch is released because its circuit is broken by its own contact. The opening of 3 immediately opens 4, killing BP-2. This deenergizes 42-H and 19, causing the running breaker 42 and contactor 19 to open, disconnecting the motor from the line. To make absolutely certain of tripping 42, a back contact of 4 closes the circuit to the trip coil 42-T. When both 42 and 19 are open, 41 opens, disconnecting the field from the exciter and short circuiting the field through its discharge resistor and the series coil, 41, the latter sealing the contacts of this circuit closed. As the machine slows down the exciter voltage falls and finally 53 opens, restoring conditions to normal. A check will show that all devices operated during the starting sequence are deenergized and in their original positions except the voltage relays 80 and 80-X. Turning lock switch 1 off immediately opens 80 and 80-X. When the breakers open the red indicaters are extinguished and the green is again lighted.

PROTECTION, WITHOUT LOCKOUT.

I. LOW CONTROL VOLTAGE.

From the description of normal shut-down above it is seen that shut down occurs when relay 3 opens. Any means causing 3 to open will therefore cause a shut down, and all the protective devices which cause shut-down then obtain their operation by either directly or indirectly opening relay 3. In case of low control voltage below a limiting predetermined value relay 80 opens its make and closes its break contacts, thus short circuiting 80-X, the current being limited by R-80-X. Hence 80-X opens, and one of its make contacts in the circuit of 3 opens the latter causing shut down from then on just as described above.

2. LOW, UNBALANCED OR REVERSED PHASE.
A.C. LINE VOLTAGE

In case of low, unbalanced or reversed phase A.C. line voltage shut down immediately occurs through the action of relay 47. This relay is held in the energized position by the presence of a torque of proper direction and magnitude on a disc bearing the moving contacts. In case of low or unbalanced voltage the torque is reduced below the necessary value and in case of reversed phase the direction of the torque is reversed. In either case the make contacts open and the back contacts close, the latter short circuiting the coil of 3, and the former preventing 3 reclosing until proper voltage is restored. The make and back contacts can be adjusted separately so that a higher voltage may be required before starting than that at which the machine may be allowed to continue to run. In this case the relay has been adjusted so that 2000 volts are required for starting but the machine will continue to run until the voltage falls to 1900 volts.

3. UNBALANCED A.C. LINE CURRENT
DURING RUNNING PERIOD.

Upon the occurrence of unbalanced A.C. line current of sufficient magnitude, relay 46, which consists of current elements in the secondaries of current transformers in all three phases, balanced against each other, will be operated, closing its make contact. If this occurs while in the running position circuit breaker 6 will be open and a circuit from

BP-1 will be established, through contact 46 and a back contact of 6, short circuiting 3 and causing shut-down.

4. SEVERE MOMENTARY A.C. OVERLOAD.

In case of a severe momentary overload, one of the relays 51 will be operated. These relays are definite minimum time induction overload relays and can be set to operate at any desired current within their limits. The contacts of 51 short-circuit 3 directly, causing shut-down.

PROTECTION, MACHINE LOCKED OUT.

1. UNBALANCED A.C. LINE CURRENT DURING STARTING PERIOD.

All the circuit-closing devices which cause lockout are arranged to operate the lockout relay, 86, through one of the annunciator drops of relay 30. A back contact of 86 is in series with the coil of 3 and opens 3 whenever 86 is operated. Since 86 is hand reset, the machine can not be restarted until this relay has been reset. When unbalanced current occurs during the starting period, relay 46 operates as described above. However, circuit breaker 6 is now closed and a make contact completes the circuit to 86. If relay 3 opens at any stage of the starting period, shut-down will occur in a manner similar to that in the running position. If the field has not been applied, only devices 3, 4, 6-X, 6-XR, 6C-XR and 6 have operated after the closing of 80 and 80-X. 6-X, 6C-X, 6-XR and 6C-XR are deenergized as soon as the control switch is released. The opening of 3 causes 4 to open immediately. When 4 opens, BP-2 is deenergized, in turn deenergizing 6-H and 6C-H, causing the circuit breakers 6 and 6-C to open and stop the set. If 53 has closed, it opens when the machine slows down. If 41 has closed, it opens as soon as 6 opens. If 41-X has been energized, it is deenergized by the opening of 41. If 19 has been energized, the circuit for opening 6 and 6C has already been completed, and the deenergizing of BP-2 will open 19 and any devices held in by it. If 42-X has been energized but has not had time to complete the closing of 42, it will be opened by the opening of 19 as well as by the deenergizing of BP-2. If 42 has closed, the machine is in the running position and shut-down occurs as described above, under normal shut-down. The remaining device involved in this sequence is 39, and it closes and opens with 42.

2. FAILURE TO COMPLETE STARTING SEQUENCE.

As soon as 3 closes, a circuit through a back contact of 42 and a make contact of 3 completes a circuit to the A.C. timing relay 48. The time of operation of this relay is adjusted so that the starting sequence, under normal conditions, will be completed before 48 operates. The final main operation of the starting sequence is the closing of 42 and when this occurs, 48 is deenergized by the back contact of 42. If for any reason 42 is not closed within the time limit of 48, 48 will operate and energize the lock-out relay, 86, causing shut-down and lock-out. Relay 48 also prevents a large number of starts in a short time because it requires a time interval to reset nearly equal to its time to operate. If a second start is made before the relay has fully reset, a shorter time will be required for it to operate, and if several such starts are made in rapid succession, a point will be reached where 48 operates before the normal sequence is completed. This arrangement prevents abuse of the auto-transformer.

3. CONTINUED OVERLOAD.

THERMAL PROTECTION.

If an overload of insufficient magnitude to operate relays 51 is maintained for a long period, it will overheat the windings and cause damage. The thermal relays, 49, energized from the current transformers, have a heat characteristic similar to that of the machine and will be overheated when the machine is. At a predetermined point 49 will operate and energize 86, causing a lock-out.

4. OVERHEATED BEARINGS ON MOTOR-GENERATOR SET.

If the bearings of the motor-generator set are overheated, the bearing temperature relays, 38, will be operated, energizing 86 and causing a lockout.

5. SYNCHRONOUS MOTOR FIELD FAILURE.

In the circuit of the exciter and synchronous motor field is placed the series operating coil of relay 40. When the D.C. field current exceeds a predetermined minimum value, relay 40 will be energized, opening its back contact. If, due to the failure of the field current to remain above the necessary minimum, this back contact should reclose after 42 has been closed for a definite period, 86 will be energized and a lock-out occur. This operation is secured as follows. When 42 closes, a back contact deenergizes relay 41-X, which was used to obtain the time interval between application of field and transfer to running position. After a period of a few seconds, approximately equal to the operating time for this relay, the back contacts of 41-X reclose. Since 42 is now closed, the circuit is completed except for the closing of back contact 40. The contact of 42 in this circuit prevents shut-down during the starting period before the field is applied. The introduction of the time interval was necessary to prevent lock-out occuring during the surge in the field circuit which occurs at the instant of transition, sometimes of sufficient magnitude to drop relay 40 momentarily.

6. OVERSPEED OF MOTOR-GENERATOR SET.

In case the speed of the motor-generator rises above normal value, the overspeed device will be operated, opening the circuit of 3 directly and causing shut-down until the device is reset. Overspeed of the motor-generator set can not conceivably occur when operating the tunnel, but may occur if the generator is connected with other sources of energy at a moment when the A.C. power supply fails.

MISCELLANEOUS.

It may be noted that loss of alternating-current voltage on the secondary circuit of the 400 VA. voltage transformer, due either to low supply voltage or to a blown fuse or burned out transformer, will prevent completion of the starting sequence by loss of energy for relay 41-X, and at the same time will keep the starting protective relay, 48, from functioning to lock-out the equipment. If the cause is low supply voltage, relay 47 will shut down the equipment. If the cause is a blown fuse or transformer failure, safety is secured by connecting one phase of the relay 47 to the same transformer circuit, so that, if trouble occurs, the voltage impressed on one phase of the voltage relay will also be low, cause a shut-down and prevent restart until the trouble is corrected.

The circuit to the hall indicator may be noticed in the upper left-hand corner of the diagram, and it shows that the indicator is lit whenever the running circuit breaker is closed, or when the motor-generator set is running. This indicator gives the watchman visual evidence that the machines are in operation, and proper steps can be taken in case shutting them down has been overlooked.

PROPELLER MOTOR.

NORMAL START.

The operation of the various devices involved is considerably different depending upon whether the main generator feeds the propeller motor or an experimental load. The operation will first be described for the propeller motor and later for an experimental load. In order to operate the propeller motor, switches 189-A and 189-C must be closed in the position connecting the generator to the motor and switch 189-B should be open. On the switchboard these switches are arranged vertically and the tunnel position is the lower throw. After the motor-generator has been started and brought to the running position, the propeller motor may be started as follows. If the dood switch, DS, is closed, indicating that the motor access door is properly shut, and the overspeed device, 112, on the propeller motor, is in its normal position, and if neither CS-4A nor CS-8 are locked in the "trip" position, closing CS-4 in the "close" position will energize relay 103, since the contact 42 was closed by the starting of the motor-generator set. Relay 103 completes its own holding circuit, as long as circuit breaker 172 is open, and so the control switch may be released immediately. In the tunnel position the back contact 189-A-e is closed and the make contact 189-A-f open. A second contact of 103, fed through 189-A-e, now completes the circuit to 141-X as soon as auxiliary relay 170-X is closed. The latter will be closed if the generator rheostat, MR-2, is "all in", indicating that the generator voltage is at a minimum value. The circuit is shown farther to the right, whereby auxiliary relays 170-X and 170-Y are energized through the limit switch "MR-2, lower". Interlocking circuits described below are arranged to run the rheostat to this position as soon as the circuit breaker 172 opens, so that if 170-X is not closed, it will close as soon as the rheostat has had time to reach the "all in" position. 141-X then operates, completing the circuit to the field breaker closing coil, 141, and closing this breaker. This operation energizes the field of the propeller motor, as shown in the lower row of connections, through the rheostat, MR-5, from BN and BP. An auxiliary contact of 141 completes the circuit of 141-XR, opening the contacts of 141-X and deenergizing the closing coil. This breaker is latched in and will remain closed until 141-T is energized or the breaker is tripped by hand. This same auxiliary contact completes the circuit to 172-X through a third contact of 103. Since 189-A-f is open, this circuit can be completed in no other way. The closing of 172-X energizes the closing coil, 172, closing the circuit breaker, 172, which connects the generator to the motor armature, as shown by the main direct-current connections. With both field and armature energized, the motor begins to rotate. As soon as the circuit breaker starts to close, the back contact 172, in the holding circuit of 103, opens, opening 103, if the control switch has been released. The opening of 103 deenergizes the coils 141-X and 141-XR and attempts to deenergize 172-X. However, 172-X parallels the contact of 103 with one of its own, so that it does not open until the closing operation of 172 is completed. When 172 is closed, an auxiliary contact completes the circuit of 172-XR, which then opens both contacts of 172-X, deenergizing 172-X, 172-XR, and the closing coil 172. If the control switch has not been released, relay 103 remains closed and holds in 141-X, 141-XR, 172-X, and 172-XR. However, the release coils 141-XR and 172-XR have been been energized, so that the contacts are open and the closing coils not energized. When the control switch is released, 103, 141-X and 172-X return to their initial positions. If 141 or 172 should immediately open, they would not again attempt to close until the control switch had been released and again operated, because of the action of 141-XR and 172-XR. This arrangement prevents "pumping" in case of overload or other tripping condition while the control switch is closed. The circuit breaker 172 is latched in by the holding coil, 172-H, which is energized through contacts 42, DS, 112, provided CS-4, CS-8 or PB-9 are not closed in the "trip" position.

The same starting operation as described above may be obtained by operating CS-8 at the observation room speed control panel, instead of CS-4, the only difference being that CS-8 is fed through contact 189-A-e so that it will be effective during operation of the tunnel only. The connections of 103, as described, are necessary in order that 103 will be deenergized when the circuit breaker, 172, is closed and not hold the breaker closed when it is tripped by its series overload coil, marked "O.L. Trip" on the drawing.

PROPELLER MOTOR
HAND SPEED CONTROL.

After the propeller motor has been started, its speed may be controlled either by hand, at any one of several control switches, or by the speed regulator. Regulated control will be described later. For hand control it is necessary to place the transfer switch, 143, in positions 1,2, or 3, and if in position 2, transfer switch 197 must not be in position 3. Position 1 of 143 allows hand control at CS-5, which is located at the "C" switchboard, position 2 transfers control to the observation room station, and position 3 transfers it to the balance room control station. Control for position 1 will be described first, in which case it is obtained by operation of CS-5. Closing CS-5 in the "raise" position completes the circuit from BP-7 through 143-1 to wire R-4. If the armature current drawn by the propeller motor is below a definite limiting value, the back contacts of 118 will be closed. Since 172 has been closed, and the "raise" limit switch of MR-2 will be closed until MR-2 is "all out", 170-R will then be energized. As 189-A-f is open, the circuit in parallel with the 172 contact is open. The closing of 170-R energizes the motor of MR-2 through one of its series fields, causing it to run in the direction which reduces the resistance of MR-2 and therefore increases the voltage of the main generator. The field of the generator is supplied from the 5 KW, exciter No. 7 which is excited from the busses BN-1 and BP-2 through the rheostats HR-2 and HR-3. Under hand control 193-B is deenergized, so that

HR-2 is effective and HR-3 short-circuited by a back contact of 193-B. The voltage of the exciter is therefore determined by the position of HR-2, which, once determined, is left unchanged. This rheostat is located at the rear of the "B" switchboard. With constant field on the propeller motor, its speed is determined by the voltage impressed on its armature, or the voltage of the main generator. With constant exciter voltage, the latter is determined by the position of MR-2, or, in other words, the speed is determined by the amount of resistance inserted by MR-2. Therefore CS-5 is held closed until the speed rises nearly to the desired value, and is then released. The speed will continue to rise slightly, due to the time lag between a change in field resistance and the corresponding change in propeller speed, and will then remain quite constant, If a higher speed is desired, the process is repeated. If a lower speed is desired, CS-5 is closed in the "lower" position, and 170-L is thereby energized, provided the rheostat is not at its lower limiting position. 170-L energizes the rheostat motor through the other series field, causing opposite rotation, an increase in resistance and consequently a reduction in propeller speed.

If the rheostat is run to either extreme position, it opens the corresponding limit switch back contact, stopping the rheostat motor, and closes the make contact which lights a corresponding indicator on the "C" switchboard. As the speed is raised, the armature current drawn by the propeller motor may become excessive. In such case relay 118 will operate, opening the circuit of 170-R and stopping the rheostat motor until the current has again come within the limiting value. 170-R will then reclose and more resistance will be cut out, until CS-5 is released.

If 143 is changed to position 2, control is transferred to the observation room panel. Here a subsidiary transfer switch, 197, allows control to be further distributed. In position 1 of the latter switch control is obtained at CS-6 on the panel. In position 2 control is transferred to an extension push button, PB-10. In either case control is the same as for CS-5 after the station has been put in control, and need not be further described. In position 3, the speed is regulated and the control will be described in connection with regulated speed control.

If 143 is changed to position 3, control is transferred to CS-7 at the balance room speed control station. The operation is identical with that of CS-5. If the transfer from one hand control station to another is made during operation, the speed will be unaffected, remaining at the value previously given it, and the new station may change it to any value desired.

PROPELLER MOTOR

REGULATED SPEED CONTROL.

Regulated speed control is obtained at the balance room station if switch 143 is closed in position 4. It is similarly obtained at the observation room station if control is first transferred to the observation room panel by placing 143 in position 2 and at that panel placing 197 in position 3.

The speed control is obtained in the first instance by the adjustment of coarse and fine rheostats HR-6 and HR-7 at the balance room station, the position of the rheostats determining the value of speed maintained by the regulator. In the second instance it is obtained at the observation room panel by a similar adjustment of rheostats HR-8 and HR-9. The action is quite similar in the two cases and will first be described for control at the balance room station. Closing 143-4 energizes 170-L through a back contact of 193-C and runs the rheostat, MR-2, to the "all in" position. If the propeller motor is in operation, this will reduce the speed to its minimum value. This proceedure is made necessary in order to protect the regulator coils from possible excessive voltage. When the rheostat reaches the "all in" position, 170-Y will close, as described previously. If the regulator switch is closed in the "Reg. On" position, 193-B and 193-C will be closed by 170-Y and will be sealed in by a contact of 193-B in parallel with the contact of 170-Y. Operation of 193-C will open the circuit which ran in MR-2 and close the circuit to 193-A. The operation of 193-A completes the circuit from the pilot generator armature through HR-6 and HR-7 to the speed regulator main coil, 190.

A second make contact of 193-B, referred to above in connection with hand speed control, now short-circuits HR-2, and the break contact which previously short-circuited HR-3 is opened. Control of the exciter voltage is thus transferred from HR-2 to HR-3, and if these rheostats are set at different points, the voltage of the exciter will change. It will be noticed, however, that the contact 190-X is shown short-circuiting HR-3, and when this contact is closed, the value of resistance in the circuit approaches zero. The condenser in parallel is used merely to reduce sparking at the contacts. In operation, as shown below, this contact is forced to vibrate so rapidly that the voltage at the exciter terminals is neither that correxponding to the resistance of HR-3 nor to zero resistance, but has an average value between these two extremes. When the contacts are closed, the voltage rises above the average, and when the contacts are open, the voltage falls below the average. These variations in exciter voltage cause variations in the generator voltage, and consequently variations in propeller speed. However, due to the inertia of the machines, the inductance of the circuits affected and the rapidity of contact vibration, the oscillations in propeller speed are so small that they are well within the required accuracy. Consequently, after equilibrium has been established, the speed maintained by the propeller, for a given position of HR-2, is dependent upon the average exciter voltage and hence upon the relative amounts of time the contacts 190-X are open and closed. This phenomenon is characteristic of all vibrating regulator systems, namely, that the quantity being regulated is not held constant, but is forced to oscillate, the amplitude of the oscillations being restricted to a sufficiently small value.

As a matter of fact, contacts 190-X are merely auxiliary contacts large enough to handle the currents in the circuit. The primary vibrating contact, 190, is arranged to cause a corresponding vibration of 190-X. The circuit is shown near the extreme right of the second row of connections. A third make contact of 193-B completes the circuit through the regulator switch in the "Reg. On" position to the contacts 158-L and 158-R, and also to the coil 190-X. The coil 190-XA is in parallel with 190-X but is energized only when 190 is closed. In accordance with Note 1 of the drawing, contacts 190-X are closed when coils 190-X and 190-XA are both energized, or when contact 190 is closed. Consequently, if 190 vibrates, 190-X will also vibrate, producing the action described above. The manner in which 190 is forced to vibrate is as follows.

The main element of the regulator consists of a pair of contacts, 190, opened and closed by the joint action of two solenoids, 190 and 190-A. One contact is attached to a mechanism operated by the plunger of 190, and the other to a mechanism operated by the plunger of 190-A. The arrangement is such that low voltage on either coil tends to close the contacts, but whether or not the contacts will close depends upon the positions of both plungers. Coil 190 is connected, in series with rheostats HR-6 and HR-7 to the pilot generator. The pilot generator is direct connected to the propeller motor and has a regulated constant current applied to its field in a manner described later. Consequently the voltage generated and the voltage drop across coil 190 will be proportional to speed. If this voltage drop is within certain narrow limits, the plunger of 190 will be balanced at some position between its two stops. If the voltage is lower, the plunger rests against its lower stop and if higher, it is pulled up against its upper stop. Coil 190-A is connected across the terminals of the exciter and therefore has a voltage drop proportional to the voltage of the exciter. If this voltage is sufficiently low to close the contacts, 190-X closes immediately and raises the exciter voltage. As the exciter voltage rises, but before it has had time to make an appreciable change in the propeller speed, the contacts open due to the action of the coil 190-A. As the contacts open, the voltage of the exciter falls and soon the contacts close again, causing the process to repeat rapidly. The exciter voltage necessary to open and close the contacts and therefore the average exciter voltage depends upon the position of the plunger at the instant the contacts separate, and this in turn is dependent upon the position of the plunger of 190, or in the final analysis, upon the propeller speed. In other words, for a given position of HR-6 and HR-7, a given propeller speed will produce a definite average exciter voltage. But we saw previously that a given exciter voltage would produce, for a fixed position of MR-2, a definite propeller speed. Thus, if we start with a given propeller speed, the regulator will hold for each position of HR-6 and HR-7 a definite value of exciter voltage. If this voltage is greater than required for the speed at which the motor is running, the motor will increase in speed until the pull on the plunger of 190 is sufficient to raise it. If the plunger was resting against its lower stop, the exciter voltage produced would take its maximum value, and remain there until the plunger started to rise. As the plunger rises, the average exciter voltage decreases, decreasing the rate of rise of speed gradually to zero. If the exciter voltage falls sufficiently, the speed may even decrease slightly. This, however, increases the exciter voltage, the speed again rises and the process is repeated. If the plunger of 190 is properly damped by dash pot adjustment, however, these swings in speed are rapidly damped out and the system settles to equilibrium at such a speed that the average exciter voltage held by the regulator is just sufficient to maintain the speed of the propeller motor.

It may happen, however, that for the original position of MR-2 the maximum value of exciter voltage is insufficient to obtain equilibrium. In this case, if it were not for the auxiliary element to be described, the speed of the propeller motor would rise to the value corresponding to the maximum exciter voltage and remain there. To overcome this difficulty and, in short, to increase the speed range, an auxiliary element, 158, is connected in parallel with 190-A and is provided with two contacts, one of which closes when the exciter voltage exceeds a definite limit, and the other when the voltage falls below a lower definite value. The closing of the upper contact reduces the resistance of MR-2 and closing of the lower contact raises it. The circuit is seen near the right of the second row of connections. As described previously, the closing of one of the make contacts of 193-B, through one pole of the regulator switch, connects the contacts 158-L and 158-R to BP-2. As these contacts close, they change the resistance of MR-2 in the same manner as one of the control switches. Thus if the voltage of the exciter produced by the regulator exceeds the closing voltage of 158-R, the resistance of MR-2 is decreased until the regulator reduces the exciter voltage again below the closing voltage of 158-R, indicating that equilibrium is being approached. With the voltage between the limiting values of 158, the regulator has complete control, but if the regulator requires a voltage outside these limits, the rheostat, MR-2, is adjusted until the requirements of the regulator are in the proper region.

If the speed of the propeller motor is too great for the value of exciter voltage held by the plunger of 190 in the corresponding position, the speed decreases until equilibrium is established in a similar manner to that described above for an increase in speed. If, during the process, the exciter voltage falls below the predetermined value, the position of MR-2 is correspondingly changed so that the exciter voltage is held within the proper limits whenever the system is in equilibrium.

When the regulator is first placed in control by the closing of 193-A, the speed of the peopeller is at its minimum value, as mentioned previously. The regulator then immediately increases the speed of the motor until equilibrium is established, corresponding to the setting of HR-6 and HR-7. If it is desired to change the speed held by the regulator, it is merely necessary to change the resistance in either or both of these rheostats. One is used for coarse adjustment and the other for fine. An increase in resistance causes the voltage drop across 190 to fall and the regulator immediately increases the speed until it is again in equilibrium and the voltage drop across 190 is within the proper limits. A decrease in resistance causes the voltage drop to increase and produces a corresponding decrease in speed. Care should be taken not to reduce the resistance too rapidly, as this impresses a high voltage across 190, which may damage it.

It is desirable to be able to place the machine on the regulator without shutting down. If the regulator were connected immediately at the speed at which the motor was running, it might happen that the speed of the motor was very high and the resistance turned into HR-6 and HR-7 very low, corresponding to a low regulated speed. The voltage produced by the pilot generator under these conditions is many times the normal voltage across 190 and serious damage to the regulator or its resistor would probably result. To avoid this condition, the circuits are so arranged that the regulator can be connected only when the propeller speed is at its minimum value.

When regulated speed control is desired at the observation room panel, switch 143 is placed in position 2 and 197 in position 3. A circuit through the contacts closed in these positions and another back contact of 193-C runs the rheostat MR-2 to the "all in" position in the same manner as above. Relays 193-B and 193-C are then energized in the same manner as before, but the circuit is through 143-2 and 197-3 instead of through 143-4. When 193-C closes, it now completes the circuit to 193-D instead of to 193-A. The closing of 193-D connects 190 to the pilot generator, but this time through HR-8 and HR-9 instead of HR-6 and HR-7. The action of the regulator is now identical with that described except that HR-8 replaces HR-6 and HR-9 replaces HR-7.

When operating under regulated control and the switches 143 or 197 are changed so that the regulator connections are broken, MR-2 remains in the same position. The opening of 193-B transfers control of the exciter voltage back to HR-2. The voltage held by HR-2 will probably be slightly different from that held by the regulator so that a slight change in speed will result, which may be either an increase or a decrease. To keep this speed change a minimum, it is desirable to have HR-2 so set that the voltage produced by it will be within the limits of voltage maintained by 158.

The action of the current regulator which maintains the current constant in the pilot ~~generaxtor~~ generator field is as follows. The main circuit may be traced from BN-1 through the field, one pole of the 2 P.D.T. knife switch, the counter-E.M.F. motor armature, the other pole of the switch, coil

157, HR-4 and contact 141 to BP-1. As 141 is closed when and only when the propeller motor is in operation, this field circuit is closed whenever the motor is running. The 2 P.D.T. switch is furnished as a disconnecting switch for the counter-E.M.F. motor and is made double throw only because it was convenient to match the contact reversing switches for 190 and 190-X, which had to be double throw. The counter-E.M.F. motor acts as an additionsl resistance in series with the rheostat HR-4, but the equivalent value of this resistance depends upon the field of the motor and hence upon the action of 157, since the contact of 157 short circuits the field when it is closed. When the current through 157 falls below a critical value, contacts 157 close, short-circuiting the field, reducing the counter-E.M.F. interposed by the motor, or in other words its effective resistance, and raising the current. The increase in current opens the contacts, the effective resistance increases, the current decreases, and the contacts close again, thus setting up a vibrating action which maintains a constant average current. The coil 157-A, with its resistor, is connected across the field terminals and acts as an anti-hunting device. It is wound in opposition to the main coil, 157, and acts on the same plunger. When the voltage across the field is high, 157-A causes the contacts to close sooner than they would otherwise, and when it is low, it causes them to open sooner. The amount of overtravel which would exist if 157 operated alone is thus reduced and the maximum and minimum current values are closer to the average.

PROPELLER MOTOR

NORMAL SHUT-DOWN.

To stop the propeller motor, it is necessary to close CS-4, CS-8 or PB-9 in the "trip" position. This short-circuits the holding coil 172-H which keeps 172 latched, CS-4 shorting directly from BP-5 and CS-8 and PB-9 from K-4, so that they are effective during tunnel operation only. 172 immediately opens, disconnecting the propeller motor armature, and an auxiliary contact completes the circuit to 141-T, through a back contact of 103, and a make auxiliary of 141. Since 103 is now open, this trips the field breaker, 141, and deenergizes the propeller motor field, the discharge contact 141 closing and allowing the field to discharge through the field rheostat, HR-5, and the discharge resistor, DR-5. The trip coil circuit is opened by the opening of the auxiliary contact 141.

The opening of the make contact, 172, in the circuit of 170-R prevents the rheostat, MR-2, being raised by any of the raising contacts, since 189-A-f is open in the tunnel position. At the same time, a back contact of 172, through 189-A-c or 196-1, if it is closed, runs the rheostat to the "all in" position, ready for the next start. If the regulator is in operation, it will continue to vibrate as long as the motor generator runs. Since the pull on the plunger of 190 is now zero, the latter will drop against its stop and the exciter voltage will rise to its maximum value.

If the main motor-generator is stopped, auxiliary contact 42 in the circuit of 103 and 172-H will open, opening 172, and the remaining operations, with one exception, will follow as described above, so that the propeller motor is immediately disconnected upon stopping of the main motor-generator set. The opening of 4 deenergizes BP-2 so that MR-2 can not be run in. However, as soon as BP-2 is again energized, this operation is completed as described above. In case the motor generator is stopped by loss of control power, sufficient voltage may not be available for tripping the field circuit breaker, 141. This causes no trouble because the field of the propeller motor is fed from the same source and if the source fails, no energy will be supplied to the field even if the breaker remains closed. As soon as control power is restored, the tripping circuit will be completed and the breaker opened.

Thus the propeller motor may be disconnected in three ways. It may be disconnected directly by its own control switch, or it may be cut off by stopping either the main motor-generator or the control motor-generator.

If the closing operation has been started by the closing of 103, but the propeller motor has not yet been connected, because, for example, the rheostat has not reached the "all in" position, the operation may be interrupted by closing CS-4 or CS-8 in the "trip" position. This short-circuits 103 and causes it to drop out. If the operation had progressed as far as the closing of the field breaker, 141, but 172 had not closed, the opening of 103 completes the circuit for 141-T, thus opening 141. This sequence can not be obtained with PB-9, so that the latter will not prevent the completion of the starting operation once it has been started.

PROTECTION, WITHOUT LOCKOUT.

1. MOMENTARY OVERLOAD.

In the normal shut-down sequence described above it may be noted that the opening of 172 causes the complete sequence to follow. This is true regardless of the reason for the opening of 172. If a momentary overload occurs, the series overload coil of 172 will trip this breaker directly, causing a shut-down of the propeller motor. The motor may be immediately restarted by the usual starting sequence.

2. OPENING OF FIELD CIRCUIT BREAKER.

If the field circuit breaker, 141, opens for any reason while 172 is closed, 172 is immediately opened. A circuit from wire K-4 through a back contact of 141 and a make contact of 172 short-circuits 172-H, causing the breaker to open immediately. With both circuit breakers open, all other operations follow in the manner of a normal shut-down.

PROTECTION, MACHINE LOCKED-OUT.

1. OVERHEATING OF PROPELLER MOTOR.

If the propeller motor overheats, relay 168, which has a temperature bulb in contact with one of the motor commutating field poles, will be operated, closing its contacts and operating 86 through one of the annunciators of 30. This will cause shut-down both of the propeller motor and the motor-generator set. Relay 168 must be reset by hand and as the relay is mounted on the front bearing bracket of the propeller motor, an inspection of the motor must be made.

2. OVERHEATED BEARINGS.

If the main bearings of the propeller motor become overheated, one of the two relays 138 will be energized, operating the lock-out relay and causing shut-down in the manner just described for relay 168. These relays are also hand reset, requiring that the bearings be inspected before the machines may be restarted.

3. OVERSPEED OF PROPELLER MOTOR.

In case of overspeed of the propeller motor, the overspeed device will be operated, opening the circuit to 172-H and causing shut-down in the same manner as described for the opening of 42 under "Normal Shut-down". This device is hand reset and the motor can not be restarted until the device is reset. The overspeed device is located at the end of the pilot generator shaft and can be reset by means of a suitable bar through the louvres in the tail of the fairing.

MISCELLANEOUS.

If the access door to the tunnel which is opposite the propeller motor is opened, the door switch, DS, is opened, causing the propeller motor to be shut down until the door is closed again.

It may be noticed that one set of "stop" contacts of CS-4, CS-4A, and CS-8, if closed, will short-circuit coil 103. Thus, although CS-4A is otherwise inoperative, if it is held or latched in the "trip" position, it will prevent the starting of the propeller motor. This may be used as a safety measure to prevent someone at the "C" switchboard starting the motor when, for example, men are at work at the "B" switchboard and require the use of the motor-generator for testing.

EXPERIMENTAL LOAD.

NORMAL START.

If the main generator is connected to an experimental load through the switches 189-A and 189-B or 189-C, depending upon whether a shunt or differential-compound connection is desired, the starting operation will be considerably different from that of the propeller motor. The closing of 189-A in the "Experimental Load" position will open contacts 189-A-e and close 189-A-f. The opening of 189-A-e renders CS-8 inoperative and starting must be accomplished by means of CS-4. If an interlocking arrangement between the position of MR-2 and the closing of 172, as described for the propeller motor, is desired, the interlocking switch, 196, should be placed in the 196-1 position. If it is desired to be able to close the circuit breaker, 172, at any voltage on the main generator, this switch should be placed in the 196-2 position.

It will first be assumed that this interlock is desired, and 196-1 is closed. If MR-2 is not in its "all in" position, it will be run there by means of a circuit energizing 170-R through a back contact of 172 and one pole of 196-1. When CS-4 is closed in the "clos" position, 103 is energized in the same manner as previously described for the propeller motor. The contacts of the overspeed device, 112, and the door switch must, of course, be in the proper positions. It would be a simple matter to arrange an auxiliary contact, 189-A-f, to short circuit these devices in the experimental load position, but no contact was available on the auxiliary switches, and it was not considered worth while to add it unless the use of this type of load justified it.

If 170-X is now closed, indicating that MR-2 is "all in", 172-X is immediately energized, starting from BN-1, through 170-X, 196-1, 189-A-f, coil of 172-X and contact 103. The closing of the circuit breaker, the opening of 103 and 172-X are the same as described for starting the propeller motor. However, in this case the field circuit breaker, 141, is not closed, because the opening of contact 189-A-e in the circuit of 141-X prevents the energizing of the latter.

After 172 is closed, connecting the generator to the load, the voltage may be brought to any desired value by setting 143 in position 1 and operating CS-5. If desired, voltage control may be transferred to any of the other control devices in the same manner as for the propeller speed control. If the regulator should be connected, the voltage would immediately rise to its maximum value, because the plunger of 190 would never be picked up, and resting against its lower stop the voltage of the exciter would exceed the setting of 158-R and the rheostat MR-2 would be turned "all out" by the action of 158-R.

If 196 had been placed in the 196-2 position, MR-2 would not be turned in by the opening of 172. The circuit which normally does this is completed through either 189-A-e or 196-1, both of which are now open. Also the circuit of 170-R is no longer opened by the opening of 172, since a parallel circuit through 189-A-f and 196-2 keeps this circuit closed around the 172 contact. Consequently MR-2 can be set at any point desired before 172 is closed.

If CS-4 is now closed, 172-X is energized through 196-2 and 189-A-f as soon as 103 closes, and 172 immediately closes. The desired value of voltage is obtained in the same manner as before by adjusting CS-5 or any of the other switches which have been put in control by means of switches 143 and 197.

EXPERIMENTAL LOAD.

NORMAL SHUT-DOWN.

Closing CS-4 in the "trip" position short-circuits the holding coil, 172-H, opening the circuit breaker 172, and disconnecting the load. If 196-1 is closed, MR-2 will be run to the "all in" position. If 196-2 is closed, MR-2 is unaffected.

Shutting down the motor-generator opens 42, and this opens the circuit of 172-H, causing shut-down as just described. However, the shutting down of the motor-generator deenergizes BP-2, and control is not available for running in MR-2, in case 196-1 is closed, until the motor-generator is started again.

PROTECTION.

1. MOMENTARY OVERLOAD.

In case of overload current exceeding the setting of the "O.L.Trip" of circuit breaker 172, the breaker will be tripped and shut-down will occur as described above.

MISCELLANEOUS.

As described previously in connection with the propeller motor, CS-4A may prevent starting if it is held or latched in the "trip" position. In this case, CS-8, although otherwise inoperative, also has this property.

CONTROL AT SEMI-PORTABLE PANEL.

If transfer switch 95 is closed in position 95-2 instead of position 95-1, all control operations except those of starting and stopping the control motor-generator are transferred to the semi-portable control panel. In this case lockswitch 1, CS-2, CS-3, CS-4 and CS-5 are replaced by lockswitch 1-A, CS-2A, CS-3A, CS-4A, and CS-5A respectively. All operations previously performed by the former are now performed by the latter group, and the description need not be repeated in detail. The only changes of importance are that the speed regulator is now inoperative and no transfer switch corresponding to 143 or 197 is used. Consequently CS-5A has control of the motor speed or of the main generator voltage at all times. In a similar manner to that described above, the latching of CS-4 or CS-8 in the trip position will prevent the operation of circuit breaker 172 by CS-4A.

NOTE.

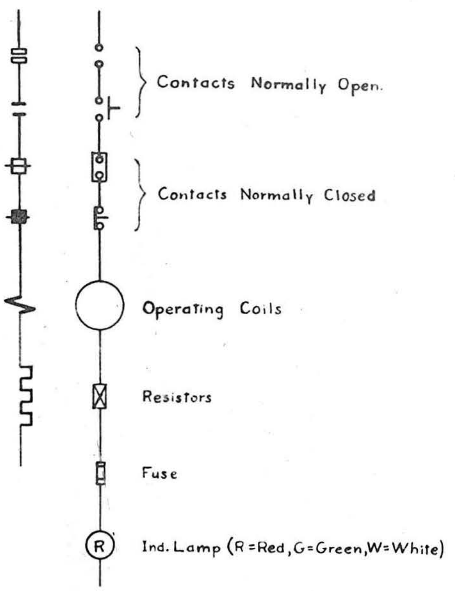
At the time this is written, the balance room station has not been built. In the foregoing analysis the equipment has been described as if this station were in operation in accordance with the present plans for its construction. Any changes which are made from these plans will very probably not affect any of the equipment already installed and will largely be in the nature of additional control features at this station. In order to be sure of having the latest information on this or any other feature which may be changed, the records of the installation on file in the Wiring Department, for use in maintenance, should be consulted.

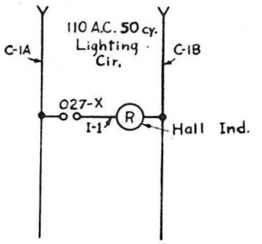
VI. CONCLUSION. The usefulness of any apparatus is largely dependent upon its accuracy and the convenience with which it may be operated. Other features of prime importance are freedom from trouble, the ease with which trouble may be located and repaired when it does occur and the convenience with which alterations may be made. The wind tunnel equipment just described is one which may be easily and quickly controlled, with little or no danger of improper operations, from points conveniently located with respect to the aeronautical equipment. The only quality of the electrical equipment which affects the accuracy of the wind tunnel measurements is the speed of the propeller, and this quality may be regulated with a high precision at any value within a wide range. Members of the Aeronautics Department have expressed entire satisfaction with the accuracy obtained.

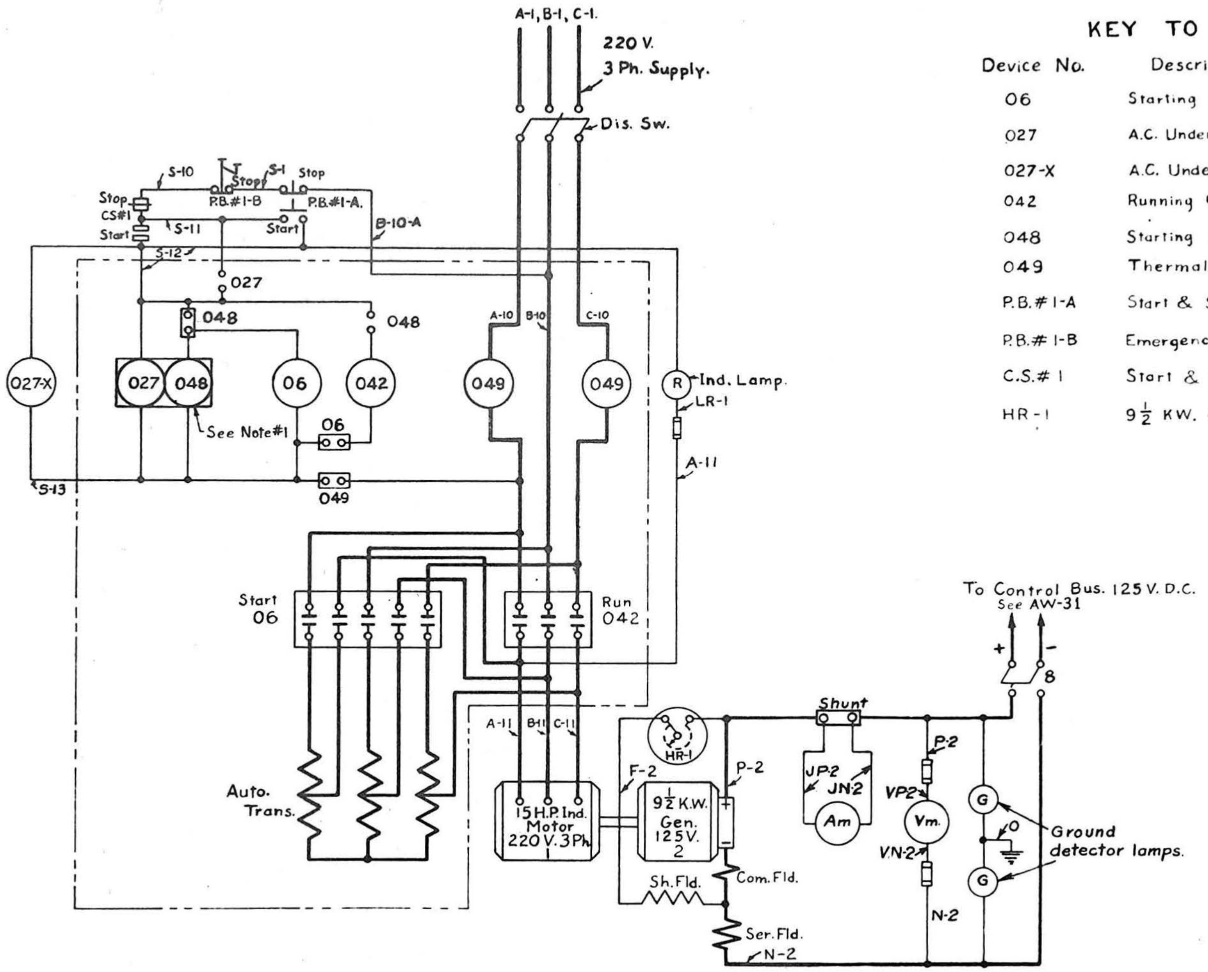
The equipment is made up to a large extent of standard apparatus which is rugged in construction and has been found to be adequately designed from its use in other places. This will tend to reduce trouble to a minimum and render replacement of worn parts an easy matter. Such troubles as have occurred have been found to be neither of a fundamental nature nor due to serious errors in design. The arrangement of wiring, with all wires entering or leaving a switchboard available at accessible terminal blocks and grouped as far as possible according to function and route, renders location of electrical trouble a relatively easy matter. This arrangement and provision for additions which were allowed in the conduit system wherever it was deemed possible that additional wiring would be required should simplify to a large extent alterations and extensions which time and operating conditions prove to be desirable.

We are therefore led to the belief that this equipment forms a successful solution of the problem of providing a suitable electric drive for the wind tunnel. In conclusion, the author wishes to gratefully acknowledge the cooperation and guidance given by Mr. L. G. Fenner, Superintendant of the Wiring Department, who exercised general supervision over the entire installation.

LEGEND







KEY TO APPARATUS

Device No.	Description Of Apparatus
06	Starting Contactor
027	A.C. Undervoltage Relay
027-X	A.C. Undervoltage Auxiliary Relay
042	Running Contactor
048	Starting Protective & Transfer Relay
049	Thermal Overload Relay-(Hand Reset)
P.B.# 1-A	Start & Stop Push Button, Near Machine
P.B.# 1-B	Emergency Stop Push Button, Primary Vault
C.S.# 1	Start & Stop Control Switch, Tunnel Control, Swbd.
HR-1	9½ KW. Gen. Field Rheostat

Note #1. After 048 Has Operated (Time Delay), Its Contacts Are Held In Energized Position By 027

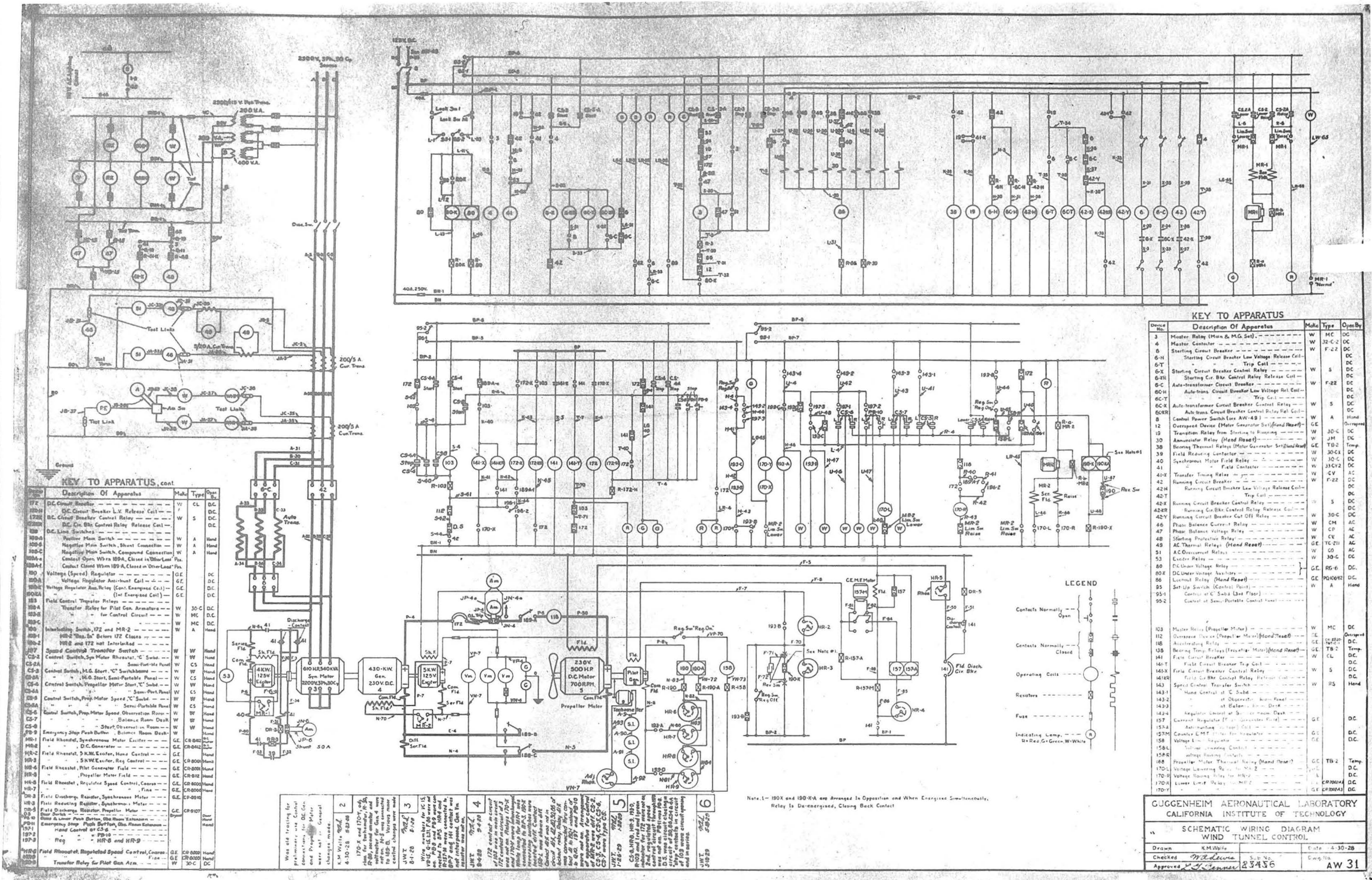
Note #2. All Apparatus Included In Dot & Dash Line ——— – – ——— Thus, Is Enclosed In Starting Compensator Case.

Voltmeter was connected differently. Ground detector lamps were not on.
J.W.T. 1-26-29
W.A.L. 1-28-29
2

GUGGENHEIM AERONAUTICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

SCHEMATIC WIRING DIAGRAM
9½ K.W. - M.G. SET

Drawn K.M. Wolfe.
Checked W.A. Lewis
Approved L.G. Fenner
Sub. No. 12
Date - 4-7-28.
Dwg. No. AW49



KEY TO APPARATUS

Device No.	Description Of Apparatus	Make	Type	Oper. By
3	Master Relay (Main & M.G. Set)	W	MC	DC
4	Master Contactor	W	32-C-2	DC
6	Starting Circuit Breaker	W	F-22	DC
6-H	Starting Circuit Breaker Low Voltage Release Coil			DC
6-T	" " " Trip Coil			DC
6-X	Starting Circuit Breaker Control Relay	W	S	DC
6-XR	Starting Cir. Bkr. Control Relay Release Coil			DC
6-C	Auto-transformer Circuit Breaker	W	F-22	DC
6C-H	Auto-trans. Circuit Breaker Low Voltage Rel. Coil			DC
6C-T	" " " " Trip Coil			DC
6C-X	Auto-transformer Circuit Breaker Control Relay	W	S	DC
6C-XR	Auto-trans. Circuit Breaker Control Relay Rel. Coil			DC
8	Control Power Switch (see AW-49)	W	A	Hand
12	Overspeed Device (Motor Generator Set) (Hand Reset)	GE		Overspeed
19	Transition Relay from Starting to Running	W	30-C	DC
30	Annunciator Relay (Hand Reset)	W	JM	DC
38	Bearing Thermal Relays (Motor Generator Set) (Hand Reset)	GE	TB-2	Temp.
39	Field Reducing Contactor	W	30-CX	DC
40	Synchronous Motor Field Relay	W	30-C	DC
41	" " Field Contactor	W	33-CY2	DC
41-X	Transfer Timing Relay	W	CV	AC
42	Running Circuit Breaker	W	F-22	DC
42-H	Running Circuit Breaker Low Voltage Release Coil			DC
42-T	Trip Coil			DC
42-X	Running Circuit Breaker Control Relay	W	S	DC
42-XR	Running Cir. Bkr. Control Relay Release Coil			DC
42-Y	Running Circuit Breaker Cut Off Relay	W	30-C	DC
46	Phase Balance Current Relay	W	CM	AC
47	Phase Balance Voltage Relay	W	CP	AC
48	Starting Protective Relay	W	CV	AC
49	AC. Thermal Relays (Hand Reset)	G.E.	TC-211	AC
51	A.C. Overcurrent Relays	W	CO	AC
53	Exciter Relay	W	30-C	DC
80	D.C. Under Voltage Relay	G.E.	RG-6	D.C.
80X	D.C. Under Voltage Auxiliary			
86	Lockout Relay (Hand Reset)	G.E.	PQ106Y2	D.C.
95	Set-Up Switch (Control Point)	W	A	Hand
95-1	Control at "C" Swbd. (3rd Floor)			
95-2	Control at Semi-Portable Control Panel			
103	Master Relay (Propeller Motor)	W	MC	DC
112	Overspeed Device (Propeller Motor) (Hand Reset)	GE		Overspeed
118	Accelerating Relay	G.E.	CR-2820-1671-C11	D.C.
138	Bearing Temp. Relays (Propeller Motor) (Hand Reset)	G.E.	TB-2	Temp.
141	Field Circuit Breaker	W	CL	D.C.
141-T	Field Circuit Breaker Trip Coil			D.C.
141-X	Field Circuit Breaker Control Relay	W	S	D.C.
141XR	Field Cir. Bkr. Control Relay Release Coil			D.C.
143	Speed Control Transfer Switch	W	RS	Hand
143-1	Hand Control at "C" Swbd.			
143-2	" " at Observation Room Panel			
143-3	" " at Balance Room Desk			
143-4	Regulator Control at Balance Room Desk			
157	Current Regulator (Pilot Generator Field)	G.E.		D.C.
157-A	Anti-hunting (Voltage) Coil			
157-M	Counter E.M.F. Motor for Regulator	G.E.		D.C.
158	Voltage Limit Regulator	G.E.		D.C.
158-L	Voltage Lowering Contacts			
158-R	Voltage Raising Contacts			
168	Propeller Motor Thermal Relay (Hand Reset)	G.E.	TB-2	Temp.
170-L	Voltage Lowering Relay for MR-2	G.E.		D.C.
170-R	Voltage Raising Relay for MR-2	G.E.		D.C.
170-X	Lower Limit Relay for MR-2	G.E.	CR7002A1	D.C.
170-Y	" " "	G.E.	CR7002A3	D.C.

KEY TO APPARATUS, cont.

Device No.	Description Of Apparatus	Make	Type	Oper. By
172	D.C. Circuit Breaker	W	CL	D.C.
172-H	D.C. Circuit Breaker L.V. Release Coil			D.C.
172X	D.C. Circuit Breaker Control Relay	W	S	D.C.
172XR	D.C. Cir. Bkr. Control Relay Release Coil			D.C.
189	D.C. Line Switches			
189-A	Positive Main Switch	W	A	Hand
189-B	Negative Main Switch, Shunt Connection	W	A	Hand
189-C	Negative Main Switch, Compound Connection	W	A	Hand
189A-e	Contact Open When 189-A, Closed in "Other Lead" Pos.			
189A-f	Contact Closed When 189-A, Closed in "Other Lead" Pos.			
190	Voltage (Speed) Regulator	G.E.		DC
190-A	Voltage Regulator Anti-hunt Coil	G.E.		D.C.
190X	Voltage Regulator Aux. Relay (Cont. Energized Coil)	G.E.		D.C.
190XA	" " " (Int. Energized Coil)	G.E.		D.C.
193	Field Control Transfer Relays			
193-A	Transfer Relay for Pilot Gen. Armature	W	30-C	D.C.
193-B	" " for Control Circuit	W	MC	D.C.
193-C	" " "	W	MC	D.C.
196	Interlocking Switch, 172 and MR-2	W	A	Hand
196-1	MR-2 "Res. In" Before 172 Closes			
196-2	MR-2 and 172 not Interlocked			
197	Speed Control Transfer Switch	W	W	Hand
CS-2	Control Switch, Syn. Motor Rheostat, "C" Swbd.	W	W	Hand
CS-2A	" " " " Semi-Portable Panel	W	CS	Hand
CS-3	Control Switch, M.G. Start, "C" Switchboard	W	W	Hand
CS-3A	" " , M.G. Start, Semi-Portable Panel	W	CS	Hand
CS-4	Control Switch, Propeller Motor Start, "C" Swbd.	W	W	Hand
CS-4A	" " " " Semi-Port. Panel	W	CS	Hand
CS-5	Control Switch, Prop. Motor Speed, "C" Swbd.	W	W	Hand
CS-5A	" " " " Semi-Portable Panel	W	CS	Hand
CS-6	Control Switch, Prop. Motor Speed, Observation Room	W	W	Hand
CS-7	" " " " , Balance Room Desk	W	W	Hand
CS-8	" " " Start, Observation Room	W	W	Hand
PB-9	Emergency Stop Push Button, Balance Room Desk	W		Hand
MR-1	Field Rheostat, Synchronous Motor Exciter	G.E.	CR-8412	D.C. Motor
MR-2	" " , D.C. Generator	G.E.	CR-8412	D.C. Motor
HR-2	Field Rheostat, 5 K.W. Exciter, Hand Control	G.E.		Hand
HR-3	" " , 5 K.W. Exciter, Reg. Control	G.E.	CR-8001	Hand
HR-4	Field Rheostat, Pilot Generator Field	G.E.	CR-8001	Hand
HR-5	" " , Propeller Motor Field	G.E.	CR-8112	Hand
HR-6	Field Rheostat, Regulated Speed Control, Coarse	G.E.	CR-8000	Hand
HR-7	" " " " , Fine	G.E.	CR-8000	Hand
DR-3	Field Discharge Resistor, Synchronous Motor	G.E.	CR-9910	
RR-3	Field Reducing Resistor, Synchronous Motor			
DR-5	Field Discharge Resistor, Propeller Motor	G.E.	CR-9107	
DS	Door Switch	Bryant		Door
PB-10	Raise & Lower Push Button, Obs. Room Extension			Hand
PB-11	Emergency Stop Push Button, Obs. Room Extension			Hand
197-1	Hand Control at CS-6			
197-2	" " " PB-10			
197-3	Reg " " HR-8 and HR-9			
HR-8	Field Rheostat, Regulated Speed Control, Coarse	G.E.	CR-8000	Hand
HR-9	" " " " Fine	G.E.	CR-8000	Hand
193-D	Transfer Relay for Pilot Gen. Arm.	W	30-C	DC

LEGEND

Contacts Normally Open

Contacts Normally Closed

Operating Coils

Resistors

Fuse

Indicating Lamp. R=Red, G=Green, W=White

Note. 1— 190X and 190-X-A are Arranged In Opposition and When Energized Simultaneously, Relay Is De-energised, Closing Back Contact.

		Was old tracing for preliminary use. Control connections for D.C. Gen and Propeller Motor were not [illegible]. General changes made.
2	K.M. Wolfe 4-30-28 WAL 5-23-28	170-X and 170-Y, adj. rhes. for tachometer, R-30, R-80, second ammeter and voltmeter for Gen. 4 were not on. N-5 was connected to 189-B. Various minor control changes were made.
3	JWT 8-1-28 WAL 8-1-28	Wire numbers for VC-15, VB-15, Q-15, L-31, F-86 were not on. PB-8 and PB-9 were connected to BPS. HR-4 and R-157-M were connected to BP-7 and 141 contact was not interposed. Gen. Vm. resistor was not on.
4	JWT 9-4-28 WAL 9-4-28	172 contact in circuit of 103 was in main circuit. 172 contact in circuit of 3 was not on. Relays 170-X and 170-Y were interchanged. White lamp for MR-1 was connected to BP-3. 190-X reversing switches were located diff. Contact 150-L was shown diff. Contact 41X was not in circuit 41X, 42, 40, 30, 86 of lockout relay. Relay 41X was connected thru contact 41 to 80X instead of to Q-10. 197 and PB-10 were not on. Arrangement of apparatus for control of MR-2 was diff. CS-2, CS-3, CS-4, CS-5, CS-6, CS-7 were type CS.
5	J.W.T. 1-26-29 WAL 1-28-29	CS-8, HR-8, HR-9, 193-D, R-103 and 1 red and 1 green indicator for 172 were not on. 2nd. regulated speed control circuit through 193 was not on. PB-11 was PB-9. D.S. was circuit closing in circuit of 30, 86, CS-4 & 4A "stop" contacts in circuit of 103 were circuit opening and in series.
6	J.W.T. 5-18-29 WAL 5-18-29	

GUGGENHEIM AERONAUTICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

SCHEMATIC WIRING DIAGRAM
WIND TUNNEL CONTROL

Drawn K.M. Wolfe		Date 4-30-28
Checked W.A. Lewis	Sub. No. 23456	Dwg. No. AW 31
Approved		