OPERATION AND MAINTENANCE OF THE LOW SPEED PRECISION WIND INSTRUMENT TEST FACILITY

by

Erich J. Plate

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Final report conducted for
Purchasing and Contracting Division,
White Sands Missile Range, New Mexico,
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ACKNOWLEDGMENTS

The need for accurately determining the performance of wind instruments, for their calibration, and for developing new or modified instruments resulted in awarding a contract for the design and construction of a low speed precision wind tunnel to Colorado State University in summer 1960. Work on the contract started in August 1960 with a detailed study of design and performance characteristics on the basis of information on existing tunnels and instruments (Ref. 1). The suggested design was accepted by the Signal Missile Support Agency of the U. S. Army Signal Corps at White Sands Missile Range, and detailed design started in January 1961. Miss H. Akari, Fred Stepanich and Douglas Strong helped in the design of the facility. Fred Stepanich contributed largely also to its final assembly.

During all phases of the design and construction, Dr. J. E. Cermak, Professor of Civil Engineering and Engineering Mechanics, supervised the project. Without his help, the writer would not have been able to execute the contract.

The construction was begun in March 1961 in the Hydraulics Laboratory Shop of Colorado State University in Fort Collins. Preston Ferrell and Ray Fanning did most of the work under the supervision of R. V. Asmus.

Detailed designs of the electrical controls, as well as their assembly were executed by G. Caduff, G. Connor, D. Mann, and Charles Kovac. The assembly took place under the general supervision of G. Caduff, Head of the Department of Electrical Engineering, Pueblo College, Colorado, who was in Fort Collins during summer of 1961.

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1. INTRODUCTION

This report is intended to explain the design features of the wind tunnel and its controls, to instruct on the operation of the facility, and to indicate maintenance procedures and means of improving the performance, if so desired.

For this purpose, the report is divided into three sections. The first section contains a general description of the wind tunnel itself, into which have been incorporated maintenance instructions for the facility, as well as suggestions for improving some of the wind tunnel characteristics.

In the second section the basic features, design principles and operations for the control panel are briefly explained. Complete circuit diagrams are furnished for all circuits involved in the controls, including information on connectors. This section is intended for facilitating repair work or circuit modifications if other areas of application for the tunnel are considered.

The third section contains information on the wind tunnel instruments. Operation procedures have been developed for each instrument and are outlined.

It is realized that other procedures of more appeal to the individual working with the facility can be developed. For the inexperienced operator, however, the instructions for operation, in conjunction with the principles outlined in other sections of this report, will provide a starting point from which to begin an exploration of the possibilities of the facility, its controls, and its instrumentation.

2. THE WIND TUNNEL

The essential parts of the wind tunnel are the duct with the test section, the power section, the carriage, and the safety features. They have been designed according to Ref. 1, and also to correspond to the specifications of Contract No. DA 29-040-ORD 2346 wherever possible; with modifications as accepted by the Contracting Officer.

2.1 Wind Tunnel Duct

The square parts of the wind tunnel are made out of 3/4 in. plyboard supported by 2 x 6 lumber frames. Round parts are made from sheet metal to avoid the costly procedure of shaping them from plywood. For transitions from round to square, as well as from the return duct to the test section, an outer shell was prepared from plyboard and lumber. Into these were fitted the transition sections which are made of 14 gage sheet metal.

The wind tunnel layout is shown in Fig. 1. The airstream, driven by the fan, is slowly expanded in the return duct section between blower and the first large corner. The expansion angle is approximately 7^0, thus, no undesired separation should occur.

The two large corners, in which the air is slowest, are each equipped with a set of turning vanes to change the direction of the airstream with a minimum of distortion of the flow and of pressure losses. The vanes are bolted together in sections, and can be taken out. If the need should arise to control the temperature inside the wind tunnel, the logical procedure for installing a climate control system would be to take out one set of vanes and replace it by the refrigeration or heating coils. Access to the vanes can be obtained by removing transition and screens between corner and test section.

The turbulence damping screens are kept in tension at all times by a number of bolts which are set into a channel iron frame. The screens are also held by bolts through their frames and through the frames of adjacent sections. The possibility of cleaning the screens has been anticipated. Due to the limited space above and around the screens, this will always be a major operation. It is, therefore, recommended not to remove the screens if it can be avoided, and to clean them frequently (about 2 times a year) by first blowing a strong air jet from a portable blower through them, and then carefully vacuum cleaning from both accessible screen sides. If the screens have to be removed, due to damage or for replacement, then all the bolts should be taken out all around the screens. For access to the bottom bolts, the plywood floor in the corner section near the screen can be removed. The transition to the test section can be put on casters by lowering the test section end down on them, and by first raising the large end, placing a 1 in. steel plate between caster support and caster top plate. For raising the section, hydraulic or automobile jacks should be used. Details of the screens and their supports are shown in Fig. 2.

The transition section is not directly connected to the test section. A 1 in. layer of foam polyethylene is put between them to avoid transmission of mechanical vibrations. The same type of connection is used on the other side of the test section also. Still, some vibration can be felt in the test section if the motor is running. Since the motion of the fan does not seem to contribute to the vibrations, the situation could be improved if the motor is better isolated from the ground and from the wind tunnel duct.

The test section has been provided with steel frames to which plyboard sheets are fastened on top and bottom. The sides have windows of approximately 4 ft x 4 ft area each, as shown in Fig. 3. They can be removed completely by unfastening the catches, taking out the windows and removing the center bar.

The windows have been constructed to fit tightly, to avoid shatter and air leakage around them. Since the coefficient of thermal expansion of the plexiglass is considerably larger than that of the test section materials, at prolonged running of the wind tunnel at high speeds the resulting rise in temperature inside the tunnel will cause the windows to fit so tightly that they cannot be removed. Window size could easily be decreased to overcome this difficulty.

The window panels scratch easily, care should be taken in handling them. For cleaning, detergent water only should be used, never any cleaner with abrasive action, or chemical cleaners like alcohol or mineral spirits.

The carriage supports go through the test section roof into side boxes in which the rails for the carriage wheels and the cables for carriage operation are located. Their lids can be removed, thus permitting access to the longitudinal drive chain, limit switches, etc.

Need may arise for adjusting the rails on which the carriage is traveling. This can be done with an open end wrench which is bent 90^0. The wrench should be inserted from the top, to grip the nuts of the supporting bolts for the carriage rail.

Downstream from the test section, the duct starts expanding at a rate which permits to keep the diameter of the small circular corners constant at 72 in. until the downstream end of the blower. Again, the corners are equipped with turning vanes. These vanes are welded into the corners. For access to the area between the two corners, if ever needed, the center section has to be removed.

Access to most other sections is provided by doors which are located in convenient positions. The downstream end of the screens can be reached through the test section, as can the duct between test section and first small corner. In order to reach the propellor end of the fan, the manhole cover in the second small corner has to be removed, after disconnecting and removing the pitch control unit.

2.2 Power Section

The power section consists of the variable pitch fan, with pitch control unit, and the magnetic clutch variable speed drive. Part of the drive system is shown in Fig. 4. Motor and fan are connected by a poly v-belt over a pulley system. The variable pitch feature in conjunction with the variable speed drive permit exceptionally smooth and stable wind speed control in the wind tunnel from practically zero to maximum speed of 75 mph.

2.2.1 The Fan

The performance of the fan depends on the fan revolutions per minute, the pitch of the fan blades, and the pressure losses in the tunnel, resulting in approximate performance characteristics as shown in Fig. 5. It was found during performance tests that a speed of 75 mph was obtained by using the thirty available HP of the motor at a speed of about 680 rpm. On this basis, the corrected load line - compared with the estimated load line, which is also shown - was drawn. It is evident that the actual pressure losses are approximately 30 percent higher than estimated; a result which is partly due to the fairly large obstruction which the carriage forms in the test section.

Tests showed that the velocity in the test volume of the test section remained constant at maximum possible speed and with optimum pitch setting. Time did not permit to determine an optimum control setting for each test velocity. However, it appeared that pitch adjustment alone permits a very precise setting of test velocities down to a very low value. The main advantage in reducing the rpm of the fan lies therefore in the reduction of fan noise and vibrations, but it is recommended to keep the fan speed well above the minimum needed at optimum pitch, and fine-adjust with the more sensitive pitch control.

The fan is a commercial axivane fan manufactured by the Joy Co. of New Philadelphia, Ohio. Its sixteen streamlined aluminum blades can rotate around their axis in the blower hub, in a manner controlled by the pitch adjust lever. The pitch adjust mechanism and blade arrangement of a similar fan are shown in Figs. 6 and 7.

The fan needs very little maintenance. About every 1/2 year, the bearings should be lubricated with any high speed ball bearing grease, pressed into the externally accessible grease nipples. Lack of lubrication, or use of wrong type of grease, can result in bearing failure.

In order to avoid damage due to overheating of bearings, overheat protecting thermostats are provided. They consist of "switch gear" thermostats operating with an expanding liquid, which causes the switch to open at 90^0 C. They are screwed into the bearing supports and can easily be removed. If a bearing should fail, the opening of the thermostat will cause the power of the fan motor to be shut off, and the appropriate signal to flash on the safety panel.

2. 2. 2 Pitch Control Unit

The pitch control unit is shown in Fig. 8. It consists of the pitch adjust lever and motor driven actuating mechanism. The motor is geared down to approximately 17. 5 rpm. It is operated on three-phase 220 VAC. By interchanging phases the direction of the motor rotation can be reversed.

The motor is connected through a coupling to a heavy screw, on which a nut travels. Rotation of the nut is prevented by a linkage between pitch adjust lever and nut. This linkage permits free movement of lever and nut in the axial direction. On the end of the screw a disc is fastened in a light-tight housing, which operates a counter on the control panel through a light-photo relay arrangement similar to those used in the carriage position indication devices. With five counts per revolution, and with ten threads per inch on the screw, the total distance of the lever travel corresponds to approximately 70 counts on the counter.

Limit switches are provided which prevent over travel of the nut.

2. 2. 3 The Motor

The fan is powered by the drive motor (Fig. 4), a 30 HP, 3600 rpm, 3 ϕ, 220 VAC induction motor, and the Dynaspede variable speed transmission. The original unit had to be adapted to the needs of the wind tunnel by replacing the 15 HP 1750 rpm motor (mentioned in the manufacturers instruction manual) by a 30 HP motor with higher speed so that it could be of same frame size. Therefore, the Dynaspede coupling can never be used fully. If the maximum speed of the fan exceeds a value of about 680 rpm, then the load on the motor, at full fan pitch exceeds the 30 HP capacity and the motor is overloaded. This will cause the motor to heat up, resulting in a slow drift of the Dynaspede's output rpm value. Therefore, if this happens, the maximum speed potentiometer on the Dynaspede control panel should be adjusted.

For operations of short duration the electronic control can be used for obtaining higher speeds than normal by setting the speed control potentiometer higher. This procedure should be used, however, only in conjunction with the use of a power meter in the supply line of the motor. If motor overloading is planned, the manufacturer should be consulted to find the permissible limit.

Another feature of the Dynaspede is the eddy current brake which has been installed in order to prevent the cooling water to act as transmission fluid at low rpm values. Its controls are located near the Dynaspede controls. The cooling water is continuously flowing through the transmission, in an open circuit system. The water supply is regulated by a temperature controlled valve. If not enough water is available, or if the valve fails and the temperature of the water rises above a safe level, then a safety switch is operated, causing the motor to stop and the sign "Dynaspede Cooling" to light up on the safety panel.

No special maintenance except lubrication is needed for the motor. For trouble shooting of the electronic controls consult the manual or the nearest representative of the Eaton Manufacturing Co.

2.2.4 V-belt Connection

Fan and Dynaspede are connected by a poly v-belt drive. The belt does not require any special maintenance. It should be checked occasionally for faulty spots, and the belt tension should be adjusted. This can be done by loosening the motor mounting bolts and tightening the belt with the adjusting screws (see Fig. 4) on the motor stand. The fan belt when tight should neither flap, nor slip, nor squeal. The instructions for the belt care (which are at present hanging on the downstream flange of the blower) should be read for proper procedure.

The remote location of the Dynaspede between the ducts of the wind tunnel make it seem unnecessary to furnish a belt guard. Care should be exercised, however, when approaching the moving belt.

2.3 Carriage

The carriage which is shown in Fig. 9, serves as positioner for instrument probes. It is designed to position the probes, by remote control, anywhere within a test volume of approximately 48 in. length, 34 in. width, and 23 in. height. The instrument probes can be moved on the instrument holder, on a 1/2 in. steel rod welded to a nut traveling on the vertical positioner, so that the test volume can be located almost anywhere within the test section.

Measurements on the positioning systems for all three directions gave counter readings which corresponded to actual distances within the required accuracy of ± .05 in. A typical set of measurements is shown in Table 1.

Table 1. Typical Carriage Read-Out

Transverse		Longitudinal		Vertical	
Count	Length (in.)	Count	Length (in.)	Count	Length (in.)
0000	00.00	0000	00.00	0000	00.00
0900	8.98	0539	5.38	0310	3.09
1426	14.33	1042	10.38	0538	5.38
1911	19.10	1501	15.00	0804	8.09
2412	24.13	2018	20.13	1607	16.12
2829	28.29	2627	26.25	2134	21.34

The fact that in all three cases, all three readings of length are almost identical with the counter readings for the longest distance traveled, shows that deviations between count and distances are probably due to errors in measuring distances rather than due to systematic deviations. Therefore, it appears to be quite adequate to use the count reading as an indication of the length traveled.

The motors for the drives in all three directions are protected against overloading due to carriage overtravel by limit switches at each end of travel. These limit switches are designed to interrupt the current supply to the motors upon closing.

For making possible removal of the carriage, all electrical connections between cables and carriage are made by plugs.

2.3.1 Vertical Travel

The instrument holder travels on a vertical screw of approximately 26 in. length. It is held against rotation by a small carriage traveling on a vertical rectangular steel bar of flat ground stock, as indicated in Fig. 10. Rotation of the vertical screw will result in the motion of the instrument holder, upwards or downwards, depending on the direction of screw rotation. Each revolution of the screw will move the instrument holder a distance of 1/20th of an inch. As can be seen in Fig. 9, a circular disc is fastened to the top of the vertical shaft. This disc has five equally distant holes. A light bulb is mounted in the pipe which forms the vertical support and a photo relay is mounted above the circular disc. Whenever light bulb, disc hole, and photo-relay are in alignment, the relay closes a circuit which operates the magnetic counter on the control panel. Each count of the counter will thus correspond to one-hundredth of an inch of travel of the instrument holder.

The circuit diagram for the wiring of the vertical control is shown in Fig. 10. All the leads are collected into a plug on the back of the vertical positioner, and are guided from there through the rail channels to the junction box. The second plug, located next to the first one, is for hot wire leads. Thermocouple wires are not interrupted to avoid accidental signal distortions.

2.3.2 Transverse Positioner

The vertical positioner is fastened to a nut which travels on a motor driven screw in the streamlined transverse carriage support. It is supported by its own weight, and can be taken off by removing the fastening bolt which connects the pipe of the vertical positioner to the nut of the traversing screw (see Fig. 9). While reconnecting this bolt, care should be taken that it is not tightened more than necessary for holding it in place; otherwise, the nut starts binding on the screw, resulting in stalling of the DC motor of the traversing screw.

Each revolution of the traversing screw makes the nut (on which the vertical positioner is traveling) move by one-twentieth of an inch. A small wheel is provided on one end of the transversing shaft, as indicated schematically in Fig. 11, which is also equipped with five equally distant holes. The only difference between vertical and transverse positioning and indicating device is to be found in the fact that only the photo resistor is mounted on the traverse beam while the relay operated by this photo resistor is located in the control panel.

Figure 11 shows the circuit which has been used for position indication of the transverse drive. The photo cell in the carriage is triggering a Thyratron, which in turn governs the current supply to the counter. In order to avoid missing counts due to a burned out wheat grain light bulb in the light bulb - disc - photo cell - arrangement of the carriage, it is put in series with another light bulb which, through another photo cell and relay, permits the DC motor of the transverse drive to operate only if both light bulbs are working.

2.3.3 Longitudinal Drive

The transverse beam of the carriage hangs on steel supports on each end. These stick through small slots into the side channels of the test section. They are connected to the longitudinal chain drive. The drive for the longitudinal positioning consists of a system of chains connected to a gear motor over four pulleys. Two of these pulleys in the upstream part of the test section are connected to a common shaft to avoid unequal motion of the carriage. The other two pulleys in the downstream section of the test section are connected over a system of gears to a DC motor. The gear system is designed such that: (a) the shaft rotates slowly enough for making the operation of the counter relay possible, and (b) each count of the counter corresponds to approximately one-hundredth of one inch. For this purpose, the gear box between counter activating disc and chain driving pulley serves to gear down the shaft rotation at a ratio of 1:200, because each revolution of the pulley corresponds to five inches of travel of the carriage, and five holes have been provided in the counter activating disc. The control circuit is shown in Fig. 12, and is identical to that for the vertical positioner.

During the performance test the experience has been made that the carriage occasionally traveled unevenly. This was found to be due in all instances to the fact that the set screws which clamp the pulleys to the shaft or which clamp the gears of the gear boxes to the drive or idler shaft, had not been adequately tightened.

2.4 Safety Features

Measures have been taken to prevent excessive damage in case of fire and to protect motor and fan against damage due to mechanical failures, and to protect personnel working in or with the tunnel.

A fire starting in the wind tunnel will be prevented from spreading too rapidly by the fire retarding properties of the paint with which the wind tunnel ducts are covered. The paint that has been used is made by the Albi Manufacturing Company. The steel has been primed with an outside oil base paint. All primed surfaces have been painted with Albi 107A paint. If need arises for repainting any part of the surfaces, then the same type of paint should be used to prevent wrinkling of the paint.

For warning against fire, over-temperature sensors are provided in two places in the duct. They are Johnson type hot water controls. One sensor is located just downstream from the test section. The other one is placed near the entrance to the first large corner, downstream from the blower. The sensors operate thermostatically controlled switches which are normally closed, and, in case of fire, close a circuit which cuts off the main power to the drive motor while at the same time switching on the appropriate light on the safety panel. The remote location of the building and the relatively low fire hazard of the wind tunnel operation make it appear unnecessary to provide an audible alarm. However, an outlet has been provided in the safety panel to connect an electrically operated warning bell or horn.

The fan is protected against damage due to bearing failure by bearing thermostats, as mentioned in section 2. 2. 1. A similar device prevents the cooling water of the Dynaspede from overheating.

For protection of personnel working in or with the wind tunnel, care should be taken that all the electric power switches are turned off after the wind tunnel has been used, or before any modification of the control panel or the carriage circuits are made. It is also recommended that nobody enters the wind tunnel test section when the fan is operating.

At the turning vanes in the corner downstream from the test section a screen has been provided. This screen is intended to prevent objects from being sucked into the fan.

3. THE CONTROL PANEL

The control panel is located rather arbitrarily near the upstream end of the test section. For convenience of working inside or before the test section, and for improving the looks of the arrangement, it should be considered to move the control panel somewhat to the west.

3.1 Description of Panel

The panel, which is shown in Fig. 13, consists of four racks which are about 5 ft 6 in. high. Into each rack have been grouped controls and instruments of similar or related functions.

The rack furthest to the left contains the drive control for the motor and the carriage. The top panel contains the carriage control. On its bottom, two switches are provided for switching on the AC power and the DC power. The AC power is supplying mainly the pilot lights, and therefore is to be left on at all times. The DC power switch is for supplying the motors. It should be switched on before anyone of the three carriage drives is used. The controls for the three individual DC motors of the carriages are grouped above the main power switches. They are essentially alike. Each contains the selection switch with three positions, for two directions and off position in the center. The two pilot lights adjacent to the switch are indicating the functioning of the limit switches. Whenever a limit switch has been hit, the appropriate light lights up. The top pilot light indicates which panel is in operation. The counters which indicate the position of the instrument, are arranged above the top pilot light.

Below the carriage control, the carriage drive is arranged. This essentially consists of a large variac which regulates the voltage to the motors of the carriage.

The third panel (from the top) contains the fan speed control and speed indication. It has in it, the push button station and speed control rheostat for the fan speed control, the DC meter for indicating the motor speed, and the counter and its controls for indicating the pitch position.

Also in this rack are the 6 VDC power supply used for filament voltage on the pre-amplifier for the velocity indication system; and, in the bottom part of the rack, a drawer for the instruction manuals.

In the second rack from the left, read-out instruments are placed. The top panel, which is not used at present, provides a space for a recorder, which might be useful at a later date for continuous recordings of wind tunnel or instrument characteristics. Underneath this, an oscillator is placed which gives sine wave signals from 6 to 6,000 cycles to be used for monitoring purposes.

Below the oscillator, the Waterman Rak-scope is arranged. This scope essentially serves for monitoring purposes. The input to it from different sources is selected in the panel underneath it. This panel has a selection switch, with twelve positions, and screw driver controlled attenuation potentiometers in series with each switch position. Only five of these input selection potentiometers have been provided in the panel.

The third rack contains essentially the velocity measuring circuitry and its accessories. The safety panel with its five positions is located on top. Underneath that, we find the power supply which furnishes a current of up to 1 amp at a regulated DC voltage of approximately 28 - 30 volts. This is used for the hot wires, whose controls are located below the power supply.

In the velocity control panel circuits and controls for the mean velocity hot wire, and for the velocity indicating hot wires are located. The top left part of the panel contains a small DC ammeter and rheostats for controlling the current in velocity indicating hot wires, and a pilot light indicating the proper functioning of the circuit.

The group of controls on the lower left consists of current control rheostats, pilot light, and range selection switch for the mean velocity hot wires. On the right side of the panel the adjustable arms of the mean velocity hot wire bridge are located, with the power switch of the panel on the bottom.

The precision read-out for the mean velocity hot wire bridge is placed in the drawer underneath the hot wire control panel. The front of this drawer shows the switch for the galvanometer and the galvanometer's sensitivity control potentiometer, as well as the fuse for the DC milliammeter. Inside the drawer a General Electric type DP-9 DC milliammeter is located and the galvanometer for the mean velocity hot wire bridge.

In the rack furthest to the right, the manometer and its controls have been arranged. The drawer underneath the manometer contains the potentiometer for measuring thermocouple emf and the thermocouple selection switch.

3.2 Cabling and Wiring Diagrams

For convenience of maintenance and trouble shooting, a number of wiring diagrams are prepared, which are placed in the back folder on the rear cover. Plan 1 contains information on all the cabling between control panel and carriage and other location. Plan 2 presents the internal connections of the panel. Plan 3 shows the wiring of the pitch and drive control as well as that of the safety panel. Plan 4 contains the circuit of the carriage control. Plan 5 gives the circuits and controls for the mean.

3.2.1 Cables to Junction Box

Two large cables lead from the control panel to the junction box. Each one has approximately 50 leads. Pins and cables leading to them are correlated in Plans 1 and 2. The cables are furnished to facilitate moving of the control panel and to permit convenient repairs inside the panel or convenient trouble shooting. In the junction box, the main cables are split up into separate smaller ones. Eight smaller cables go from the junction box to the carriage, the pitch control unit, and the safety devices. They are clearly indicated on the main cabling diagram (Plan 1) and reference to each of these cables has also been made in the wiring diagram for the individual control circuit.

3.2.2 Junction Box

The junction box, besides serving as a convenient place to separate the main cable into smaller ones, serves also as relay station for the selection of a low velocity indicating hot wire, and as location for the preamplifier of the velocity indication circuit (which must be close to the carriage and the signal source, for avoiding pick up of random noise).

The junction box serves also as connector station for the manometer tubing. Whenever manometer tubings should be replaced or interchanged, then it is necessary only to connnect a new piece of tubing or to interchange tubes between carriage and junction box.

The junction box has been constructed with removable front panel and top panel. The cable connectors are shielded by a sheet-metal box.

3.3 Drive Control

Three different types of drive control are provided, for the fan, the fan pitch, and for the carriage. Also included in the drive controls are the indication systems for fan speed and carriage position.

3.3.1 Speed Control Station

The push button station for the motor of the fan is located on the left side of the control panel. The push button station for the Dynaspede coupling is located on the drive control panel. It has a potentiometer knob above the stop button through which the speed of the fan can be controlled. For the details of the control section for the Dynaspede reference is made to the instruction manual of the Eaton Manufacturing Co.

Two different systems are available for indicating the speed of the fan. The one consists of a DC meter showing the voltage of the Dynaspede's governing tacho-generator. According to information received from the manufacturer before delivery of the Dynaspede, this generator was supposed to produce a DC signal. When the signal was tested it was found to be AC. Therefore, a rectifier had to be introduced for using the DC volt meter. This circuit is shown in Fig. 14.

Figure 14 also shows the second speed indicating device. This consists of a small AC generator which has been connected through a piece of rubber tubing to the back end of the fan shaft. The AC generator (a simple bicycle generator) generates two cycles of a sine wave per fan revolution. This signal is fed into the vertical channel of the oscilloscope through the oscilloscope input selection panel. On the oscilloscope screen it is matched against the output from the audio-oscillator. A steady ellipse on the oscilloscope screen indicates that oscillator signal and generator input are of equal frequency. The adequacy of the performance of the wind tunnel drive can be judged from the fact that this signal remains remarkably steady on the oscilloscope screen.

3.3.2 Pitch Control Circuit

The circuit of the pitch control unit is shown in Fig. 15. It is complicated by the fact that the limit switches have to control all three phases simultaneously without permitting the possibility of an accidental short across two phases. This is accomplished by a relay arrangement as shown in Fig. 15.

The pitch position indicating counter can only be used qualitatively because no protection has been provided against over travel. Whenever the current to the pitch control motor is shut off, the lamp activating the photo relay is shut off also, thus the relay does not operate during the time while the motor is coasting to a stop. This will result in a loss of counts whenever the pitch control unit is stopped.

3.3.3 Carriage Drive

The indicating circuits for all three carriage positions have already been discussed in Chapter 2.3. All relays and the read-out counters are located in the carriage control panel. A variable potentiometer has been provided in the back of the carriage control panel which controls the bias voltage for the Thyratron. This potentiometer should always be adjusted to optimal position which is indicated by precise functioning of the transverse drive position indicating counter.

The drive control circuits are detailed in Plan 4. Besides drive circuit and position indication they contain the circuits which protect the DC motors, and the circuits which prevent the counters from missing counts.

These operations essentially are tied to the handling of the variable voltage transformer knob. Before carriage drive circuits can be activated the carriage control knob must be turned to zero position. This operates a micro-switch which will close through a relay, the armature circuit. This prevents overload of the armature while the motor field circuit is open. A mechanical stop has been provided on the variable voltage transformer which prevents the three motors from running faster than the counters can follow.

A source for inaccuracies in position indicating counts lies in the arrangement of lamp, counting wheel, and photo resistors. If the current supplying lamp and photo resistor is interrupted while lamp, relay, and hole of counting wheel are in alignment, then an extra count is obtained when the circuit is re-energized. A relay system has been provided in each one of the indicating circuits to prevent this. However, these relays cease to function properly if the voltage supplied to the carriage motors is too low. It is always necessary after stopping the carriage in one position to turn the voltage control knob on the carriage drive control panel to maximum voltage. This will cause the DC motors to continue operation until the path between light and photo resistor is interrupted, so that the carriage will always stop in such a position.

The power supply to the carriage DC motors is obtained by rectification. The voltage level is adjusted before rectification by a variable voltage transformer. This has been included to avoid excessive heating in the panel by the power dissipated in a rheostat. The details of the drive control circuit are shown in Fig. 16.

3.4 Oscilloscope and Oscillator

Oscilloscope and audio-oscillator are described in the manufacturer's instruction manual. Their functions are described elsewhere.

3.5 Safety Panel

Figure 17 shows the safety devices and their circuits. The sensors have been described elsewhere. They operate relays which cut off the main power in case of danger and which are located on the drive control chassis. From them connections lead to the safety panel where in the case of bearing failure or fire the respective lights indicate the reason for shutting off of the main power. The circuits and all the connections for safety panel and safety devices are shown in Plan 3.

3.6 Velocity Measuring Controls

3.6.1 Control Selection

A selection switch has been provided on the hot wire control panel to select appropriate hot wires and for either mean velocity measurements or for low velocity indication. This switch has multiple decks to make possible all the necessary switching procedures.

3.6.2 Mean Velocity Bridge

The bridge used for measuring mean velocity in hot wires is shown in the circuit diagram of the hot wire control panel in Plan 5. A block diagram of the bridge is shown for convenient reference in Fig. 18.

The two low current branches of the bridge are made adjustable. The branch opposite the hot wire contains two helipots of each 500 ohms. These helipots have a dial which is graduated in 1,000 divisions. Each two divisions, therefore, correspond to one ohm. The second low current branch is formed by a decade resistance which serves for balancing the bridge initially.

The other two branches of the bridge are self-explanatory. The whole bridge has been designed to give satisfactory operation for hot wires of .001 inch diameter, made from platinum. However, other materials and other sizes can be used, and the bridge is sufficiently flexible to accommodate them.

The current through the bridge is adjusted by two rheostats in the return wires. It is measured by the precision General Electric DP-9 milliammeter. For obtaining maximum precision of current reading different meter ranges are provided which are selected by using the range selection switch. Operating the range selection switch does two things: it puts a series resistance into the return line from the bridge so that the current can never exceed the maximum safe output of the power supply, or exceed the meter scale. It also shunts the meter, thus permitting the measurements of different currents on the same meter scale.

The bridge balance is determined with a Leeds Northrup type 2340 - D DC pointer galvanometer. This galvanometer has a sensitivity of .1 micro amps per scale division. This high sensitivity may make it difficult in many instances to read the signal accurately, since the needle goes off scale. Therefore, a sensitivity adjustment shunt potentiometer has been provided. Care should be taken to avoid overloading of the galvanometer under all circumstances. This can be done by always leaving the galvanometer at the lowest sensitivity position, and also by always switching the galvanometer off (which shorts out the galvanometer) if it is not needed, or if the needle goes off scale.

3.6.3 Low Velocity Indicating Circuit

The low velocity indicating circuit is shown in Fig. 19. Two hot wires are provided for indicating purposes. A relay has been provided in the junction box which makes it possible to switch from one hot wire to the other without increasing the length of the leads. The signal from the hot wires is supplied to the preamplifier inside the junction box and in amplified condition to the scope selection box and from there into the oscilloscope, where it is matched against the output of the oscillator.

The current for the low velocity indicating hot wires is provided from the same AB 128 DC power supply which is used for mean velocity hot wires. However, the current adjusting circuit and the current read-out circuits are different. The reason for having different current control circuits is to permit changing from low velocity indication to mean velocity measurement, which is needed mainly for calibrating hot wires at low velocities, without readjusting currents.

The preamplifier is operated on batteries to keep noise at a low level. The bias batteries are located on the hot wire control chassis. For filament heating, a separate 6.3 V power supply is furnished, which is located in the drive control rack.

The circuit shown in Fig. 19 may not reflect recent changes.

3.7 The Manometer

The manometer which is used for measuring pressures and velocities is a Meriam Micromanometer Model 34 FB2. The principles of its operation have been described in Ref. 1. The manometer can be read accurately to 1/1000 of an inch of water; however, no accuracy can be gained by interpolation of the manufacturer's scale. Reference 1 contains a figure which shows the percentage errors which can be made in measuring velocities if readings are accurate to 1/1000 in.

The liquid used for the micromanometer is Meriam indicating fluid concentrate specification number D-2930. It has a specific gravity of 1.000 compared with water at 4^0 C. Its characteristics are identical to that of water so that its properties can be determined from handbooks.

3.7.1 Manometer Input Selection

The manometer input selection panel contains six three-way stop cocks, which are made out of precision ground glass. Care should be taken that the stop cock is always greased properly. However, if too much grease is applied, then there is danger that the grease plugs the holes in the stop cock. Therefore, at regular intervals all stop cock holes should be cleaned out.

The valves are connected at present as shown in Fig. 20. If need arises for changing manometer leads these changes should be made on the junction box.

4. THE INSTRUMENTATION

4.1 Velocity Measurements: Mean Values

The wind tunnel is equipped with three different velocity measuring - devices, a Prandtl tube with manometer, a hot wire probe with Wheatstone bridge, and an eddy shedding device. The Prandtl tube is the more reliable instrument for high velocites. Its drawbacks are, however, its large physical size, the generally slow response, and the difficulty to use recorders for continuous operation. In contrast to this, the hot wire is well suited for use in large gradient type flow, because of its smaller size. It can easily be adapted to produce continuous records, through electrical recorders. Its drawbacks are the frequent need for recalibration, wire breakage, and possibly the need for changing wires for changes in velocity ranges. It is, therefore, recommended to employ the hot wire technique for measuring mean velocities only when the Prandtl tube, for some of the reasons mentioned, cannot be used.

Due to the difficulty in handling it, the eddy shedding device is intended to be used exclusively as a low velocity standard.

4.1.1 Velocity Measurement with Eddy Shedding Device

For indicating low velocities (from 1/2 mph to about 20 mph) the observed fact is used that a cylinder immersed in an air flow sheds periodic eddies. The frequency at which these eddies are released into the air stream depends upon the wire diameter, the flow viscosity, and the velocity of the air stream, according to the experimental relation (see Ref. 2).

$$\frac{nd^2}{\gamma} = 0.212\, R_e - 4.5 \qquad (1)$$

where

R_e = Reynolds number $\frac{Ud}{\gamma}$

n = frequency (1/sec)

U = velocity (fps)

d = diameter of wire (ft) .

This relation is valid for a range of Reynolds numbers from 50 to 150. In order to cover the range of velocities from 1/2 mph to 10 mph with overlap between wire sizes, four different wires should be used for eddy shedding cylinders. The ranges of their use have been indicated in Table 2. Their approximate characteristics are shown in Fig. 21.

Table 2. Eddy Shedding: Calculated Frequency vs Velocity

d (in.)	ν (ft²/sec)	$\frac{Ud}{\nu}$	U (fps)	U (mph)	n (1/sec)
1/8	$1.62 \cdot 10^{-4}$	50	0.78	0.53	9.1
1/8	$1.62 \cdot 10^{-4}$	150	2.34	1.60	41
1/16	$1.62 \cdot 10^{-4}$	50	1.56	1.06	36.3
1/16	$1.62 \cdot 10^{-4}$	150	4.68	3.14	161
1/32	$1.62 \cdot 10^{-4}$	50	3.12	2.12	146
1/32	$1.62 \cdot 10^{-4}$	150	9.37	6.38	656
1/50	$1.62 \cdot 10^{-4}$	50	4.89	3.33	356
1/50	$1.62 \cdot 10^{-4}$	150	14.60	9.95	1592

The frequency of the eddy shedding is measured by picking up the periodic velocity fluctuations with a hot wire anemometer mounted in the wake of the cylinder. The voltage across the hot wire will vary according to the velocity fluctuations from about 0.1 millivolt to 10 millivolts. It is fed through a preamplifier into the vertical deflection beam of the oscilloscope. By establishing an ellipse on the screen of the oscilloscope, the frequency of the signal is matched against the output of the oscillator, and thus, determined.

The method has the advantage of being independent of the changes in hot wire characteristics, so that only one calibration of the cylinders suffices for all times. The calibration of the thinnest cylinder should present no problem, since the frequencies can be compared against velocities measured with the Pitot tube. For other sizes, the procedure used in Ref. 2 consists of assuming the linear relationship Eq. 1 to hold, and extrapolating the characteristics downward, through continuous wire ranges which overlap. This method cannot be accepted with full confidence for the very low velocities which are of interest in the application of the wind instrument test facility. Therefore, a low velocity standard of different design will be made available which is in the process of development at Colorado State University. Pitot tube and low velocity standard should be used to calibrate all wires, over the whole range of velocities, and over the whole range of temperatures encountered in the facility.

Operation of Eddy Shedding Device:

1. Make hot wire for indicating probe, and place it behind the desired cylinder on the indicating stand. The hot wire should be parallel to the cylinder, and in the horizontal plane which passes through the upper edge of the cylinder, at a distance of about 6 cylinder diameters downstream from the cylinder axis. Small displacements may be necessary for finding position of maximum sensitivity.

2. Switch hot wire selector switch to desired indicator position. Switch oscilloscope input selector switch to desired position.

3. Display the signal from the hot wire on the oscilloscope screen (with horizontal deflection on sweep). Slowly increase current through wire, with current increase on hot wire control panel, until signal becomes most pronounced. (For 0.001 in. platinum wire in air flow of about 1 mph, a current of about 350 milliamperes is not too high.) Be careful not to burn the wire. If the wire is properly adjusted, the eddy shedding frequencies can actually be observed in the changes of color which the wire undergoes.

4. Switch horizontal scope input to oscillator, establish ellipse on screen.

5. Read frequency off oscillator dial, use it to find velocity from calibration chart for the temperature and cylinder size used.

6. To prevent burn out of hot wire, make sure to reduce current in indicating circuit before decreasing velocities or stopping fan.

4.1.2 Velocity Measurement with Prandtl Tube

The velocity measurement with a Prandtl tube is based on the application of Bernoulli's energy principle for ideal fluids, which states that along a stream line the total energy H remains constant, or

$$\rho_a \frac{v_1^2}{2} + p_1 = \rho_a \frac{v_2^2}{2} + p_2 \qquad (1)$$

where x_1 and x_2 are any two points on the stream line, at which the pressures are p_1 and p_2, and the velocities v_1 and v_2 respectively. If the flow at point 2 is completely stopped, as at the stagnation point of a Prandtl tube (see Ref. 3), then the equation reduces to

$$\rho_a \frac{v_1^2}{2} = p_2 - p_1 \qquad (2)$$

The Prandtl tube is so designed that the static pressure p_1 is measured through a number of holes in the outer shell, so that the measured pressure difference is exactly given by equation 2. This pressure difference gives rise to a difference Δh in liquid level in the two arms of a manometer which is therefore a measure of the velocity. The velocity can be computed from the relation:

$$\rho_a \frac{v^2}{2} = \gamma_w \cdot \Delta h \quad \text{or} \quad v = \sqrt{\frac{2\gamma_w \cdot \Delta h}{\rho_a}} \qquad (3)$$

where γ_w is the specific weight of the manometer liquid. This equation has been evaluated for different atmospheric pressures and different temperatures in Fig. 22. For convenience in presentation, the factor $\frac{v}{\sqrt{\Delta h}}$ is shown as function of temperature, with pressure as third variable. The calculations are based on air temperatures as stated, with the temperature of the manometer liquid assumed at a constant of 68^0 F. Reference 4 has been used for determining air and water densities. It should be noted that γ_w changes very little in the range from 40^0 F to 80^0 F, so that within this range no additional corrections are needed.

Included in the factor $\frac{v}{\sqrt{\Delta h}}$ are conversion units which will result in the dimension ft/sec for v if the dimension inch is used for Δh; so that the manometer differential reading can directly be used for computing the velocity.

Measurements obtained with a Pitot-static or Prandtl tube are among the most reliable mean velocity data that can be taken. The data ceases to be accurate, however, if high intensity turbulence exists in the flow. An extensive discussion of the influence of turbulence on readings of Pitot tubes (or Prandtl tubes) can be found in Ref. 5. The flow around Pitot tubes is discussed in Ref. 6.

Instead of using a Pitot-static tube, a Pitot tube can be used in conjunction with a wall piezometer. Since the pressure in a section perpendicular to the flow direction remains constant, it is in this case possible to move only the Pitot probe, which then can be made much finer, thus, permitting more accurate velocity measurements, especially in flows with large velocity gradients. Shape and location of piezometer holes will, however, influence the readings to some extent, so that a well constructed Prandtl tube is to be preferred.

Example of velocity measurement - Measurements have given the following results:

Air temperature: 100° F   Manometer temperature: 60° F

Manometer Readings (in.)	Valve Position High	Valve Position Low
0.022	Outside 1	Outside 2
2.987	Pitot tube 1	Static Pitot 1
Barometric Pressure: 660 mm H_g		

These readings show that the zero is slightly displaced to the high side, so that all measurements have to be reduced by 0.022, with the result

$$\Delta h = 2.987 - 0.022 = 2.965$$

For a temperature of 60° F, no correction is necessary for the density of the manometer liquid. From Fig. 22 one finds for a barometric pressure of 660 mm H_g at $T = 100^0$ F: $\frac{v}{\sqrt{\Delta h}} = 72.5$, so that

$$v = 72.5 \cdot \sqrt{2.965} = 125.0 \text{ fps}$$

4.1.3 Velocity Measurement with Hot Wires

The hot-wire method operates on the fact that the heat transfer from a heated cylinder to a cool air stream depends on the velocity of the air. The relation between the current necessary to maintain the wire at constant temperature and the velocity of flow is expressed analytically by King's equation (for references see Appendix 2):

$$I^2R = (C_1 + C_2\sqrt{v})\ (T_W - T_A)$$

where

I = current through hot wire

R = wire resistance

T_W = wire temperature

T_A = temperature of ambient air.

By keeping the wire temperature constant, and thus, also the wire resistance, the velocity varies at constant air temperature with I only. The relation between I and v is determined experimentally by means of a wire calibration. The measured quantities are the currents necessary to maintain the wire resistance at a constant value. The measurements are made by placing the hot wire into one arm of a Wheatstone bridge and balancing the bridge for different air velocities by adjusting the current through the bridge.

Temperature compensation is needed only if the air temperature at which the hot wire has been calibrated is different from the air temperature at which the tunnel is operated. This situation may arise after prolonged running of the wind tunnel, or during the testing of heated models. The method of compensation is described in Appendix 2.

Compensation for lead resistance is necessary whenever the resistance of the lead used for calibration is different from that of the lead used for testing. The method of compensation consists simply of rebalancing the bridge, after hot wire calibration and exchanging of leads by using only the lead resistance helipot.

The decade resistor is used for balancing the bridge at zero velocity. It also compensates for small differences in wire characteristics or probe resistances.

Of importance is the current which flows through the hot wire at zero velocity, for it determines the wire resistance and wire temperature. Generally, the wire sensitivity increases with lowering of the temperature. However, at low temperatures the response of the wire to small temperature changes becomes more pronounced, and a compromise is required. Experience at Colorado State University led to choosing $\sim$ 150 MA zero currents for platinum hot wires of 0.001 in. diameter. It is recommended to investigate the most suitable zero currents for the velocity range of this wind tunnel.

The meter range switch, in its present arrangement, provides a total of four ranges for the meter. In their maximum positions, that is, with the current adjustment rheostats set at minimum resistance, they permit use of the following total currents:

Range 1: Full scale of MA meter approximately equal to 950 MA
Range 2: Full scale of MA meter approximately equal to 700 MA
Range 3: Full scale of MA meter approximately equal to 520 MA
Range 4: Full scale of MA meter approximately equal to 300 MA

Other ranges can be obtained by changing or adding current limiting resistors, and by adjusting the meter range shunts. It should be possible to do most of the testing in ranges 3 and 4, as long as 0.001 in. platinum wire is used.

Based on the design of the hot wire bridge and experience at Colorado State University the following procedure of hot wire operation is recommended.

Procedure for Making Hot Wires

1. By using the stand provided, align hot wire and hot wire probe. Make sure that wire touches prongs.

2. Place clean soldering iron tip against point of contact between platinum wire and carefully solder coated prongs. Dip fine coreless solder into flux (Borax or other flux suitable for soldering steel to platinum) and touch prong with it. Wait till it melts and covers prong and wire.

3. Cut off wire on both ends, remove excess length by bending it back and forth (it will break at the joint).

4. Remove all indications of dirt or grease which can be seen with the microscope by wiping the wire with a thread dipped in nitric acid. Clean off excess acid with water.

5. Place hot wire in hot wire holder of carriage, and run enough current through it (see procedure below) to make it glow at a dull red (about 250 MA on power supply). Leave it for about 3 minutes.

6. Cut off current and inspect wire. If wire has a bend, carefully straighten it again by spreading the prongs with the spread screw.

7. Replace cap on hot wire probe.

Procedure for Setting the Bridge

1. Prepare bridge by setting lead resistance and temperature compensation Helipots each at 500, and decade box at about 2000 ohms.

2. Make sure that galvanometer switch is in 'off' position, and hot wire selection switch in 'disconnect' position.

3. Set current adjustement rheostats to lowest current position, and switch meter range switch to desired range.

4. Start AC power, set power supply at 30 v.

5. Switch selection switch to desired hot wire.

6. Set meter at approximately 150 MA by adjusting meter adjustment rheostats.

7. Switch on galvanometer and balance bridge with the decade resistor.

8. Switch off galvanometer.

Procedure for Calibrating Hot Wire

1. Remove hot wire cap and push back probe tube.

2. Set mean wind speed at desired value as determined by velocity indication system.

3. Switch on galvanometer thereby use maximum suitable sensitivity of galvanometer and adjust current until bridge balances. Record the temperature.

4. If balancing at range 4 of meter is not possible, change meter range and try again to adjust bridge.

5. Record I and v values and repeat procedure for full velocity range desired, by using range 4 for low speeds, and others as required for high speeds, with overlap in ranges.

6. Return to meter range 4 and setting of 150 MA. Replace cap and determine whether bridge balances. If it does, the calibration is completed. If it does not, either the preheating current has been too low or the wire has suffered some damage, due to overheating current during tests, or bending of wire.

7. Plot I^2 vs v . This is the desired calibration curve.

Procedure for Velocity Measurement

The same procedure is used for both measurement of velocity and for hot wire calibration. However, instead of determining v directly, the calibration curve is used to find v for a known I . Care should be taken to compensate for lead resistance and temperature differences, if necessary.

4.2 Velocity Measurements: Turbulent Quantities

For measuring turbulent quantities, a model IIHR, Type 3A hot-wire anemometer has been furnished which was manufactured by the Hubbard Instrument Company of Iowa City, Iowa. This instrument permits the measurement, with a single wire, of the root mean square of the velocity fluctuation in the direction of the mean velocity, as well as with cross wires and two channels of the bridge of the root mean square values of the fluctuation in the direction of the mean flow and in the direction perpendicular to the mean flow, and of the root mean square of the product of fluctuating velocities in the direction of the mean flow and perpendicular to the direction of the mean flow. The principle of operation as well as the calibration procedures for the electronic circuitry have been described in the operation manual for this hot-wire anemometer. However, since publication of the operating manual, a few modifications on the circuits have been made mainly on the rms-analyzer. The circuit for the new rms-analyzer has been appended to the operating manual. The calibration procedure for the rms-analyzer is described below.

In addition, the operating procedure for the use of crossed wires is described which supplements the operating instructions given in the operating manual. Also given are instructions on the fabrication of hot-wire probes.

4.2.1 Calibration Procedures for New rms-Analyzer

1. DC Bal control potentiometer on rms-analyzer chassis should be adjusted to give zero DC through panel meter. With selector switch set to OFF, adjust the DC Bal until panel meter reads zero.

2. To check gain, press CAL switch: Meter should read full scale with multiplier at 1. If reading is not full scale, adjust with GAIN control on chassis.

3. BAL control is for use in balancing the phase inverter output to exactly equal to in-phase signal. To adjust, set SELECTOR at B, press CAL switch, and observe meter. If reading is not zero, adjust to zero with BAL pot.

4. To adjust CAL, refer to p. 28 in manual. (This hardly ever needs adjusting. Mainly when the OA2 or the 12AL5 is changed.)

4.2.2 Fabrication of Probes

The taking of turbulent data requires the utmost care and depends largely on the precision with which wire probes are made; therefore, an outline will be given of the method which has given probes of good quality.

A. Wire Material

It is advisable to use tungsten wires for hot-wire material since tungsten has a higher tensile strength than platinum and thus will last longer. The better durability is paid for, however, with some disadvantages. Tungsten wire cannot be copper-plated and has less sensitivity than platinum wire. To overcome the first disadvantage, it is recommended to order from the Sigmund Cohn Company tungsten wire of approximately .00014 in. diameter which has been etched to a resistance of approximately 2,800 ohms per foot, and then flash plated with platinum to increase the weight by about 10 percent. This procedure will result in a platinum covered wire which has a final resistance of approximately 2,200 ohms per foot.

B. Copper Plating of Platinum Tungsten Wire

Before the tungsten wire is used, it has to be copper plated. This serves a double purpose. The copper-plated wire can be handled much easier without danger of breaking it. Also, the copper coating permits to etch out a piece of the tungsten wire of precise dimensions as required for the use of the hot-wire anemometer.

The plating solution can be made with copper sulfate crystals as follows:

94 grams $CuSO_4 + 5\,H_20$

16 cc concentrated H_2S0_4

500 cc distilled water

Plating is accomplished by immersing the wire in this solution and passing approximately 100 microamperes per inch from the wire to the solution for five hours. Use a copper wire for the positive electrode in this process, and limit the current by an external resistor. Avoid touching or otherwise contaminating the portion to be plated, and if necessary, clean the wire in sulfuric acid just before plating. At the end of the plating procedure, the wire should be cleaned by reversing the current direction for a short time.

C. Soldering of Wires to Prongs

Wires are fastened to the tips of the probes with soft solder and electronic-type resin flux such as Kester Resin Five. Prepare the prongs just as those for mean velocity hot wires. Before soldering the wires to the prongs, make sure that the wire is straight and, in the case of crossed wires, that the wires are perpendicular to each other. Any initial stresses due to bending may result, after etching, in a crooked wire. It is, therefore, recommended to simply place a small piece of wire across the prongs and, with a hot soldering iron, touch the solder plated prongs until the wire is bonded to it. This should be assured by checking carefully under the microscope. The copper plating is left on the wire until the probe is ready to use.

D. Etching Procedure

Before use of the wire, the copper plating has to be removed by etching the wire with nitric acid. This has to be done in agreement with steps 7 and 8 of the operating procedure outlined in the instruction manual on page 22.

There is no standard technique for etching the copper away from the central portion of the wire, but the following method has been found to give excellent results: make a small brush by drawing out a small (4 mm) glass tube to a nozzle form in a flame. Insert a cotton thread (No. 50) in this tube to complete the brush. Drop a few drops of concentrated nitric acid with a pipette from above into the tube. The acid is held by capillary action, feeding out as it is used up. With practice, this brush can be used to etch and precise-control the active length of the wire. Be sure to etch on both sides of the wire for best results.

The etched wire should be inspected under the microscope before put into use. For crossed wires, both wires should be etched to the same resistance and both wires should be checked to make sure that they are straight and perpendicular. If the wires are not perpendicular, they can still be used, provided that corrections are used in the computing of turbulent quantities.

4.2.3 Operating Procedures

The operating procedure for the hot-wire anemometer is outlined in the operating manual. Based on experience at Colorado State University it appears to be desirable to modify the procedure for crossed wires as follows:

1. Follow procedure of instruction manual until step 7. Set resistance control to 5 on both panels.

2. Etch the wires under microscope observations. Try to etch both wires so that the galvanometer balances at the same resistance (about 5 ohms). Make sure by microscope inspection that both wires are straight and perpendicular. If they are not perpendicular, correction factors in the computing formulas have to be used.

3. Set resistance controls to 1.8 times value for resistance at which galvanometer balances. Turn operation switch to 0 and wait 5 minutes. This serves for overheating the wire and stabilizing it. Then reduce overheating ratio to about 1.6 (which is a fairly stable ratio, and which usually corresponds to a resistance value of 8 ohms).

4. Wait about 30 minutes until meter set readings stop drifting. The initial meter set reading should be approximately 0.5.

5. Turn wire No. 1 perpendicular to maximum velocity air stream and adjust the METER SET to obtain full scale reading on panel meter. Then turn wire No. 2 perpendicular to air stream and adjust the meter set reading to make both panels equal. Repeat the process a few times. If the wires remain stable, lock the Helipots in their position and note the readings.

6. With the air stream still at maximum velocity, place the X-wire probe parallel to the flow direction. Rotate the X-wires in their plane slightly until equal readings are obtained on both wires. This indicates the angles between air velocity direction and both wires are equal.

7. Change the flow velocity gradually from a high to a low speed. Plot the relationship of velocity vs current in both channels. For good wires the straight line of velocity vs current should have the same slope for both wires and both channels. For each velocity obtain the signal from wire 1 in both channel 1 and 2, and also the signal from wire 2 in both channels*. The plots of I vs U of each wire should not be much different for each of the channels. If it is, then the channels have to be readjusted. (Consult operating manual.) If both panels agree for one wire, then the slope of the I vs U lines for both wires must be compared. The two slopes should be identical. If this is not the case, then they should be made identical by trial and error by changing the over-heating ratio slightly for one wire.

8. For the remaining steps, use the instruction manual.

9. The meter reading at low velocity gives a convenient check of the stability of the wire. After each run this velocity should be checked to make sure that the wire characteristics have not changed. If changes have occurred, then the wire should be recalibrated. As a matter of routine, the wires should be calibrated once every day.

4.3 Velocity Measurements: Flow Direction

Velocity directions are determined with spherical yaw probes. The probe consists of a semisphere into which two holes have been drilled perpendicular to each other. One of the holes is connected to the high pressure side of

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*This requires turning around the amphenol connector between hot-wire cable and instrument. This is only possible if the key on the amphenol socket has been filed off.

the manometer, the other one to its low pressure tap. The principle of operation is as follows (Ref. 7):

If the yaw probe is placed exactly parallel to the flow direction into a zone where the flow velocity is uniform, so that the flow pattern around the semisphere is symmetric with respect to the holes, then the pressures measured on both taps are equal. Consequently, the manometer is balanced at zero reading. Conversely, if the manometer is balanced, then the yaw probe is placed parallel to the direction of flow. If, on the other hand, the yaw probe is inclined under an angle to the direction of flow, then the manometer will be unbalanced. The manometer reading will be the larger, the larger the angle of inclination is between flow direction and yaw probe. Therefore, the difference in manometer readings Δh is a measure of the deviation of yaw probe direction from flow direction, and if the former is known the latter can be determined from a calibration curve. One calibration curve can be used for measurements if the reading is made dimensionless with the reading Δh_{st} for local stagnation pressure by plotting

$$\frac{\Delta h}{\Delta h_{st}} = f\text{ (yaw angle)}$$

It should be noted that the yaw probe can only be applied successfully if no appreciable gradient exists in the velocities across the undisturbed yaw probe location.

4.3.1 Calibration of Yaw Probe

1. Mount calibration protractor to vertical positioner of carriage, and secure tightly. During the whole calibration procedure, the protractor position should not be changed.

2. Mount the yaw probe on the calibration protractor and move it so that it points downward, forming an angle of about 50^0 - 60^0 with the horizontal. Connect both yaw probe taps to appropriate manometer tubes. Place the whole calibration device into the center of the test section by moving the carriage.

3. Start wind tunnel and set desired velocity. Take manometer reading.

4. Turn yaw probe about 5^0. This can be done without opening of test sections doors if the yaw probe tubing is fastened to some fixed point on the vertical carriage bar and the screw holding the yaw probe on the calibration protractor is tightened only slightly. Then, if the vertical position of the calibration device is changed by moving the instrument holder up or down, the yaw probe pivots and the angle is changed. Take manometer reading.

5. Repeat procedure until a total range of about 100^0 to 120^0 is covered. Convert manometer readings to relative pressure readings by dividing through maximum reading (or better: stagnation pressure reading as measured with a Pitot static tube). Convert angles by shifting zero to that point where manometer gave zero reading.

6. The calibration curve is obtained by plotting relative pressure readings against absolute values of adjusted angles.

4.3.2 Measurement with Yaw Probe

1. Place calibrated yaw probe in location where flow directions are to be measured.

2. Take manometer reading. This must be made dimensionless. For most purposes, if the deviations of the stream lines from parallel to the test section are small, the manometer reading corresponding to the ambient air velocity (as obtained from velocity indication probes) will suffice to make the manometer reading of the yaw probe dimensionless. This is permissible since under these conditions the difference in relative readings for the actual case and for the assumed case cannot be very large. Otherwise, the actual velocity has to be used for approximate positioning of the Pitot tube. Since the Pitot tube is not very direction sensitive within $\pm\ 15^0$, this will definitely be sufficient.

4.4 Temperature Measurements

It is recommended that, for measuring the temperature of the ambient air, a mercury manometer is used which is to be located in the duct downstream from the test section. Its bulb should be readable from the outside.

For temperature profiles, smaller temperature sensors, with faster response, are needed. The temperature sensors are copper-constantan thermocouples. Their emf is measured with millivolt potentiometer, Leeds Northrup type 8686. The standard equipment consists of 4 thermocouples, 2 of which are mounted on the carriage, 1 in the tunnel, and 1 is not connected to an instrument. Their location is shown in Table 3.

Table 3. Thermocouple Locations

Position on Selection Switch	Location
1	Tunnel floor downstream from test section
2	Carriage: instrument holder of transverse
3	Carriage: instrument holder of vertical
4	Not connected: on vertical
5	Reference junction: junction at mercury thermometer in manometer casing

The temperature is measured by using reference junction and desired couple. The procedure is as follows:

4.4.1 Preparatory Adjustments

1. Familiarize yourself with the operation manual of the potentiometer bridge and with the conversion tables.

2. Turn thermocouple selector switch to position 5 "Reference Junction."

3. Turn potentiometer switch to "Standardize," and scale of potentiometer to zero millivolts.

4. Adjust mechanical zero and battery.

5. Turn potentiometer switch to "Reference Junction."

6. Read temperature off mercury thermometer on manometer, look up corresponding millivoltage for copper constantan thermocouples in conversion tables, and set this voltage on the dial of the potentiometer.

7. Adjust Reference Junction knob until galvanometer balances for the given voltage.

4.4.2 Measurement with Thermocouple

1. Set potentiometer switch to "TC Measurement."

2. Set thermocouple selector to desired position.

3. Balance galvanometer for the thermocouple.

4. Record voltage and find corresponding temperature in conversion table.* Example: Reference junction temperature 21^0 C. From conversion table one finds 0.827 mv. Potentiometer set at this voltage and galvanometer balanced. For measuring thermcouple one gets, say, 2.481 mv, so that temperature = 61^0 C.

---

*Conversion tables and testing methods for thermocouples are given in Ref. 8 and 9.

REFERENCES

1. Plate, E. J. and Cermak, J. E., "A study of design and operation of a low speed precision wind instrument test facility," Colorado State University, Fort Collins, Colorado, November 1960, CER60EJP58.

2. Roshko, A., "On the development of turbulent wakes from vortex streets," NACA Report 1191, 1954, 24 pp.

3. Prandtl, L. and Tietjens, O., "Applied hydro-and aerodynamics," Dover, New York, 1954.

4. Handbook of Physics and Chemistry.

5. Hinze, J. O., "Turbulence," McGraw Hill, New York, 1959.

6. Lester, W. G. S., "The flow past a Pitot tube: part 1 and part 2," Aeronautical Research Council (Gt. Brit.), July 11, 1960, 18 pp, ARC22070, Abstract NASA, January 5, 1961, order from NASA N-89559.

7. Pope, A., "Wind tunnel testing," John Wiley and Sons, Inc., New York, 1947.

8. United States Department of Commerce, National Bureau of Standards, "Methods of testing thermocouples and thermocouple materials," NBS Circular 590, February 1958.

9. United States Department of Commerce, National Bureau of Standards, "Reference tables for thermocouples," NBS Circular 561, April 1955.

APPENDIX 1

FIGURES

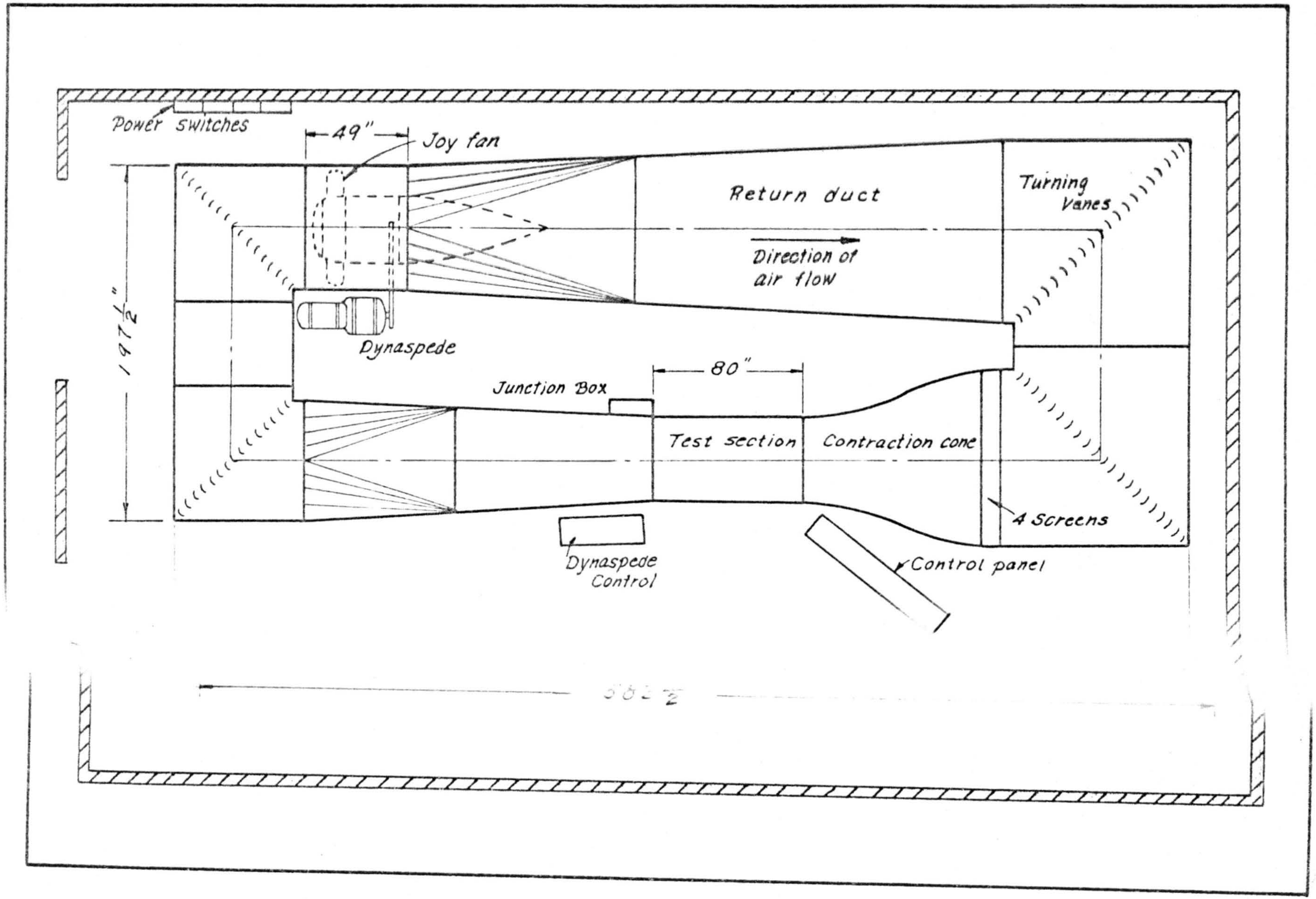

Fig. 1 Wind Tunnel Layout

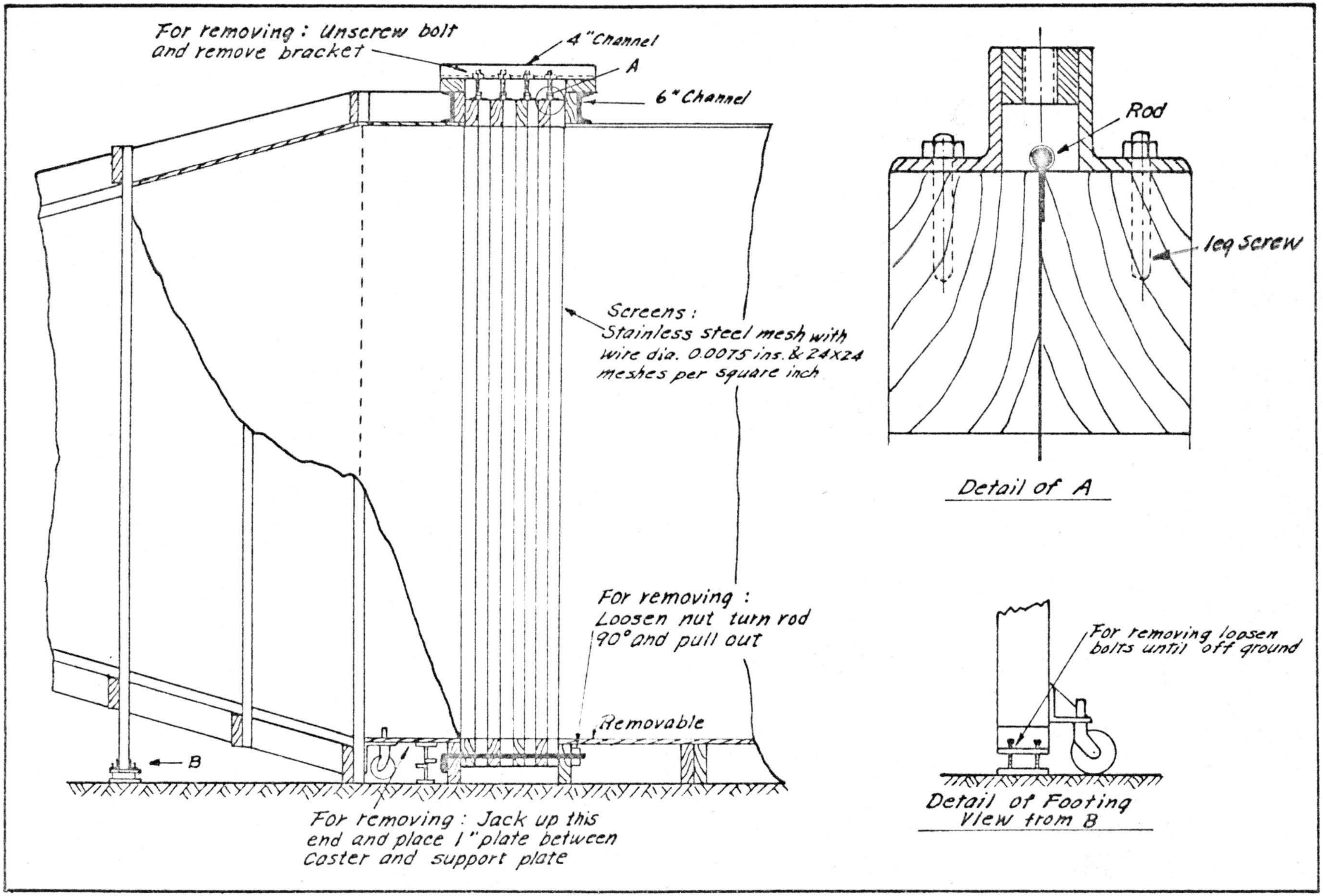

Fig. 2 Section Through Screen

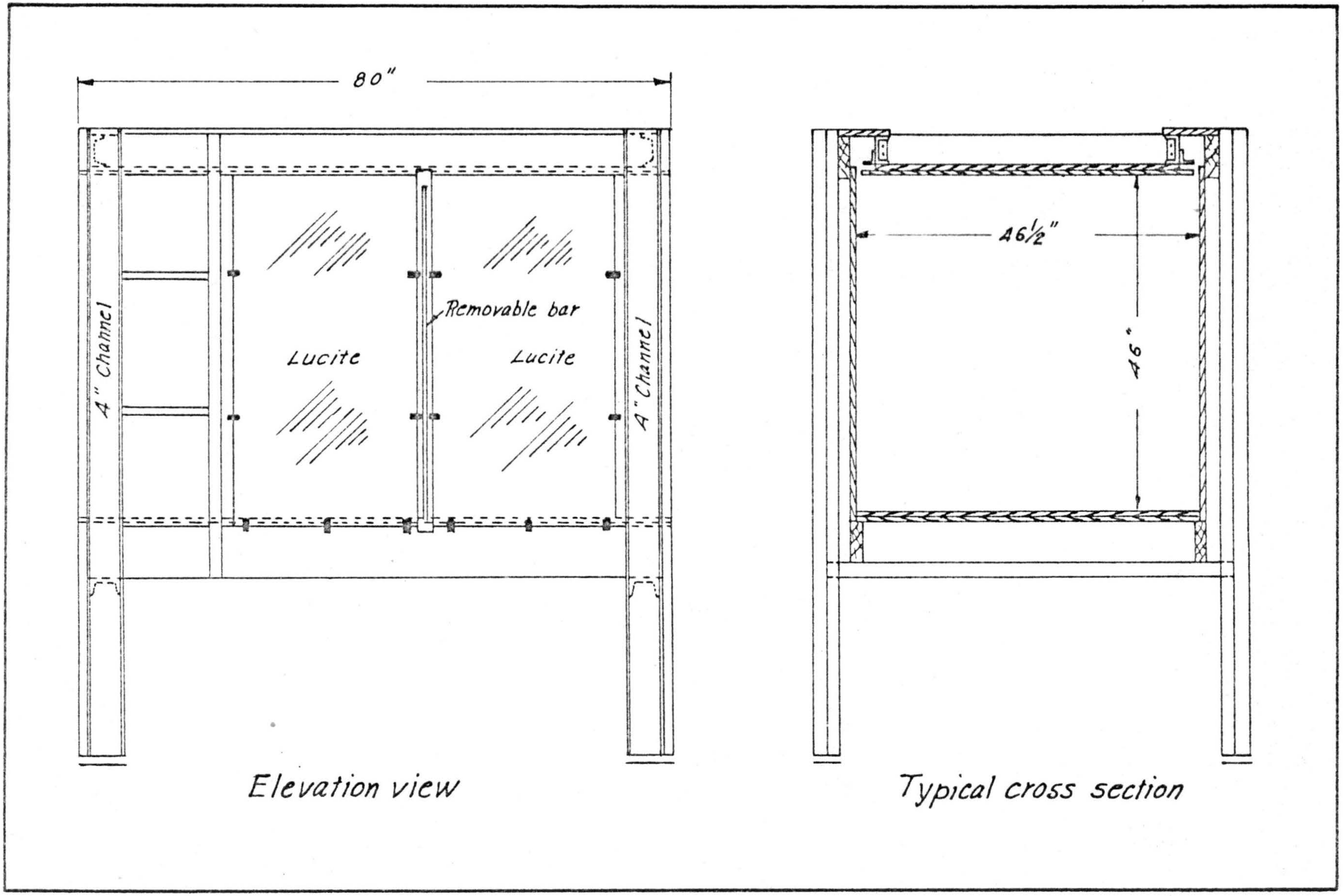

Fig. 3 Test Section

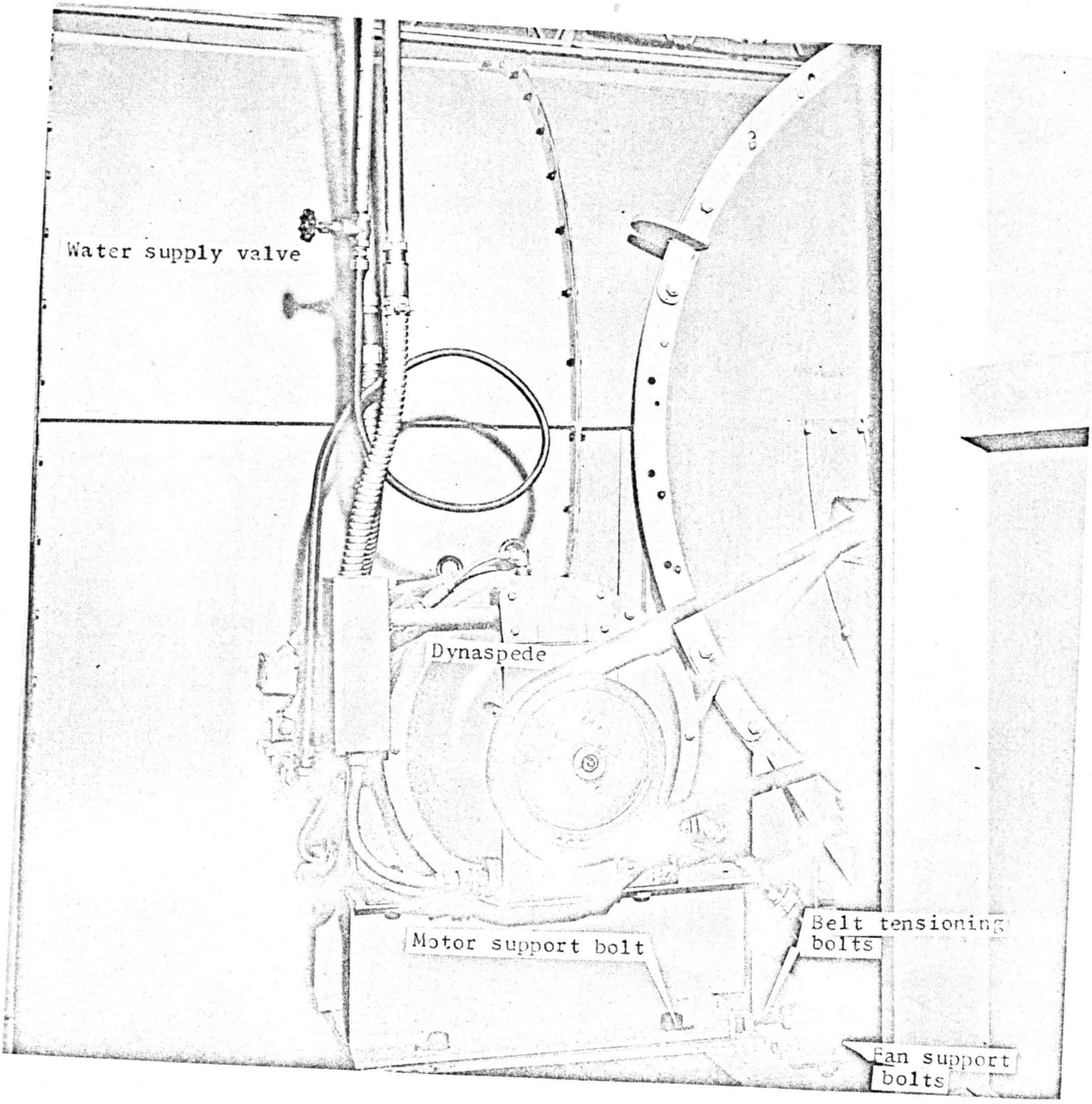

Fig. 4 Motor-Fan Arrangement

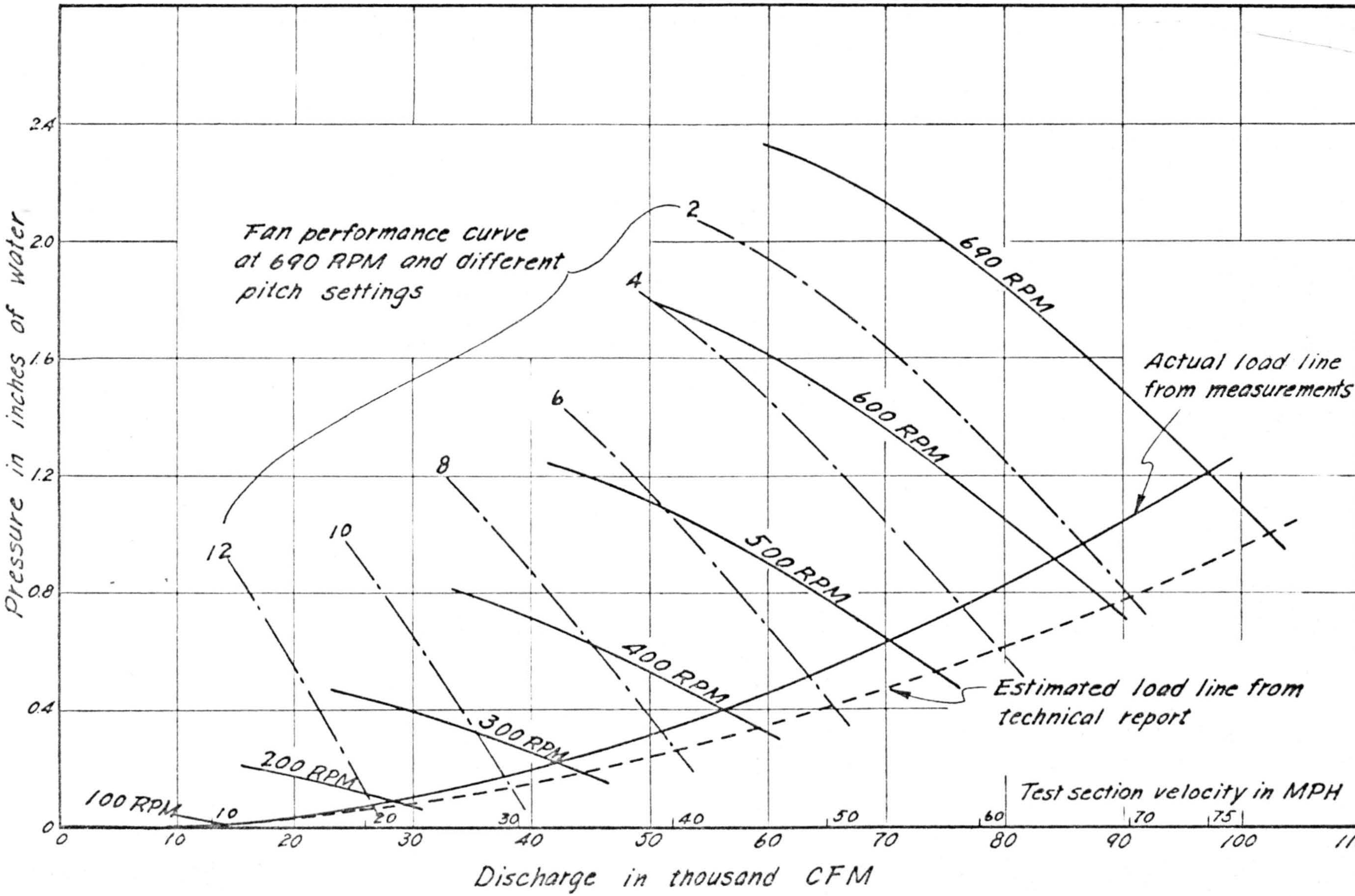

Fig. 5 Typical Characteristics of a 72" Diameter Joy Fan
(Based on Joy Co's Drawing No. C-1804)

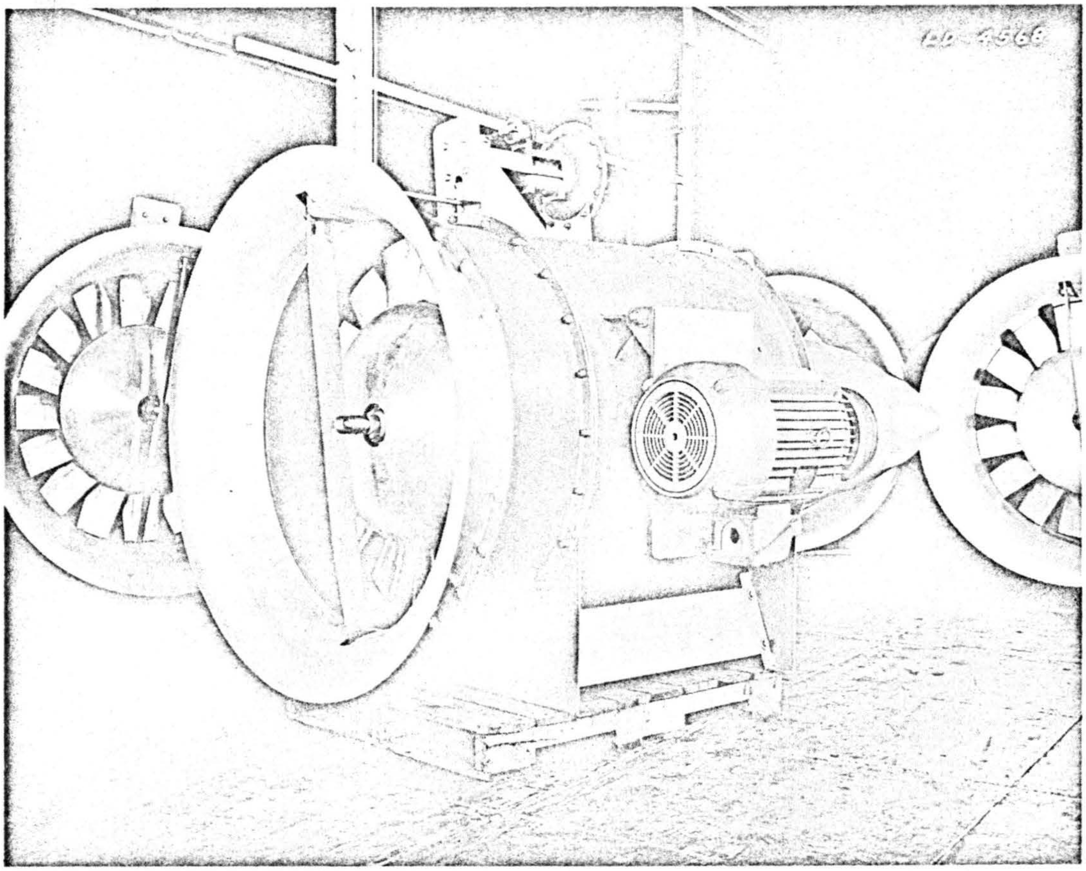

Fig. 6 Joy Series 1000 Variable Pitch Fan Side View (after body can be seen in rear).

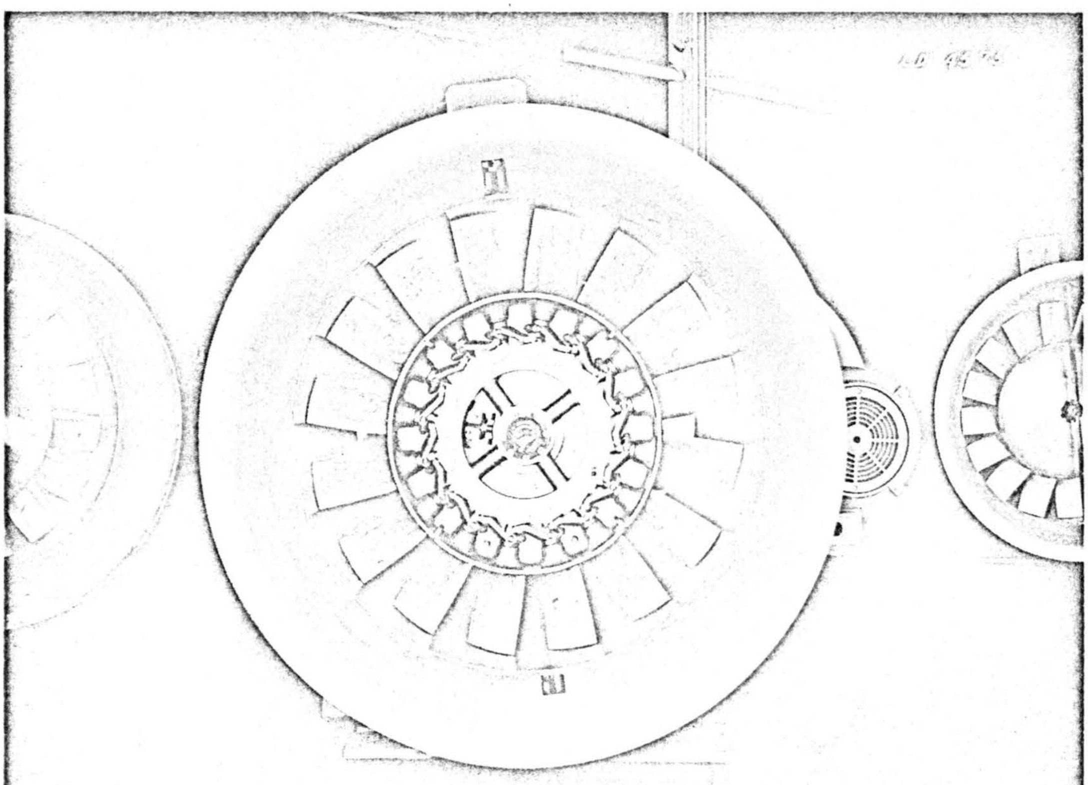

Fig. 7 Joy Series 1000 Variable Pitch Fan Front View with hub removed.

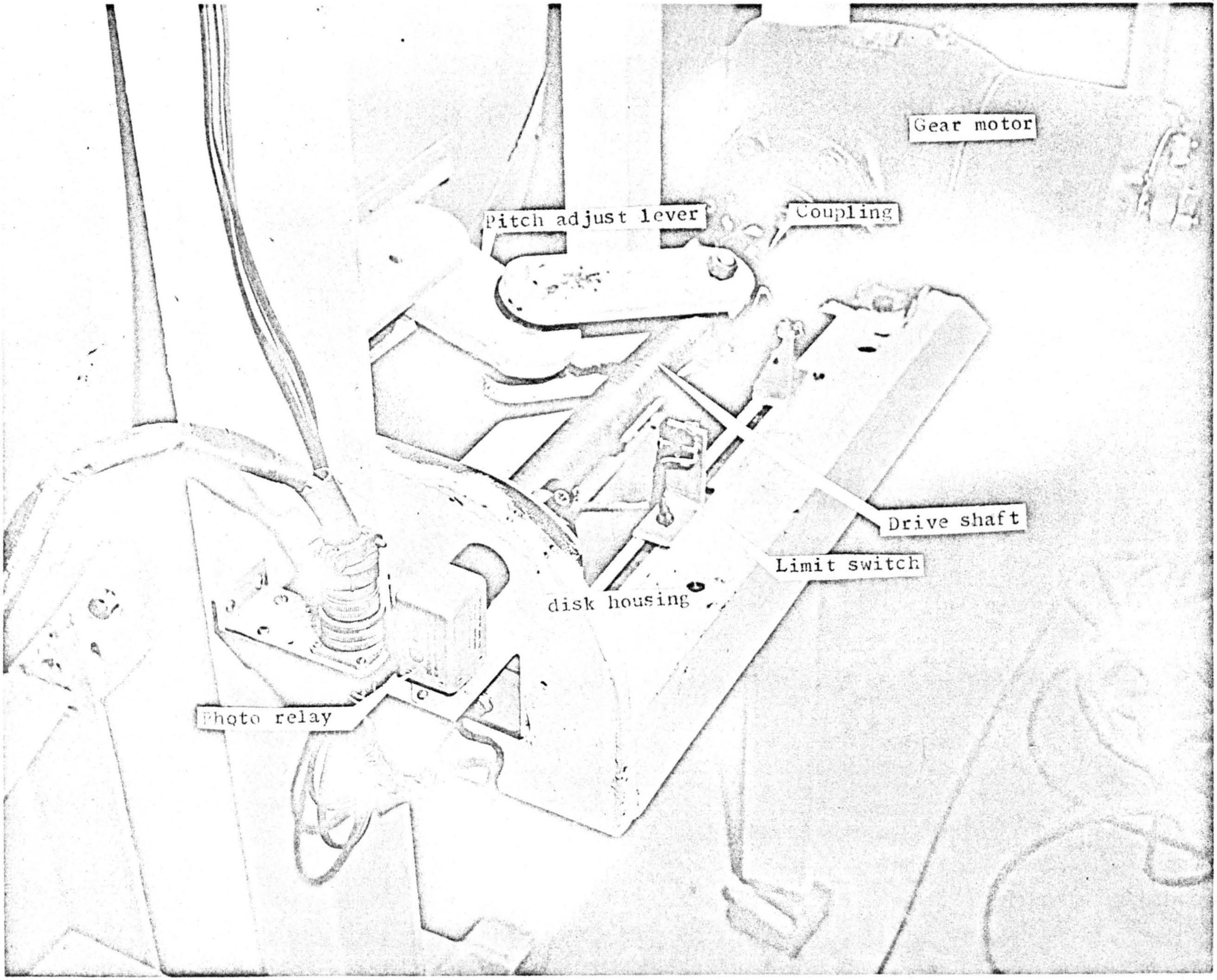

Fig. 8 Pitch Control Unit

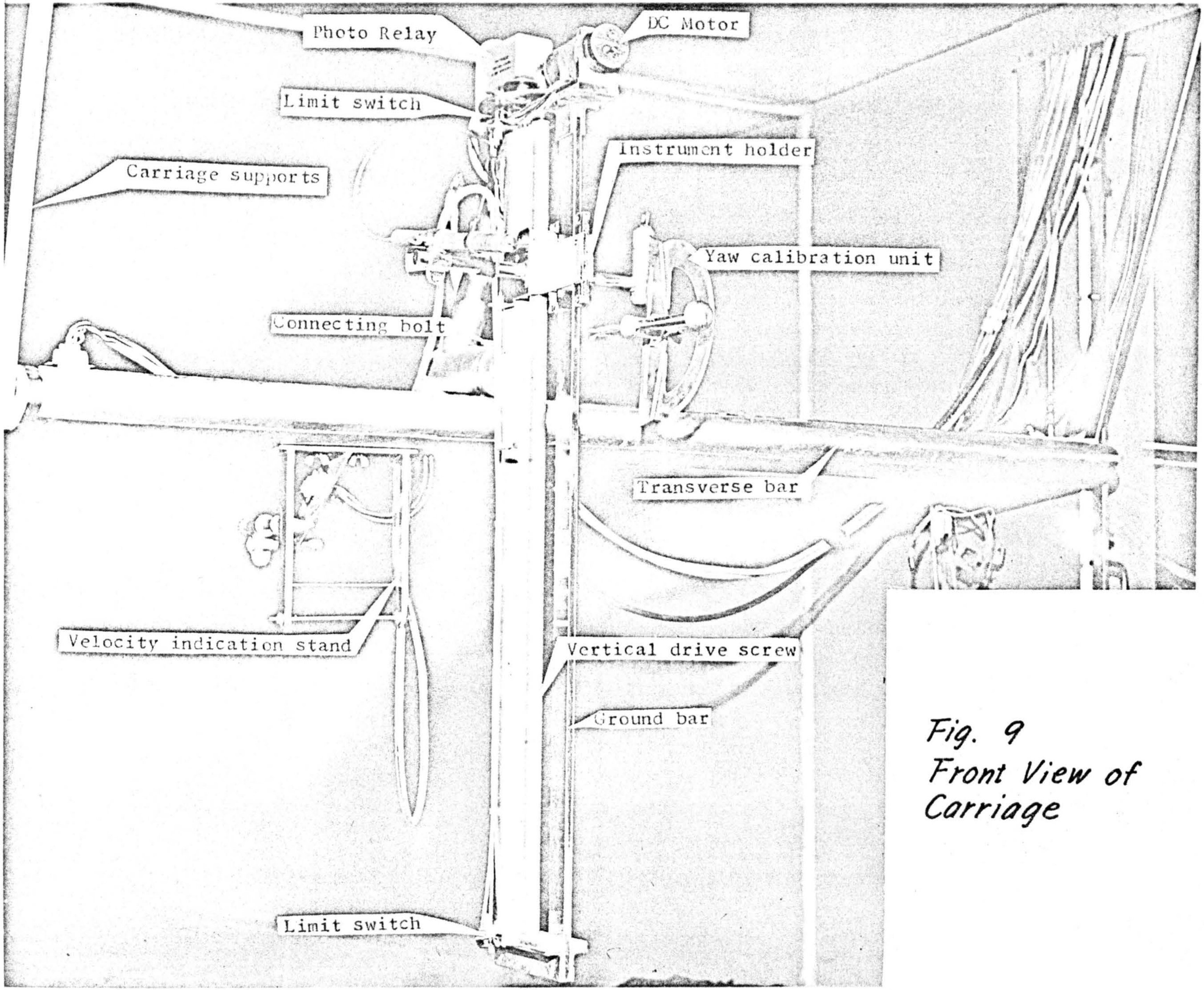

Fig. 9
Front View of Carriage

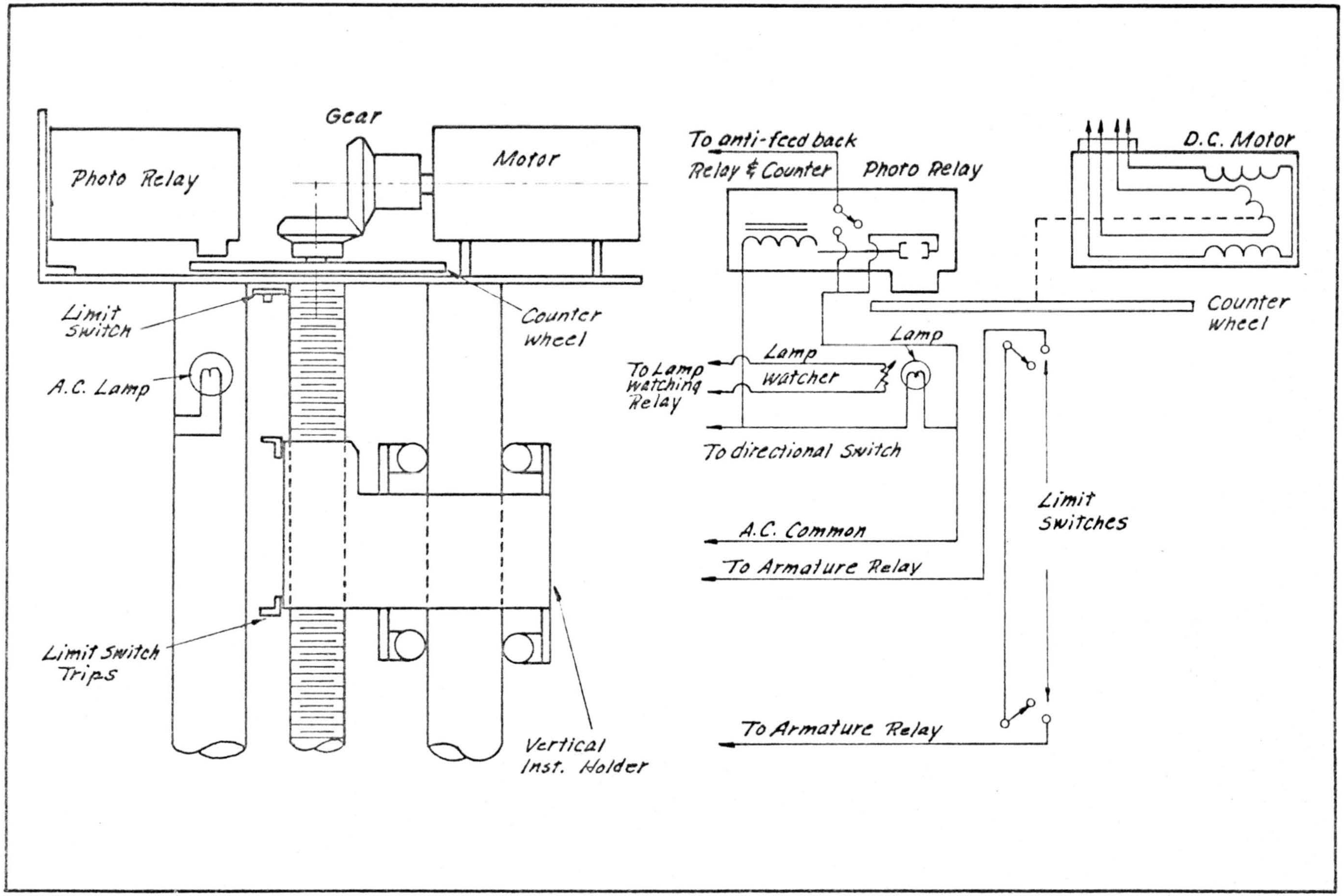

Fig. 10 Vertical Drive and Circuit

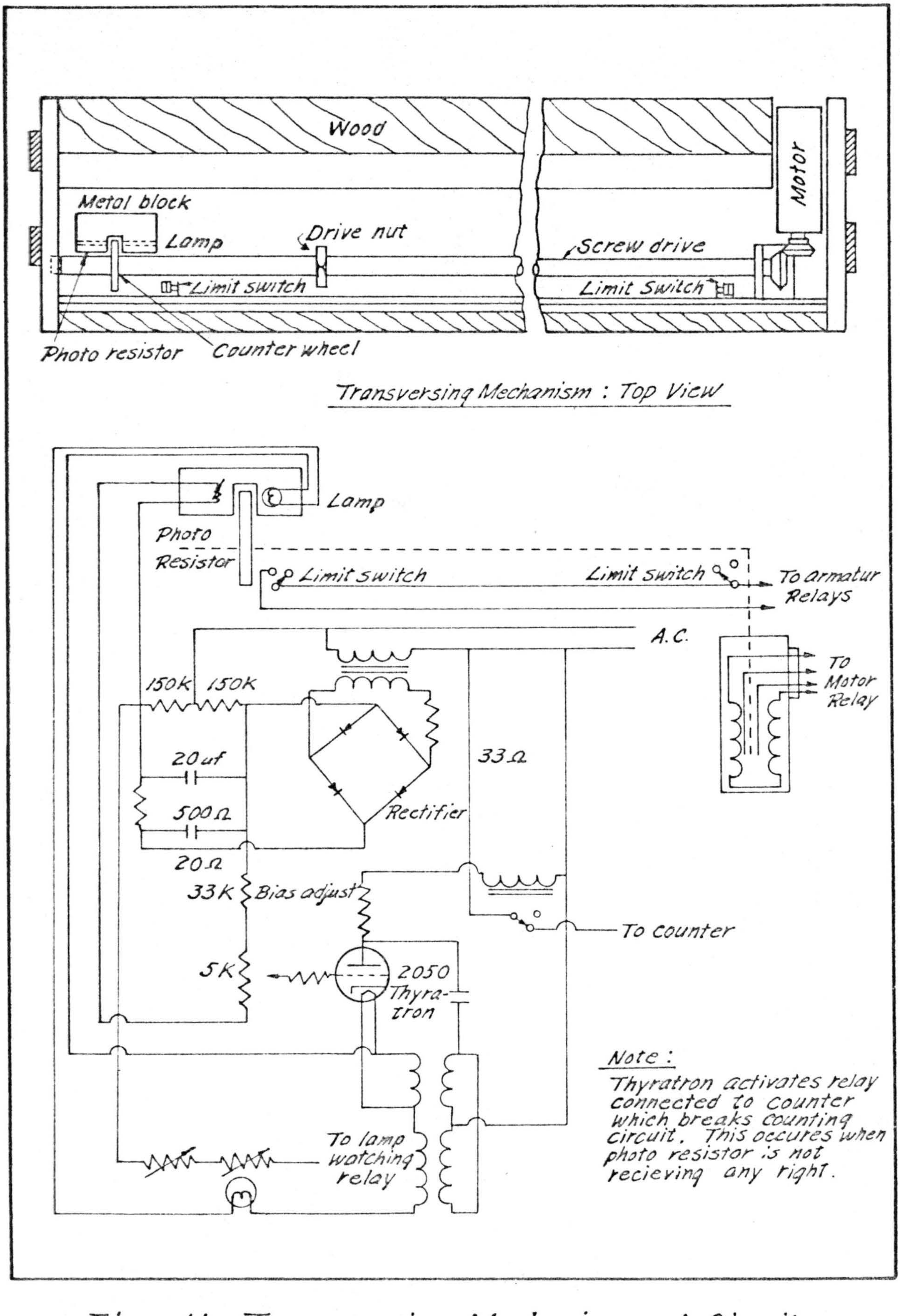

Fig. 11 Transversing Mechanism and Circuit

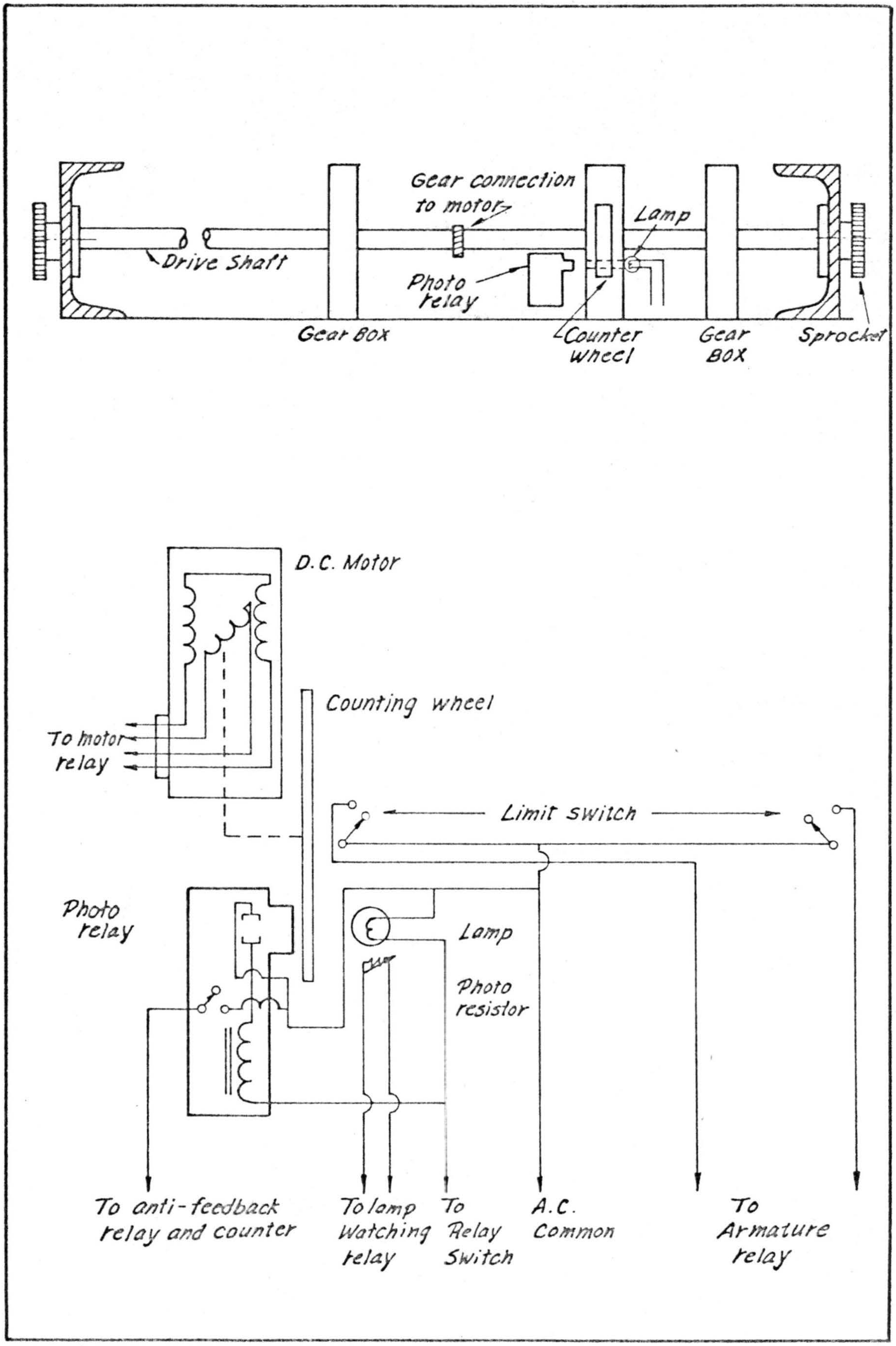

Fig. 12 Longitudinal Drive and Circuit

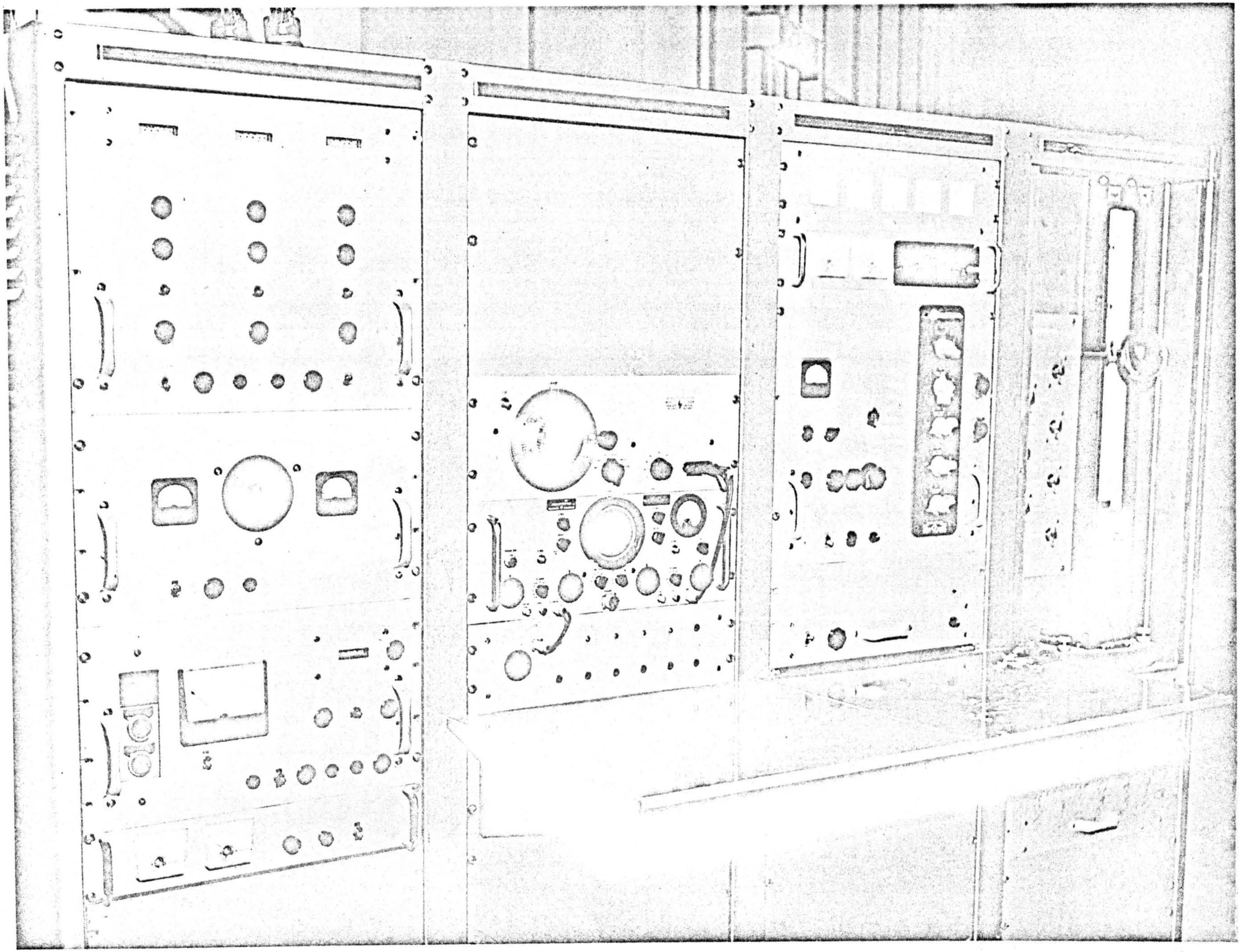

Fig. 13 Control Panel

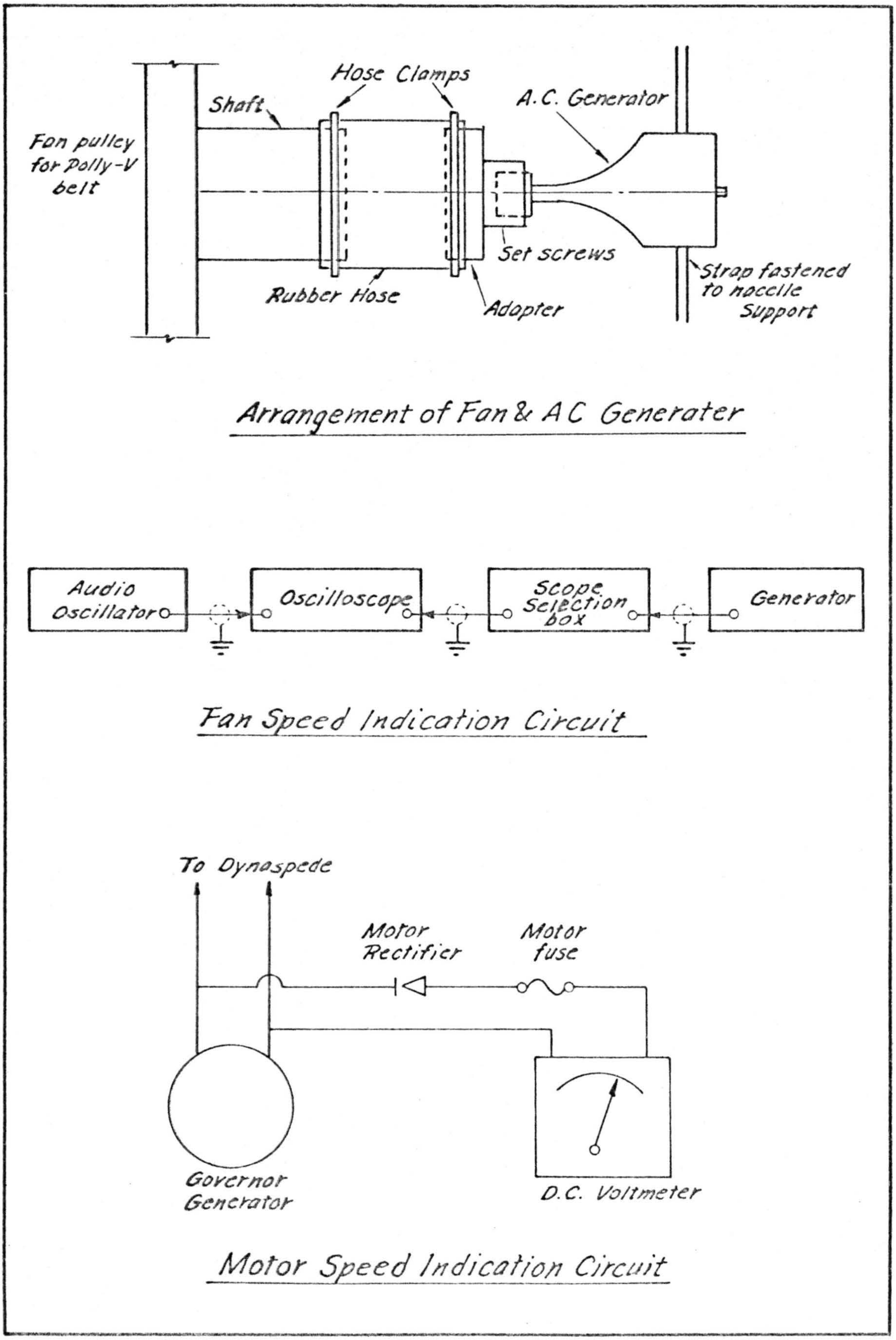

Fig. 14 Fan Speed Indication Circuits

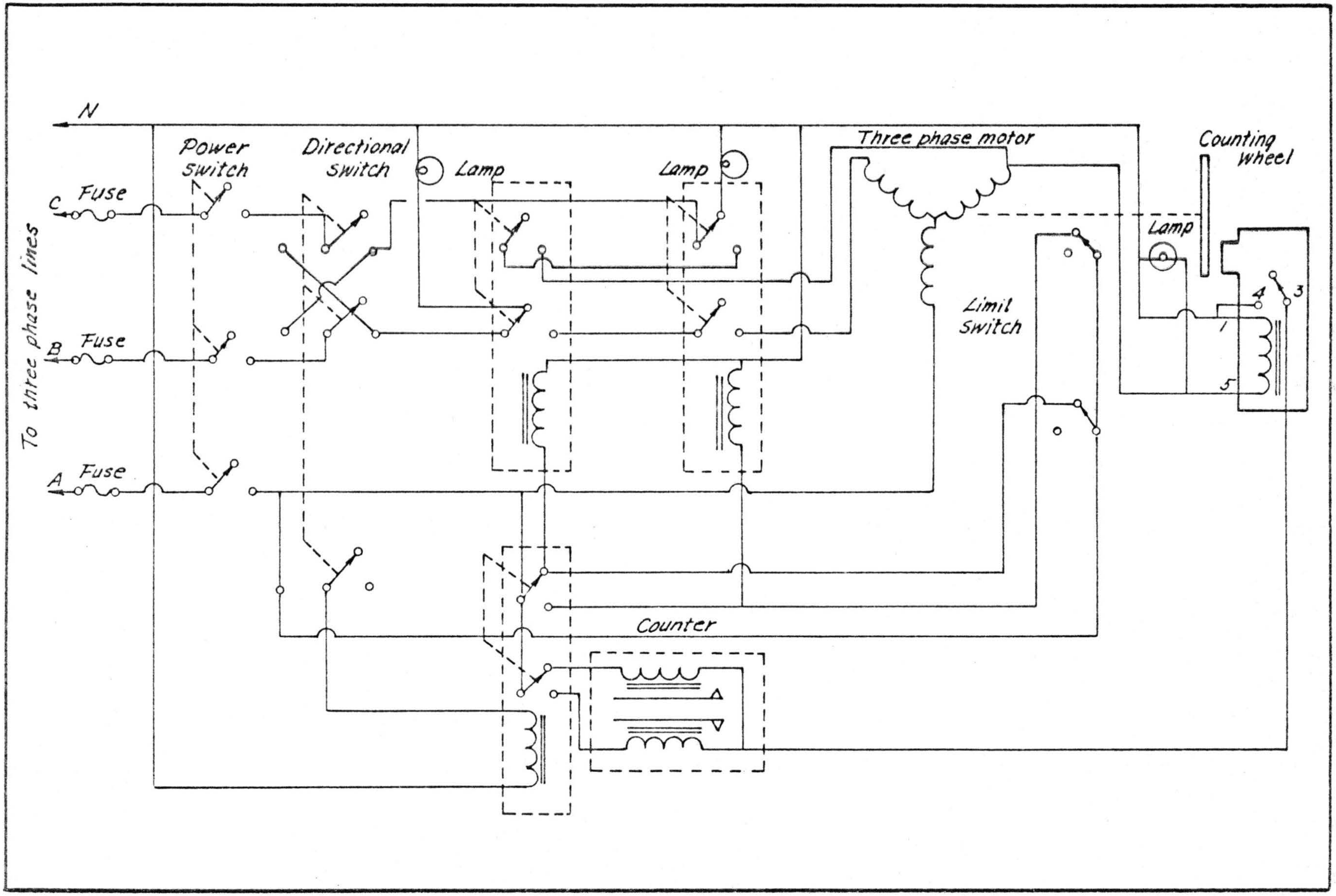

Fig. 15 Pitch Control Circuit

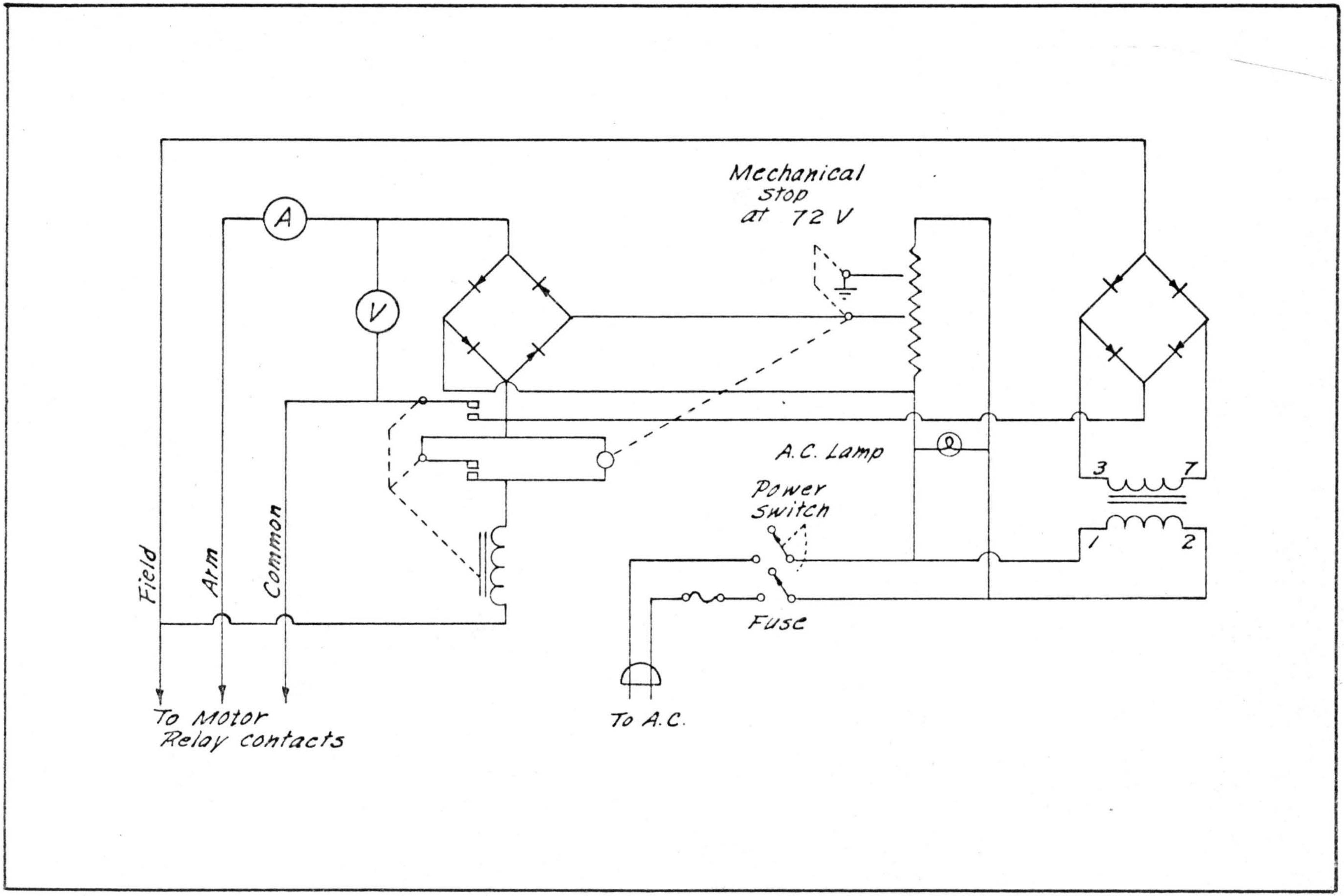

Fig. 16 Carriage Motor Control Circuit

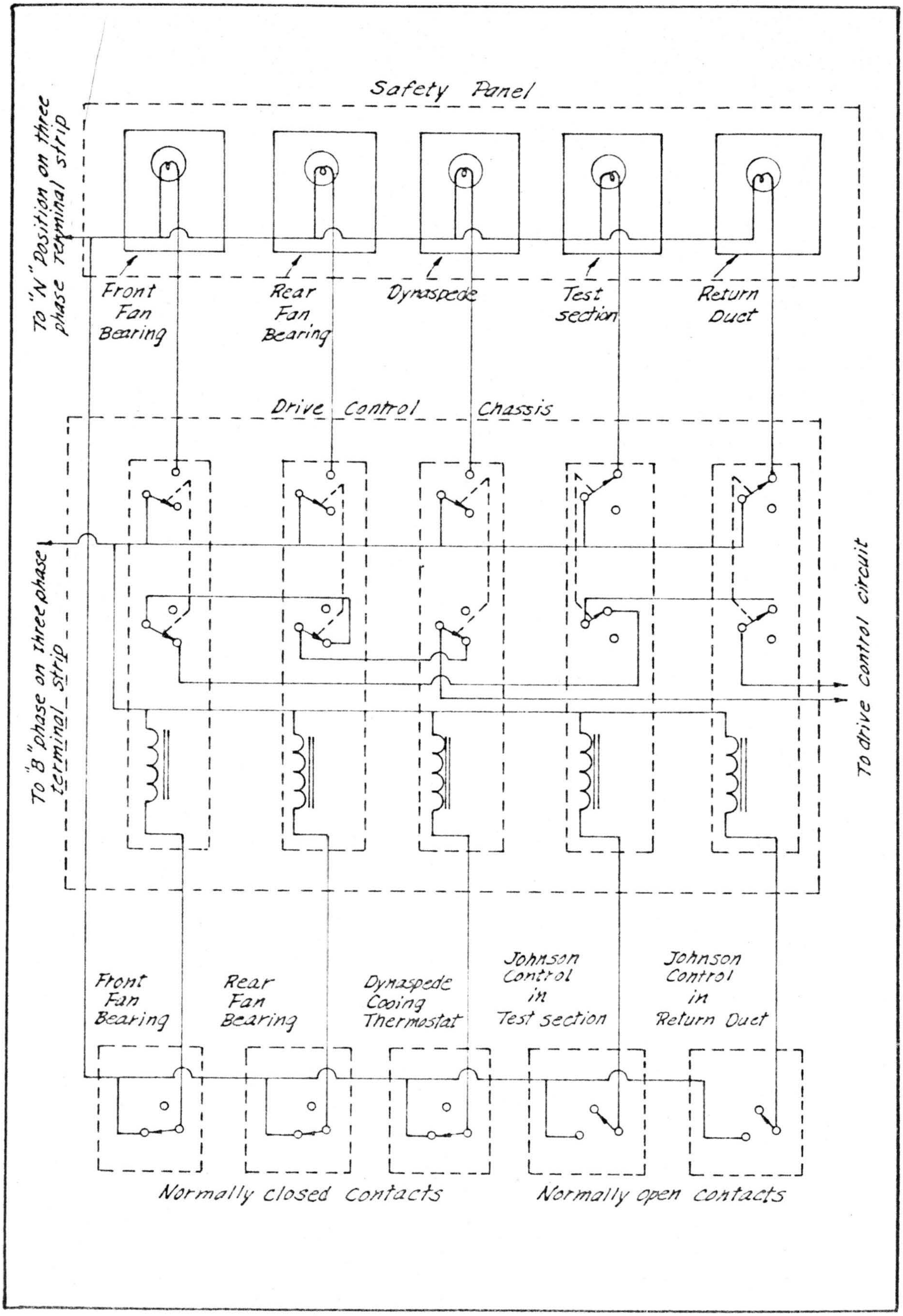

Fig. 17 Safety Circuits

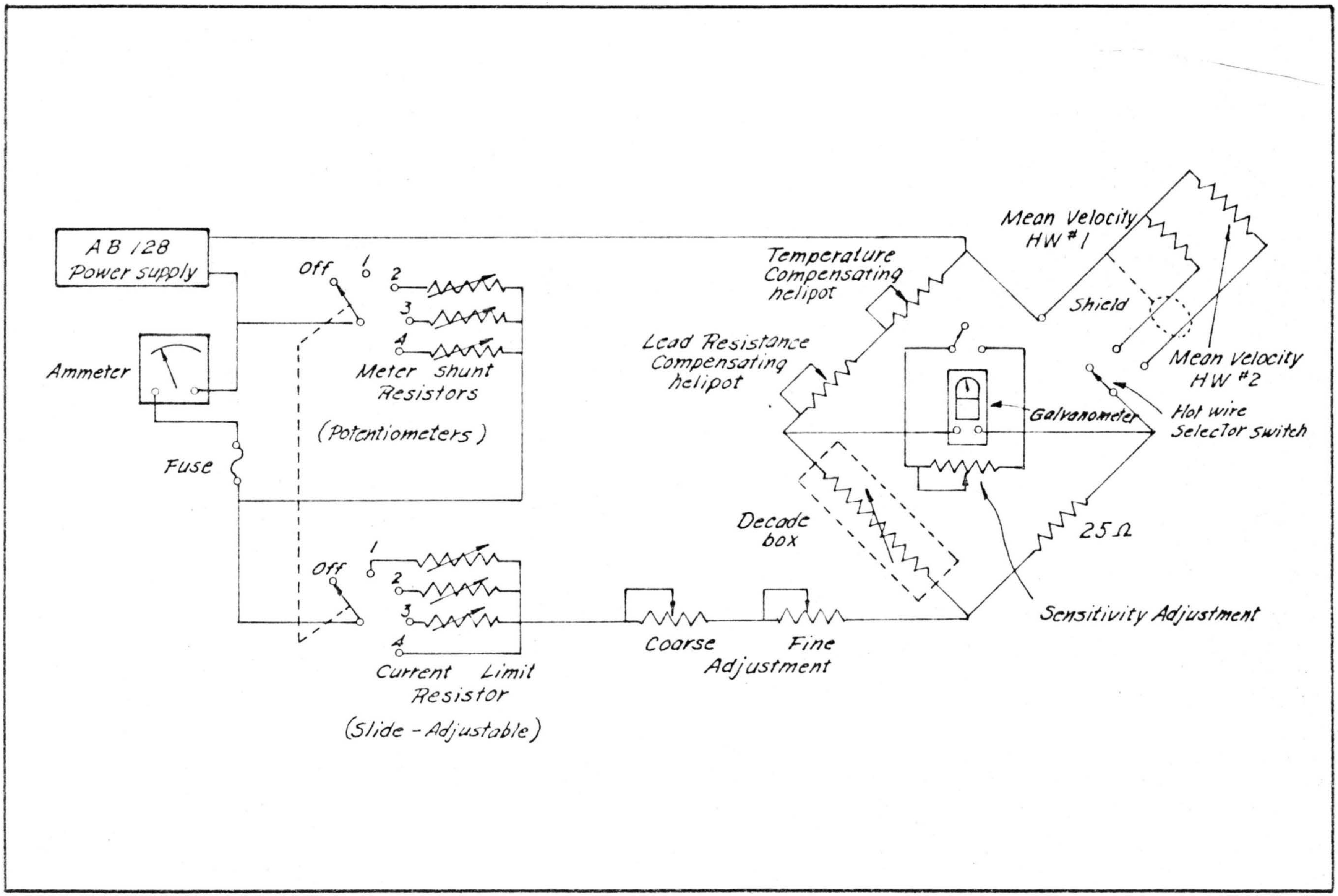

Fig. 18 Mean Velocity Hot Wire Circuit

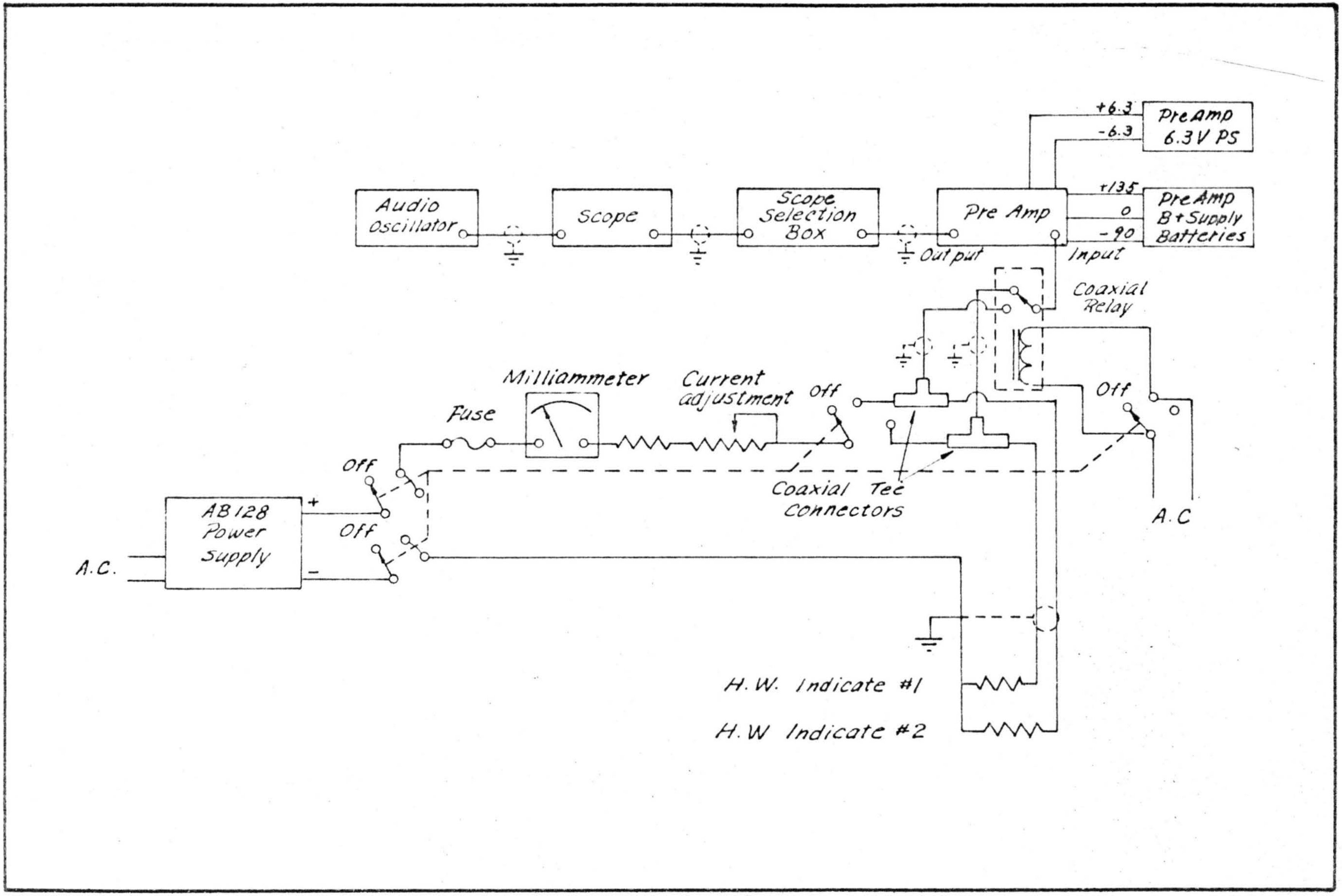

Fig. 19 Low Speed indication Circuit

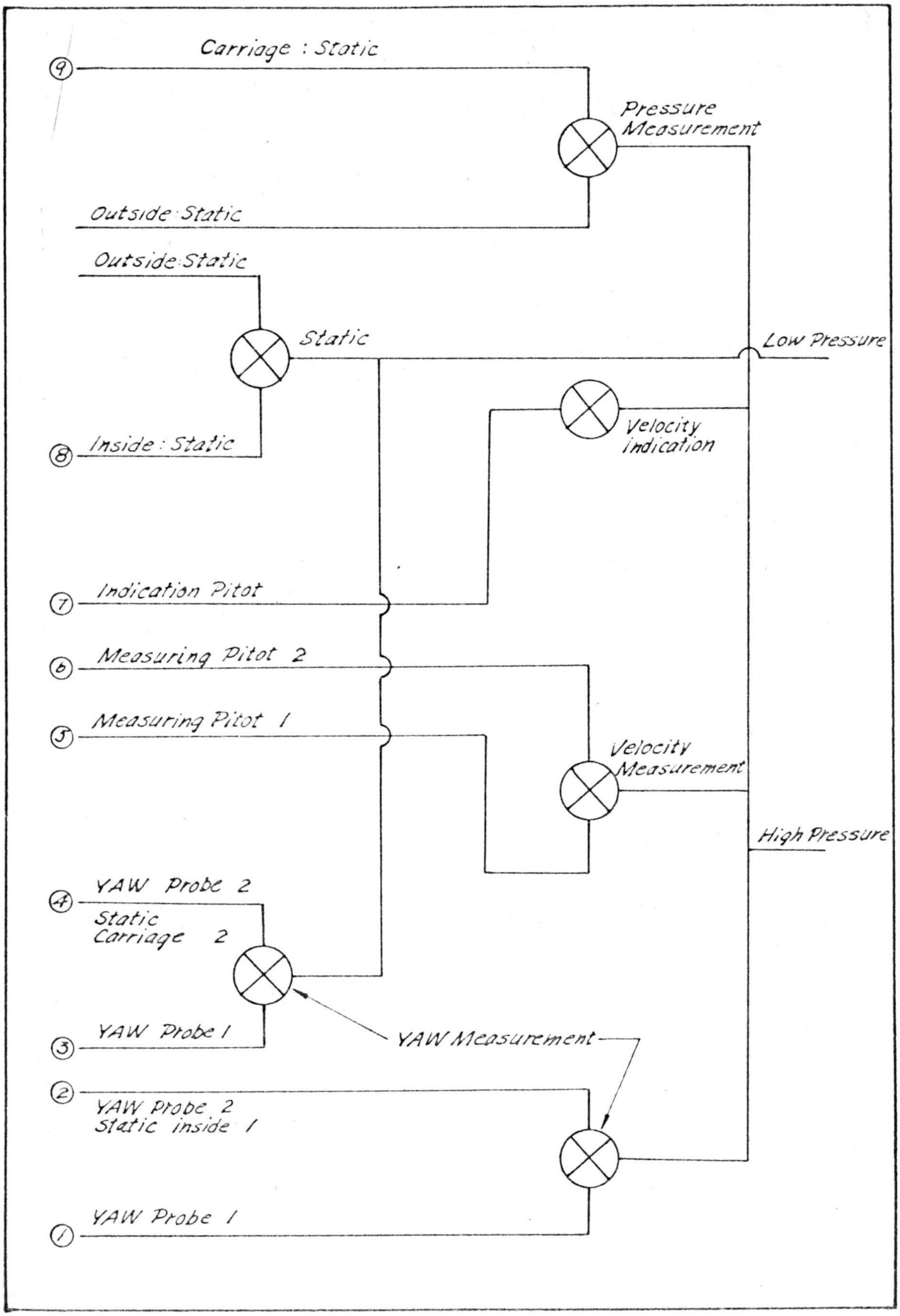

Fig. 20 Manometer Control

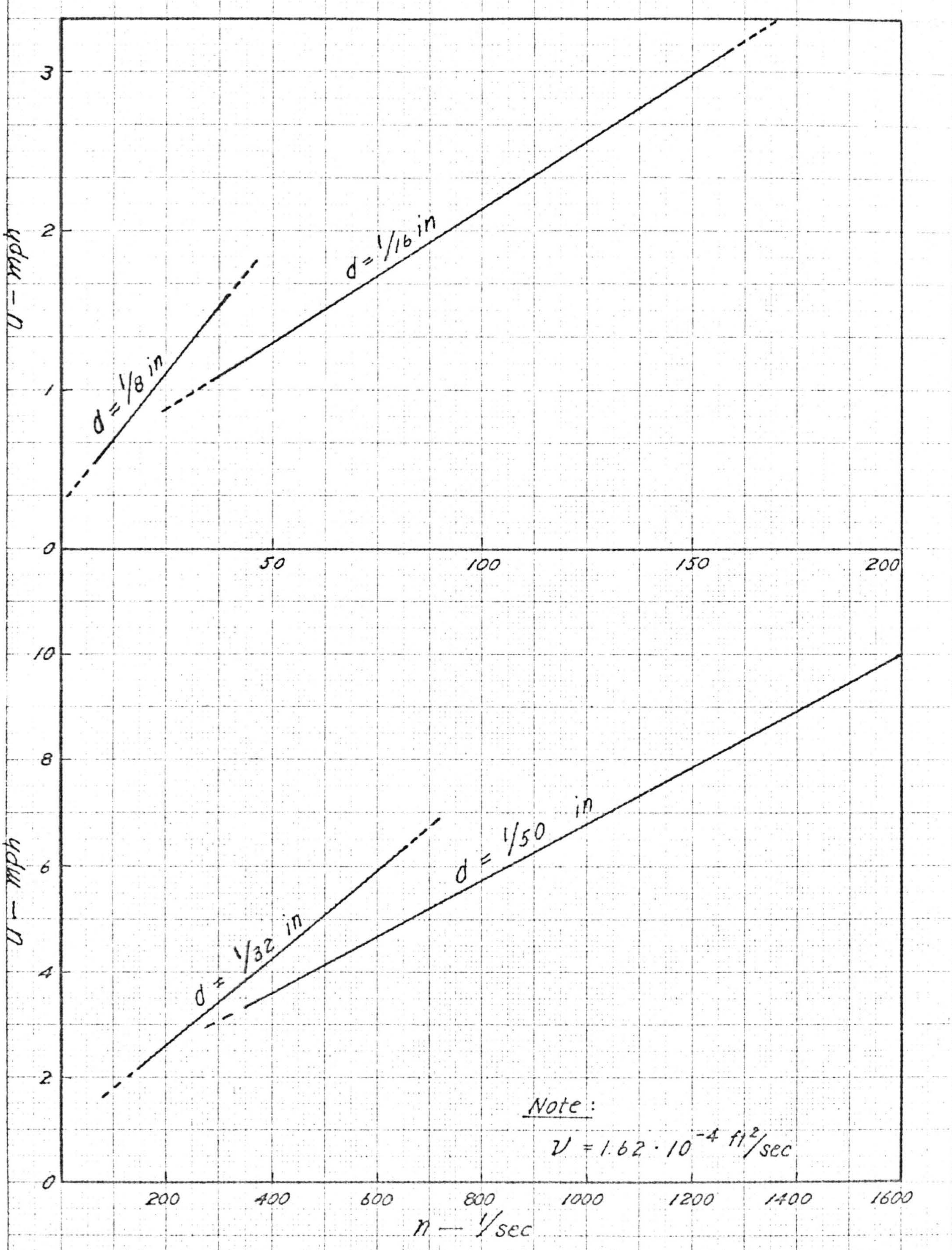

FIG. 21 Frequency vs Velocity for Different Eddy Shedding Wires

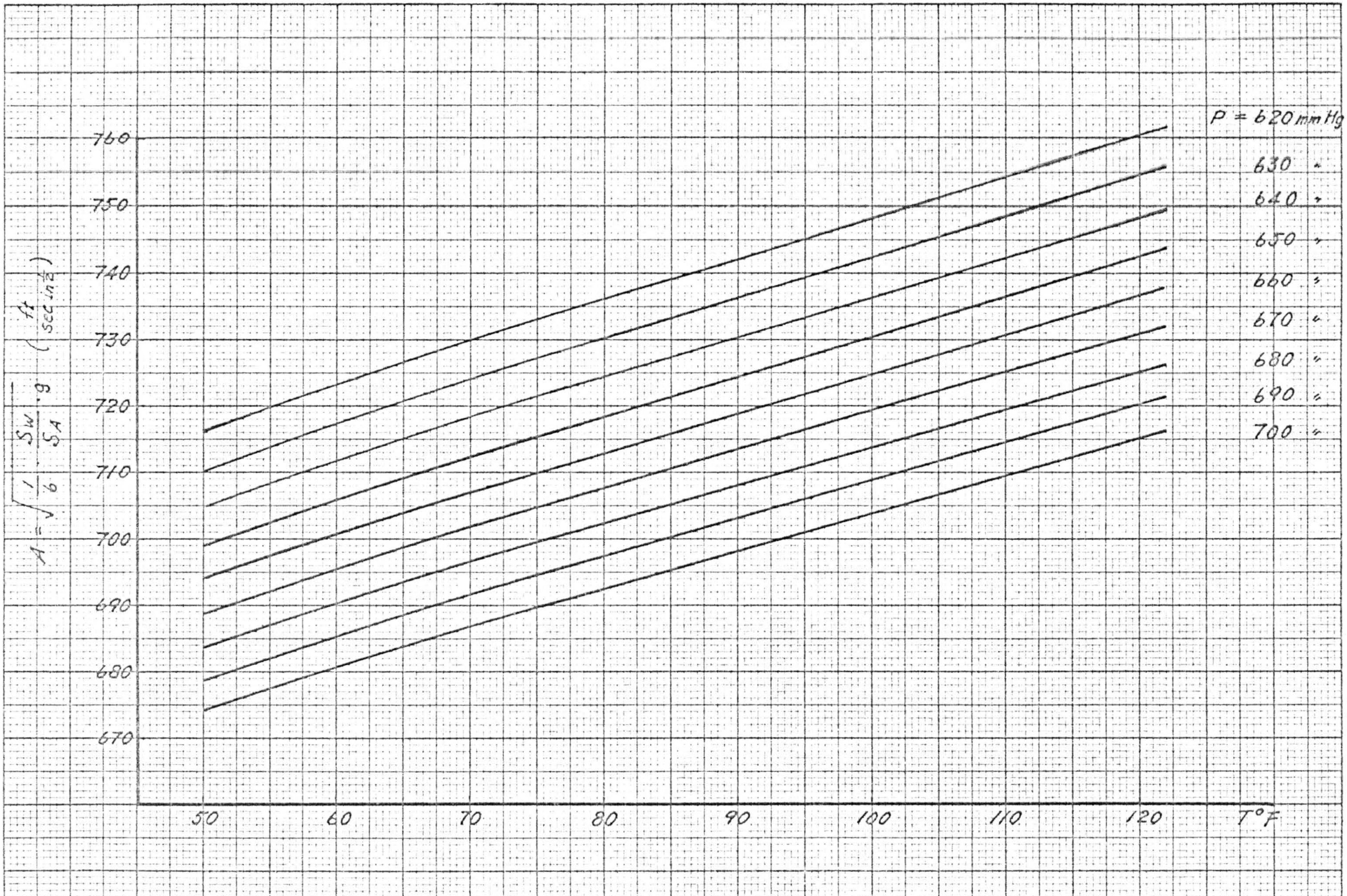

Fig. 22 Manometer Coefficient as Function of Temperature & Pressure

APPENDIX 2

TEMPERATURE COMPENSATION OF THE MEAN VELOCITY HOT-WIRE ANEMOMETER FOR SLOW SUBSONIC FLOWS

TECHNIQUE USED AT COLORADO STATE UNIVERSITY

TEMPERATURE COMPENSATION OF THE MEAN VELOCITY
HOT-WIRE ANEMOMETER FOR SLOW SUBSONIC FLOWS

TECHNIQUE USED AT COLORADO STATE UNIVERSITY

Temperature compensation of the mean velocity hot-wire anemometer for slow subsonic flows:

Using the circuit shown in Fig. 1, for the hot-wire anemometer, the power loss I^2R_W of a heated wire due to the combined effects of radiation axial conduction and forced convection can be determined. This power loss and the subsequent behaviour of the hot-wire anemometer, for slow subsonic flows, is governed by King's Equation

$$I^2R_W = (A + B\sqrt{u})\ (R_W - R_a). \qquad (1)$$

At this time it is instructive to note that King's law is only a very special case of hot-wire sensitivity. The 0.5-power dependence of the power loss I^2R_W (or the Nusslet number Nu) on the velocity (or Reynolds number Re), as indicated by King's Equation, is well established in slow subsonic continuum flow; but heat-transfer data indicates that this correlation does not hold for an appreciable range of velocity (see, ref. 1).

Thus the temperature compensation technique outlined in this note is valid only for slow subsonic flows, ($Kn = \frac{\lambda}{D_W} = \frac{\text{Mean free path of gas}}{\text{Wire diameter}} < 0.001$, $M = \frac{U}{C} = \frac{\text{Velocity of gas}}{\text{Sonic Velocity}} < 0.3$).

In the range of validity of King's Law the normal mode of operation, where t_a is relatively constant, requires that the current I be adjusted so that R_W remains constant. For this case a plot of $I^2R_W = f(\sqrt{u})$ will give a straight line, as can be seen from Equation 1. If t_a and thus R_a is not constant, the power loss I^2R_W for a given air velocity will no longer be a unique value for any particular wire. Fig. 2, shows the effect of t_a in more detail, being a plot of $I^2R_W = f(\sqrt{u})$ for different ambient air temperatures t_a, with R_W being kept constant. In this case, the normal method of operation of the anemometer has to be modified to compensate for t_a.

The compensation procedure consists of varying R_{TC} in Fig. 1, manually, in such a way that the quantity I^2R_W is a constant for a given velocity for any value of t_a. If A and B are assumed independent of temperature, it follows from Equation 1, that the difference $(R_W - R_a)$ must be kept constant.

The quantities R_W and R_a can be written as

$$R_W = R_o(1 + \alpha\Delta t_W)$$

and

$$R_a = R_o(1 + \alpha\Delta t_a)$$

where

$$\Delta t_W = t_W - t_o \text{ and } \Delta t_a = t_a - t_o.$$

Then

$$R_W - R_a = R_o(t_W - t_a)\alpha. \tag{2}$$

If t_a changes by an amount ΔT_a, then R_a will change by ΔR_a, and

$$R_W - (R_a + \Delta R_a) = R_o\alpha(t_W - \left[t_a + \Delta T_a\right]), \tag{3}$$

and subtracting Equation (2) from Equation (3),

$$\Delta R_a = R_o\alpha\Delta T_a. \tag{4}$$

To cause this change in R_W the resistance R_{TC} must be given the value

$$\boxed{\Delta R_{TC} = R_o r_b \alpha\Delta_{Ta},} \tag{5}$$

where r_b is the bridge ratio. Thus, if, for a change in t_a of ΔT_a, R_{TC} is changed by the amount ΔR_{TC} given by Equation (5), then the value of I^2R_W determined from the anemometer will be the same for a given velocity for any temperature; and thus the curve $I^2R_W = f(\sqrt{u})$, determined for any t_a, can be used for any other value of t_a.

Earle (2) experimentally verified the compensation procedure given above. This experimental verification was necessary because: (1) the quantities A and B are functions of the air temperature, but the magnitude of their variation with temperature is unknown; (2) the value of the quantity α is not known with sufficient accuracy; and (3) the power loss I^2R_W varies in a complicated nonlinear manner with air and wire temperatures (see ref. 1).

Earle's experimental procedure consisted simply of determining standard velocity calibration curves for different values of t_a, using different values of α until for some α a set of curves for different temperatures was found to coincide. Using this procedure, the best value of

α was determined to be 0.00189/°F for platinum wire. Fig. 3 is a typical plot of $I^2R_W = f(-\sqrt{u})$ using the above value of α and the compensation procedure outlined above.

When measurements are to be made in air having a temperature gradient, then, the first step is to calibrate the hot-wire at room temperature, t_{ai}, and plot the $I^2R_W = f(-\sqrt{u})$ curve, where $R_W = r_b\ R_{TC} - R_{LC}$, which should give a straight line.

Then, to be able to apply Equation (5), one must know the following:

$\alpha = 0.00189/°F$ (determined experimentally for 0.001" platinum wire).

$r_b = \frac{R_c}{R_b}$, by definition

$\Delta T_a = t_a - t_{ai}$, which is determined by measurement

and R_o

To determine R_o, first determine R_W as before, using three or four values of I, where $I \ll I_1$ (the smaller the better). Then plot the curve $I^2 = f(R_W)$. The intersection of the curve with the line $I^2 = 0$ gives the value of R_{WT} when the wire is at room temperature, or $t_W = t_{ai}$. Then, from

$$R_{WT} = R_o\left(1 + \alpha\left[t_W - t_o\right]\right)$$

we get

$$R_o = \frac{R_{WT}}{\left[1 + \alpha(t_{ai} - t_o)\right]} \tag{6}$$

Thus,

$$\boxed{\Delta R_{TC} = \frac{R_{WT}}{\left[1 + \alpha(t_{ai} - t_o)\right]}\left(\frac{R_c}{R_b}\right)(t_a - t_{ai})(0.00189)} \tag{7}$$

If, as is frequently the case, the temperature in the tunnel, or other test area, is not equal to t_{ai}, then the current at which the bridge is to be balanced is no longer I_1, but some corrected value I_t. Since

$$I^2_i R_{Wi} = I^2_t R_{Wi}$$

where

$$R_{Wi} = R_o \left[1 + \alpha (t_{Wi} - t_o)\right]$$

and

$$R_{Wt} = R_o \left[1 + \alpha(t_{Wt} - t_o)\right]$$

$$= R_o\left[1 + \alpha (t_{Wi} - t_o) + \alpha \Delta T_W\right] ,$$

we have

$$I^2_t = I^2_i \left[\frac{1 + \alpha(t_{Wi} - t_o)}{1 + \alpha(t_{Wi} - t_o) + \alpha\Delta T_W}\right]$$

$$= I^2_i \left[1 - \frac{\alpha \Delta T_W}{1 + \alpha(t_{Wi}-t_o)} + \frac{\alpha^2 (\Delta T_W)^2}{1 + \alpha(t_{Wi}-t_o)^2} - \ldots\right]$$

or, since $\alpha\Delta T_W \ll 1 + \alpha (t_{Wi} - t_o)$,

$$I^2_t = I^2_i\left[1 - \frac{\alpha\Delta T_W}{1 + \alpha(t_{Wi} - t_o)}\right].$$

But

$$R_{Wi} = R_o\left[1 + \alpha(t_{Wi} - t_o)\right] \text{ and } \Delta T_W = \Delta T_a$$

$$\therefore \alpha(t_{Wi} - t_o) = \left(\frac{R_{Wi}}{R_o} - 1\right).$$

Thus

$$I^2_t = I^2_i\left[1 - \alpha \Delta T_a \frac{R_o}{R_{Wi}}\right]$$

or,

$$\boxed{I_t = I_i\sqrt{\left(1 - \alpha \frac{R_o}{R_{Wi}} \Delta T_a\right)}} \qquad (8)$$

Thus, when the bridge is to be balanced in the tunnel the current should be set at I_t and R_{TC} should be set at the appropriate value, as determined from Equation (7). Thereafter, for any change in temperature ΔT_a, using Equation (7) determine the correct value for R_{TC}. Then using the original $I^2R_W = f(\sqrt{u})$ curve the velocity can be found.

LIST OF SYMBOLS

Symbols:	Definition
A, B	empirical constants in King's Equation.
I	current through the wire.
r_b	bridge ratio.
R_W	hot-wire resistance at operating temperature.
R_o	hot-wire resistance at t_o.
R_a	hot-wire resistance at t_a.
R_{WT}	hot-wire resistance at $t_a = t_{ai}$.
R_c, R_b	bridge resistances (see fig. 1).
R_{LC}, R_{LT}	lead resistances from the bridge to the hot-wire probe when it is the calibration tank and tunnel respectively.
R_{TC}	variable bridge resistance used for compensating for temperature changes.
t_a	temperature of air surrounding the wire in ^oR.
t_W	temperature of wire in ^oR.
t_o	32^oF.
u	mean velocity of air past hot-wire.
α	thermal coefficient of resistance --- $0.00189/^oF$, for 0.001"d. platinum wire (as found experimentally).
ΔR_a	change in R_a due to temperature change.
ΔR_W	change in R_W due to temperature change.
ΔR_{TC}	change in R_{TC} due to temperature change.
Δt_a	$t_a - t_o$.
Δt_W	$t_W - t_o$.
$\Delta T_W = \Delta T_a$	$t_W - t_{Wi} = t_a - t_{ai}$.
( )i	values when bridge is initially balanced in the calibration tank.
( )t	values when bridge is initially balanced in the tunnel after calibration.

References:

1. Baldwin, L. V. Slip-flow heat transfer from cylinders in subsonic airstreams. NACA TN 4369, September 1958.

2. Earle, E. N. Mean velocity profiles for flow over a plane, smooth, heated boundary. M. S. Thesis, 1960, Colorado State University.

List of figures:

1. Circuit diagram of mean velocity hot-wire bridge, (basic circuit used at Colorado State University Aerodynamics Laboratory.)

2. Effect of ambient air temperature on $I^2R_W = f(-\sqrt{u})$, for a constant R_W.

3. Effect of ambient air temperature on $I^2R_W = f(-\sqrt{u})$, for $\Delta R_{TC} = R_o r_b \alpha \, \Delta T_a$.

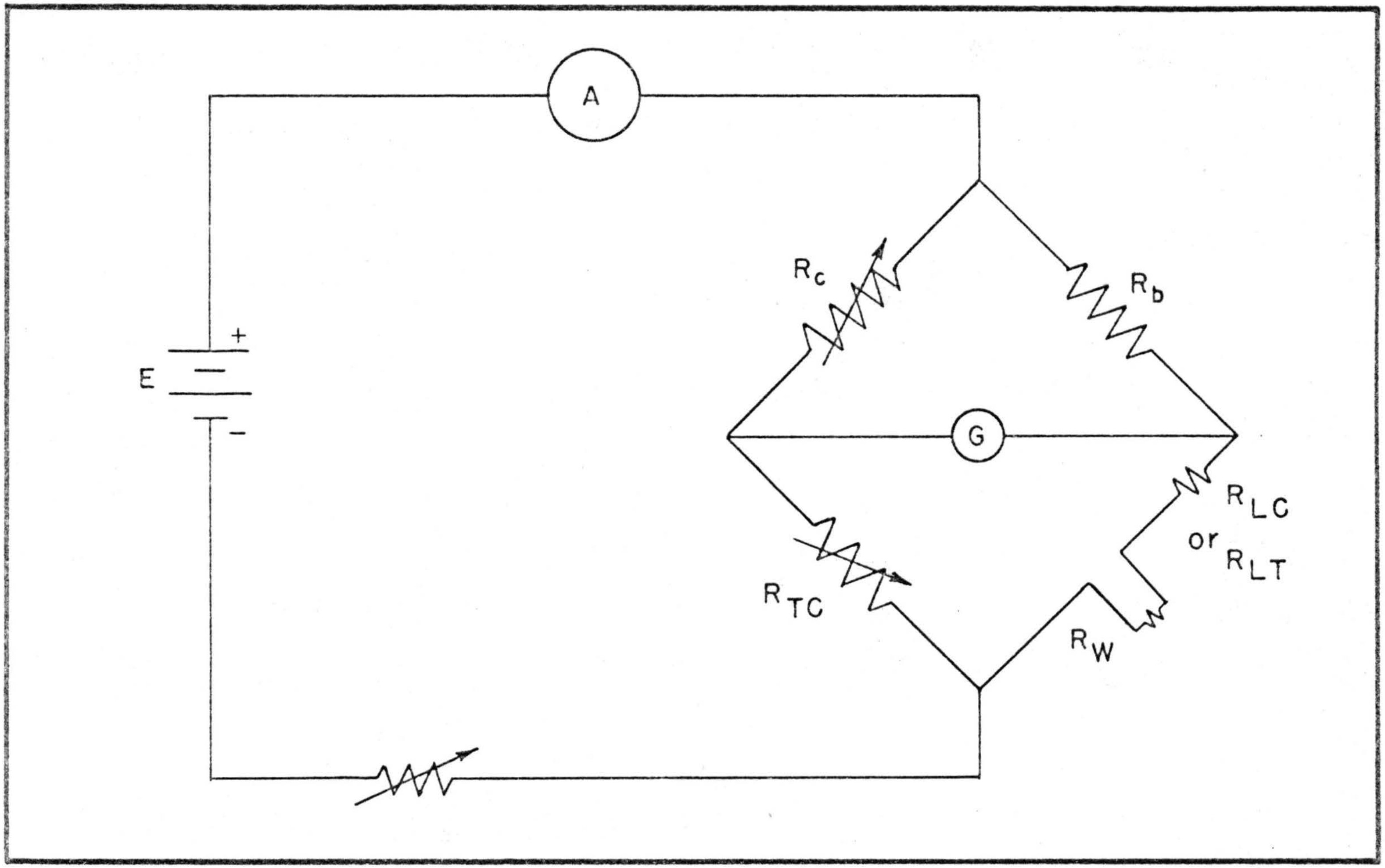

FIG. 1 CIRCUIT DIAGRAM FOR MEAN VELOCITY HOT—WIRE ANEMOMETER
(BASIC CIRCUIT USED AT CSU AERODYNAMICS LAB.)

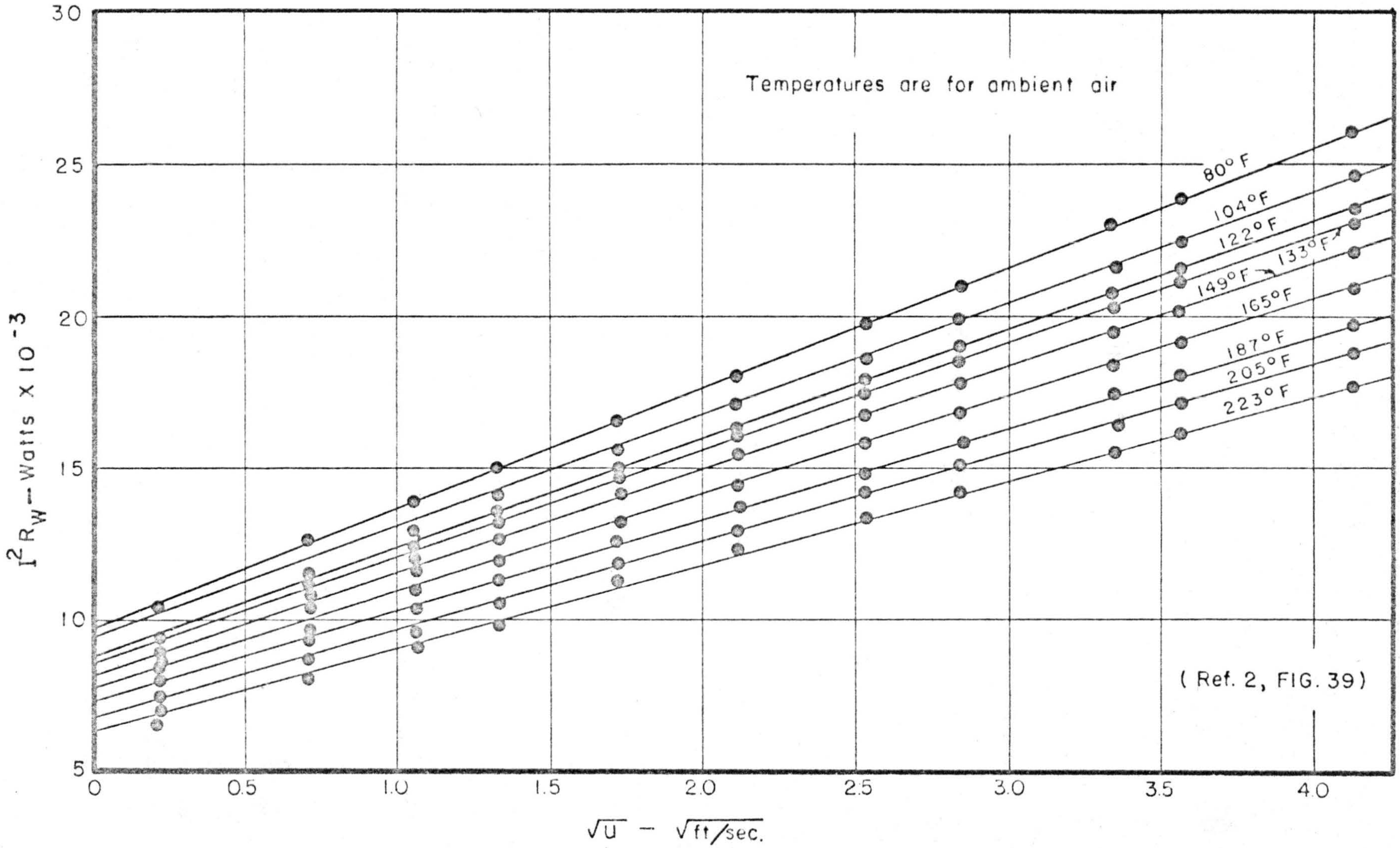

FIG. 2 EFFECT OF AIR TEMPERATURE ON CALIBRATION CURVE FOR R_W CONSTANT

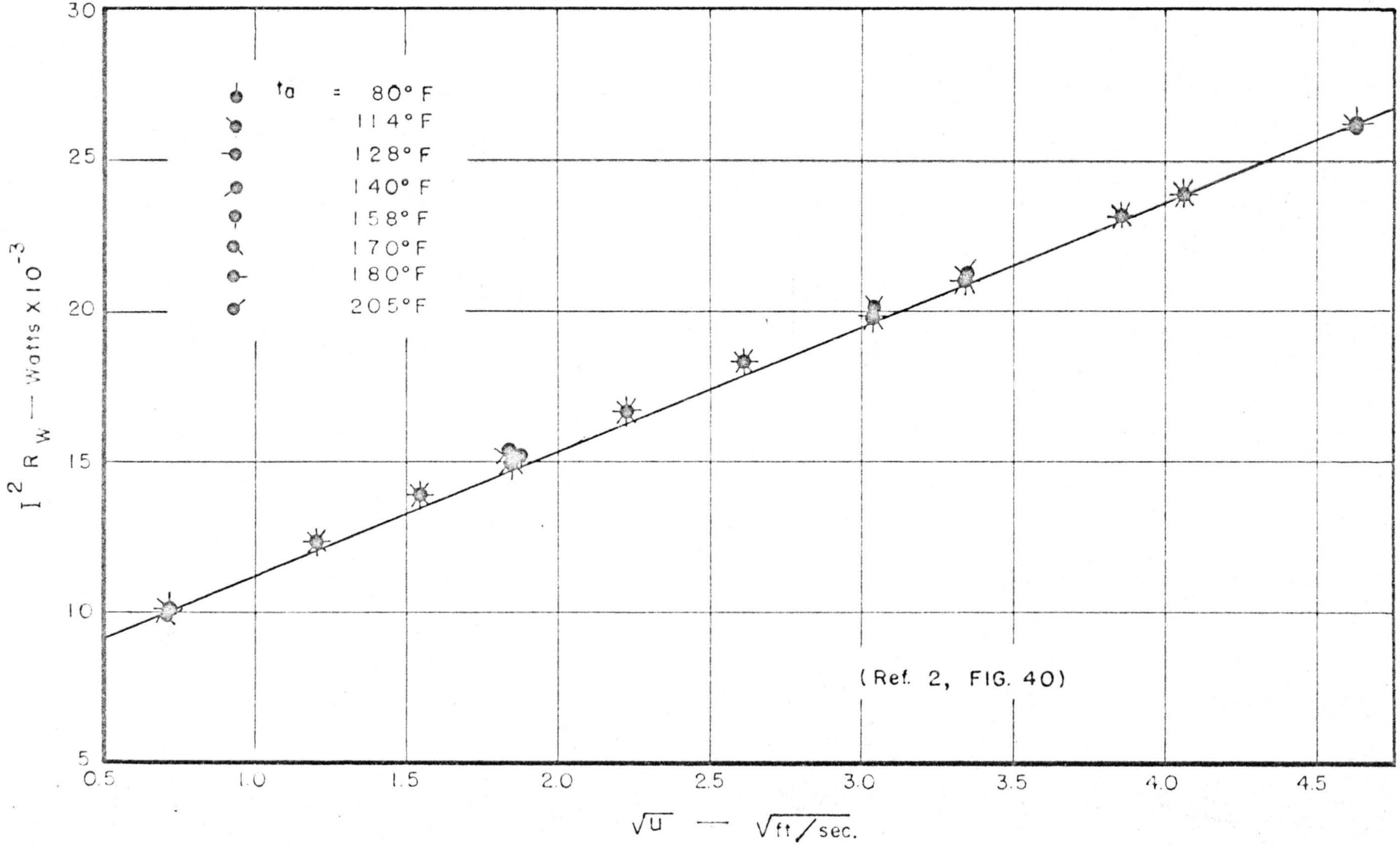

FIG. 3 EFFECT OF AIR TEMPERATURE ON CALIBRATION CURVE FOR $\Delta R_{TC} = R_o r_b \alpha \Delta T_a$

APPENDIX 3

A LIST OF MANUALS FURNISHED BY COLORADO STATE UNIVERSITY

Instrument	Type	Manufacturer	Type of manual
Pre-amplifier	122	Tektronix Instrument Co. S. W. Millikan Way P. O. Box 500 Beaverton, Oregon	Instruction manual
Water cooled Dynaspede	WCM-210	Eaton Manufacturing Co. Dynamatic Division Kenosha, Wisconsin	Instruction manual
Audio Oscillator	200 J	Hewlett-Packard Co. 275 Page Mill Road Palo Alto, California	Operating and servicing manual
Oscilloscope	S-12-C Rak-scope	Waterman Products Co. Philadelphia 25, Pa.	Instruction manual
Millivolt Potentiometer	8686	Leeds-Northrup Co. 4907 Stenton Ave. Philadelphia 44, Pa.	Directions
DC pointer Galvanometer	2340 d	Leeds-Northrup Co. 4907 Stenton Ave. Philadelphia 44, Pa.	Bulletin ED 2 (2) 1960
- -	- -	Leeds-Northrup Co. 4907 Stenton Ave. Philadelphia 44, Pa.	Conversion tables for thermocouples

Appendix 3 continued on next page.

Appendix 3 - cont'd

Instrument	Type	Manufacturer	Type of manual
DC Milliammeter	DP-9	General Electric Co.	Instrument instructions GEJ-447J
Turbulence Hot Wire Bridge	IIHR	Hubbard Instrument Co. Iowa City, Iowa	Operating manual, State Univ. of Iowa, Studies in Engineering, Bulletin 37
DC Power Supply	16 FL	Scintillonics Instrument Co. Fort Collins, Colorado	Circuit schematics
DC Power Supply	AB 128	Scintillonics Instrument Co. Fort Collins, Colorado	Description
Manometer	34 FB 2	Meriam Instrument Co. 10920 Madison Ave. Cleveland, Ohio	Bulletin G-14
Decade Resistor	1432	General Radio Co.	Catalog pages 155 and 156
Gear Motor	IR-SC	Century Electric Co. St. Louis 3, Missouri	Bulletin 4 - 1 pages 1 and 2