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A VENTILATION INDICATOR FOR
SUBMARINE STORAGE BATTERIES

By Tad L. Hankins, G. W. Work,
M. H. Boyer and F. S. Thomas

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Approved by:

J. C. White, Head, Electrochemistry Section

Dr. P. Borgstrom
Superintendent, Chemistry Division

Rear Adm. A. H. Van Keuren, USN (Ret.)
Director, Naval Research Laboratory

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ABSTRACT

An instrument for the measurement of the individual cell ventilation of submarine storage batteries is described. It is based upon the principles of hot wire anemometry, is simple in construction and easy to build. It has been found to possess a stable calibration over periods of time as long as it has been observed. Details of its construction and adjustment are given.

It is shown that with certain changes the instrument can be adapted to the measurement of many other types of air or gas flow such as wind velocity, air flow in ducts, air speed indication, etc. It can be used with recording electrical instruments in order to obtain a continuous record.

INTRODUCTION

A. Authorization.

1. The study was authorized by Bureau of Ships letter SS/S65-4 (8638) of November, 1942, Bureau of Ships Base Project Order No. BP7R.

B. Statement of the Problem.

2. The problem consisted of the development and procurement of an air flow-meter suitable for the measurement of the individual cell ventilation of submarine storage batteries.

C. Known Facts Bearing on the Problem.

3. A submarine storage battery evolves hydrogen gas at various rates during charge and at a very low rate during discharge or stand. In order to remove this hydrogen from the space above the electrolyte in the cells, they must be separately and properly ventilated. This is done by drawing air from the battery compartment into and through the cell and discharging it outboard or into some other part of the submarine. The rate of ventilation depends upon the particular region of the normal charge-discharge cycle in which the battery is operating; in general it is about 1 cubic foot per minute per cell during stand and discharge and about 4 cubic feet per minute per cell during charge. The system which supplies this ventilation is so arranged that all cells in a battery tank are connected in parallel to the input of a single ventilation blower. Such an arrangement is subject to wide variation in the flow of air through individual cells if small differences exist in the flow resistance either of the cells or the ventilation ducts leading to them. In order to make possible the equalization of this air flow, a variable restriction is built into each cell top so that its resistance can be adjusted until all cells are being ventilated at approximately the same rate.

4. In balancing the air flow through a large number of branches of a parallel system, the measuring instrument which is to be used must either cause negligible disturbance of the air flow or the same proportionate disturbance in all branches. The effect of inserting a measuring instrument will, however, depend upon the relative values of the pressure drop across the instrument and the pressure available for forcing the air through the system. If they are of the same order of magnitude the disturbance will be very large. If the drop across the instrument is very small compared to the total, the disturbance will be negligible.

5. The vacuum produced by the ventilation blower of a battery tank is a few inches of water. Most of this is lost in the ventilation system, the drop through the cell itself being about 0.25 inch of water at a flow of 6 c.f.m. and at the largest restrictor opening. It is very likely that the pressure loss in the ventilation system is different at different points in the system so that the vacuum available at the cells will vary throughout the battery. It is also expected that the resistance of the cells will be subject to considerable variation. These expectations are borne out by the differences in restrictor settings which are

necessary to balance the ventilation. It is therefore presumable that alteration of the cell resistance by a comparatively large amount, such as would be obtained with insertion of the conventional types of air flowmeters into a cell ventilation system, will have a disturbing effect which will not be the same throughout the battery. Proper equalization of the ventilation would consequently be impossible with such instruments and it has been desirable to obtain, for this use, air flowmeters which cause negligible alteration of cell resistance. Two fundamentally different instruments which approach satisfaction in this requirement have been used, namely the Alnor "Velometer" and a modified type of the Ower vane anemometer.

6. The Alnor "Velometer" introduces a small pressure loss into the air flow path and utilizes this loss to drive a vane against a spring. The vane is suspended by means of a pivot and moves in a circular path. Its displacement depends upon the air flow rate and is indicated visually by means of a pointer fastened directly to the pivot, which moves across a scale calibrated directly in cubic feet per minute.

7. It has been determined that this instrument has a pressure drop equal to or somewhat larger than that across a cell. It is used by placing it on the cell intake vent in place of the regular battery cap, and the change in pressure resulting from the substitution is equal to the difference between the drop across the instrument and that across the cap. The drop across the cap is less than $1/2$ the drop across the cell, depending on the restrictor setting; consequently it is seen that substitution of the instrument for the battery cap will produce a comparatively large change in total cell resistance. In view of this fact the Laboratory has been of the opinion that the instrument is not suitable for ventilation balancing. [Reference (a)].

8. Beyond the pressure drop involved, the instrument is also somewhat unsatisfactory in that it exhibits a serious fluctuation of the reading which makes accurate estimation of the air flow difficult, has its lowest sensitivity in the region of 4 to 6 cubic feet per minute where it is most frequently used, and is inclined to be somewhat unstable in calibration [Reference (b)]. It has one distinct advantage over the "Ower" instrument however, in that it gives direct and nearly instantaneous readings of the air flow in cubic feet per minute.

9. The Ower instrument was developed at this Laboratory in conjunction with the Supervisor of Shipbuilding, Groton, Connecticut. It consists of a low range Short and Mason "Ower" vane anemometer built into a funnel shaped tube. The small end of this tube is of the proper size to fit into a cell intake vent; the large end contains the anemometer, straightening vanes and a cover which permits entrance of air around the edge. The velocity of air passing through this tube and thus the volume per unit time is indicated by the speed of revolution of the anemometer fan. There is no means for showing the instantaneous speed of this fan; instead it is back geared 50 to 1 to a pointer, the average speed is determined by timing one revolution of the pointer with a stopwatch, and the airflow is then read from a calibration curve giving cubic feet per minute against time required for one revolution of the pointer. The extra time and inconvenience involved in this operation renders the instrument somewhat inferior to the Alnor "Velometer" in case of use.

10. Measurement of the pressure loss across the "Ower" anemometer gave a value of 0.004 inch of water at a flow of 6 c.f.m. At the same flow, the drop across the battery cap is 0.06 c.f.m. Since the total drop across the cell is about 0.25 inch at this flow and with the largest restrictor opening, it is thus seen that this instrument can cause about a 25% decrease in the resistance of a cell when it is substituted for the regular battery cap, as a consequence of which the cells of a battery balanced with this instrument should normally be receiving less than the indicated amount of ventilation. This in itself would not be serious, however, since in service the ventilation of a battery is always adjusted by means of the installed flowmeter. Of more importance is the error in equalization of the ventilation which results. It is doubted that this error is as large as would be indicated by the approximately 25% change in resistance which occurs when the instrument is placed in a cell. At the present time there is little or no information on this point except in the reports of the Supervisor of Shipbuilding, Groton, Connecticut, to Chief of the Bureau of Ships on the battery ventilation balancing of submarines built at the Electric Boat Company. These show, over a period of several years, that the sum of the air flows through the cells of a submarine battery as read on an Ower type air flowmeter are less than the total ventilation as read on the installed flowmeter by amounts varying from 5 to 20%. It is seen, however, that this error is in the opposite direction from what would be expected. Since a cell has a lower resistance with the instrument in place, the flow should be higher and the sum of the readings should exceed that of the installed instrument. At the present time the explanation of these anomalies is not available.

11. The subject instrument represents an attempt to resolve the difficulties which exist in present methods of measuring cell ventilation. It was developed in conjunction with the Wm. O. Hebler Company and represents a modification of this company's standard instrument for the measurement of thermal conductivity of gases, in which the cooling of a hot wire by convection or gas velocity has been substituted for cooling by thermal conductivity. It has been possible to eliminate from this instrument all of the objectionable features mentioned in connection with the "Ower" and "Alnor" indicators. It reads air flow directly, adds no effective resistance and in no way disturbs the air flow through the cell. The reading exhibits almost no fluctuation under steady flow, the calibration is stable over long periods of time and can be adjusted to a linear or almost any other form desired. The parts are inexpensive and easily procurable. Its only apparent disadvantage is that each unit must be individually adjusted by hand to the desired characteristics. At the present time 25 units of the instrument have been built for the Bureau of Ships and distributed to various activities of the U.S. Navy as directed by Reference (c).

THEORETICAL CONSIDERATIONS

12. The most comprehensive studies on the loss of heat from a body immersed in a fluid have been made by King [Reference (d)]. The subject is also extensively treated by Ower [Reference (e)]. The conclusions which are presented in these treatises may be outlined as follows.

13. Heat may be lost from a body mainly in three ways; namely, radiation, thermal conductivity and convection, and the total loss will be the sum of the losses by these three processes. The first two are independent of fluid flow past the wire, the latter however, depends upon the velocity of fluid flow according to a law which has been mathematically derived only for regions somewhat removed from the zero point. This law indicates that the heat loss from a body by convection is proportional to the square root of the velocity. That is:

$$H_c = K V^{1/2} \theta \quad (1)$$

Where

H_c = heat loss by convection.

θ = temperature difference between the body and its surrounding fluid.

K = a constant

V = velocity of the fluid.

14. It has been shown by Reference (d) that this law is substantially obeyed if the temperature of the hot body is maintained constant. However, if the heat input to the body is maintained constant instead, then at equilibrium the total heat loss will equal the heat input and the temperature of the body will depend upon the fluid flow as follows:

$$H = K V^{1/2} \theta + K_T \theta$$

where K_T is the thermal conductivity of the fluid. (The heat loss by radiation is neglected since at low temperatures it will be inappreciable.) Then

$$\theta = \frac{H}{K V^{1/2} + K_T} \quad (2)$$

It will be observed from this equation that as the fluid velocity increases, the temperature drops by an amount which tapers off and approaches asymptotically to a line representing the condition where the temperature of the body has reached the temperature of the fluid. This behavior is shown by Curve 2 of Plate 1.

15. In the region of air flows approaching the zero point the preceding considerations do not apply. The phenomena which take place here do not appear to have been satisfactorily treated from a theoretical standpoint. It has appeared, however, from brief studies conducted at the Laboratory that in this region the heat loss by convection varies according to something resembling the square of the velocity for comparatively low temperatures. Similarly to the previous manipulations, this leads to the relation

$$\theta = \frac{H}{K V^2 + K_T} \quad (3)$$

The Curve corresponding to this relation for low value of V is shown by Curve 1 of Plate 1. This equation also predicts as S shaped curve for somewhat higher values of flow. Such curves can be obtained experimentally as shown on Plate 2.

16. The above considerations do not include the effect of changes in the density of the air under observation such as would result from changes in barometric pressure. It has been shown, however, in References (d) and (e) that loss of heat by convection from a hot body varies as the square root of the density of the gas for the regions of air flow in which Equation 1 applies. It then follows from Equation 2 that the temperature of the wire will vary inversely with the square root of the density. For regions of air flow in which Equation 3 applies, no information as to the effect of density on the heat loss is available.

17. It should be noted at this point that measurements on the cooling of hot wires discussed in References (d) and (e) were carried out with the wire suspended in a comparatively large volume of free air space. Under these conditions free convection currents were set up around the wire which had a cooling effect in addition to that from the measured air flow past the wire. It was suspected by Reference (e) that certain anomolous results which were obtained in the region of zero measured air flow were due to the presence of this free convection. In the subject work, however, measurements were made upon a hot wire enclosed in a small tube, the desired air flow past the wire being obtained by passing air through the tube. It is known that free convection currents are negligible around hot wires which are enclosed in this way [Reference (f)]. It is therefore to be expected that the true relation between air velocity and wire temperature would be obtained down to zero velocity. In support of this is the fact that the anomolous behavior reported in Reference (d) was not observed. It should also be noted in conjunction with these considerations that the work of References (d) and (e) deals with a straight wire suspended perpendicular to the flow stream. The subject work was done with wires wound in the form of a helix and suspended nearly parallel to the air stream.

18. The electrical resistance of most metals closely approximates a linear function of temperature within certain limits of temperature. Consequently the resistance of a metal will change within this region in the same way as does the temperature, and Curves 1 and 2 of Plate 1, therefore, also represent the relation between the change of electrical resistance of a metal, and the velocity of the surrounding fluid. Application of the foregoing considerations to the measurement of air flow is thus accomplished by measurement of the cooling effect on a hot wire through its change in resistance when it is subjected to the air stream under observation. The wire is included as one leg of a Wheatstone bridge and is heated by the bridge current. If the bridge then is balanced with the hot wire in still air, its subsequent exposure to an air flow will cause an unbalance which will be proportional to the change in resistance of the wire. This unbalance may be measured by means of a suitable microammeter connected across the bridge. It will be observed that deflections obtained on such a meter will be proportional to the decrease in temperature of the wire. Consequently, the curves of deflection against air flow will be of the same shape as those of temperature decrease against air flow. Curves 1 and 2 of Plate 1 were obtained by measuring the unbalance of such a bridge for various rates of air flow.

19. Inspection of Curves 1 and 2 of Plate 1 reveals that they are supplementary to each other; that is, where one has its maximum sensitivity the other is at a minimum and vice versa. It is seen that if they are added, the sum will be a curve which will approach a straight line. It has been found possible to construct an air flowmeter for which use is made of this phenomena to produce a straight line calibration. It is based upon the fact that when a fluid is flowing through a tube containing a restriction of any type, a difference will exist in the fluid pressure on the two sides of the restriction and if a by-pass is inserted around the restriction, this pressure difference will cause fluid to flow through the by-pass. The rate of such flow will be function of the rate of flow through the main tube, and a hot wire inserted in the by-pass can be used to measure the flow through the restriction.

20. The subject instrument makes use of two such by-passes; one is of large diameter throughout and permits rapid flow past the wire; the other contains a restriction to limit the flow to a low value; both of these rates, however, being dependent on the rate of flow through the main tube. These two by-passes contain hot wires which are operated at low and high temperatures respectively. It is thus seen that flow through the main tube will produce in one hot wire a change in resistance corresponding to Curve 1 of Plate 1, and in the other a change corresponding to Curve 2. These two hot wires may then be connected into a suitable Wheatstone bridge network so that the sum of their resistance changes is shown on a suitable microammeter. By proper selection of rates of flow through the by-passes and of wire temperature, this sum can be made to assume an essentially linear relation to rate of flow through the main tube.

21. The resistance change of the two hot wires are caused to add by connecting them as opposite legs of a Wheatstone bridge, as shown in Plate 3. Legs 1 and 4 are the active legs and legs 2 and 3 are inactive. Leg 1 is in the high flow by-pass and consequently must be operated at a lower temperature than leg 4 which is in the low-flow by-pass. This is accomplished by means of the resistance R_3 which shunts part of the bridge current around leg 1. In order to maintain bridge symmetry a similar shunt must be placed around leg 3.

STRUCTURAL CONSIDERATIONS

A. General Form.

22. The subject instrument has been designed around the theoretical principles outlined in the preceding sections. It consists of a main flowtube through which the flow to be measured passes and to which is mounted the by-pass and hot wire bridge assembly; and a control box containing electrical connections, necessary rheostats and resistors, and the indicating meter. The two are joined by any desired length of five conductor cable.

23. The flowtube is so designed that one end is a replica of the standard battery intake vent, including the cap. The other end is designed to fit into a battery intake vent in place of the regular cap and form a continuous extension of the vent tube. The net result of placing the flowtube in a battery is thus merely the lengthening of the vent tube by about 6 inches which produces negligible disturbance of the normal air flow through the battery. The restriction which provides the pressure drop in the flowtube is the battery cap. It has been found that the drop across a battery cap at a flow of 6 c.f.m. is about 0.06 inches of water. Under normal operation this drop creates a vacuum of that magnitude in the flowtube which is utilized to draw air through the by-passes and over the hot wires or filaments. A diagram of the flowtube, including the by-pass and filament assembly, in place is shown in Plate 4.

24. In order to maintain a symmetrical arrangement of the four hot wires which comprise the Wheatstone bridge and thus minimize errors due to temperature changes and thermal conductivity of the gas, they are made into four identical legs and placed in four symmetrically located chambers in a single brass block. One of these chambers is included in each of the two by-pass paths and the filaments they contain comprise opposite legs of the bridge. The other two filaments are isolated from all flow effects, provision being made however for the surrounding atmosphere to enter their chambers by diffusion. This balances out any changes in the thermal conductivity of the air due to the presence of hydrogen, carbon dioxide or other gases. The filament block is shown in the drawing of Plate 7 and the photograph of Plate 5.

25. The control circuit for the instrument consists essentially of means for measuring and controlling the bridge current, for adjusting the bridge balance, and for indicating the unbalance which occurs with flow. The same meter is used to indicate both bridge balance and bridge current. A switch is used to select the desired indication. The instrument normally possesses a temperature coefficient due to changes in gas density, temperature coefficient of the meter, and perhaps other causes, which acts to increase the reading for a given air flow as the temperature increases. This has been eliminated by insertion of a nickel compensating resistor in the bridge current measuring circuit which automatically increases the bridge current as the temperature rises. By adjustment of the magnitude of this resistance it is possible to compensate the instrument so that a given reading indicates air flow independently of temperature either according to the weight of air which is passing, or according to the actual volume at the temperature of the measurement. The subject instruments were all adjusted to possess the former type of compensation since the rate of hydrogen evolution by a battery is by weight rather than by volume. If desired, the true volume of gas passing through the flowtube at the ambient temperature of the measurement can be calculated by means of the following equation.

$$V = \text{Reading} \times \left(\frac{\text{Temperature } (^{\circ}\text{F}) + 459}{534} \right)$$

V = True Volume

B. Details of Design.

26. The Flowtube. A working drawing of the flowtube is shown on Plate 6. It consists of a wooden tube shaped as indicated with a flat place cut into the center section to receive the filament block base plate. Since wood is attacked by sulfuric acid solutions to some extent it was thought advisable to impregnate the end of the tube which is to be inserted in the battery vent with an acid resistant resin. Polystyrene was used for this purpose, but was not found to be very satisfactory. It is believed that a more satisfactory solution would be to mold the tubes completely from hard rubber or a suitably acid resistant synthetic resin.

27. Filament Block and Base Plate. Working drawings for the filament block and base plate are shown in Plate 7. The two are designed to fit together so that the passages through them are connected by a substantially gas tight joint and are in perfect alignment. This is accomplished by means of a male-female joint, which is formed by allowing the two tubes in the base plate to extend slightly from the surface which is to receive the filament block and countersinking the corresponding passages in the filament block to receive them. Necessity for care at this point is due to the fact that leakage or any projections into the passage may cause disturbances in the flow past the filaments which will produce fluctuations in the reading. For this reason also it is necessary that air enter the filament chambers through entrance tubes which are long enough to permit smoothing out of turbulence in the air flow created by the entrance.

28. The flow rate through the low-flow by-pass is restricted by means of an orifice about 0.028 in. diameter. Because of its small size any alteration in its characteristics can have a comparatively large effect on the calibration of the instrument. In order to minimize the possibility of changes in this orifice over a long period of time, the orifice plate is made of 0.020 inch gold sheet. It is soldered to the end of the by-pass entrance tube which is cut off at a 45 degree angle to facilitate drilling of the orifice in place (as shown). Since conventional lead-tin solders alloy rapidly with gold, a special solder for gold, consisting of 96.5% tin and 3.5% silver, manufactured by the Sigmond Cohn Company of New York City, is more suitable for this purpose.

29. A photograph of the assembled flowtube and filament block unit is shown in Plate 8.

30. The Filament. The selection of the proper material for the filaments was a problem involving considerable investigation. Platinum has long been used satisfactorily for such purposes; its chief disadvantages being its softness, and its low temperature coefficient of resistance as compared to some other elements. Nickel has been similarly used to some extent and possesses the advantages of hardness and higher temperature coefficient of resistance over platinum. For use in air mixtures containing hydrogen, both of these metals suffer from the disadvantage of being somewhat catalytically active toward the reaction between hydrogen and oxygen; platinum much more so than nickel. A third metal which appeared to have many excellent qualities for this purpose was tungsten.

It has a high temperature coefficient of resistance, is very hard and springy, and is not catalytically active. Its biggest advantage, however, is that tungsten filaments are commercially procurable from the electric lamp industry.

31. A very important requirement of the four hot wires in the bridge of the subject instrument is that they maintain constant resistance indefinitely. This in turn requires a high resistance to corrosion. Since platinum was the only one of the three metals for which the corrosion resistance was known, it was necessary to set up tests to determine this property for nickel and tungsten. The test consisted of suspending filaments of these two metals in an atmosphere saturated with water vapor and observing their resistances over extended periods of time. A saturated atmosphere was chosen because this represents the most corrosive condition to which the instrument could be subjected in service.

32. The test brought out immediately the fact that commercial tungsten filaments are unsatisfactory due to a tendency to develop variable contact-resistance at the contact between the filament and its lead. Connection at this point was made either by crimping or nickel welding; in general the nickel welded contacts were more stable but neither type was completely satisfactory. It was subsequently discovered that an electrically stable bond could be made between the filament and its lead by flame soldering the contact with common silver solder. A number were so treated and placed on test along with an assortment of unsoldered tungsten filaments and some nickel filaments made at this Laboratory, the contacts of which had been soft soldered. The observations which were made from these tests may be listed as follows:

- (a) The unsoldered tungsten filaments all developed variable contact resistances after a few days with the exception of a few special nickel welded types.
- (b) After a few weeks the tungsten filaments began to develop open circuits. This process proceeded slowly and required 4 to 6 weeks for its completion. Eventually, however, it extended to all of the tungsten filaments including those which had been silver soldered.
- (c) Tungsten filaments which had been silver soldered showed no variation of resistance up to the time they developed open circuits.
- (d) The nickel filaments showed no variable resistance and no open circuits after approximately 16 weeks on test.

33. The above results indicate clearly that tungsten is inferior to nickel as a filament material for the subject instrument. Nickel filaments were accordingly adopted for use.

34. The hot wire filaments which have been used are diagrammed in Plate 9. The supporting button is of bakelite, $3/32$ " thick and $1/4$ " in diameter. Leads entering through the bottom are of copper; the filament center support is of phosphor bronze and extends a distance of about $7/16$ " from the inner surface of the bakelite button to the loop at its outer end. The filament leads extend about $1/16$ " through the button so that the filament is of a length of $3/8$ " on each side. The filament itself consists of 140 turns of 0.001" nickel wire formed by winding on an 0.008" mandrel. This requires about 4" of straight wire and produces a cold resistance of about 21 ohms. The above specifications are not critical and some adjustments could probably be made. Specifications as to the rest of the electrical circuit are however, probably strongly dependent upon the filaments and would require corresponding changes. In any case the filaments should be made as consistently as possible in all respects in order to minimize subsequent adjustments on the instruments. Filaments which have been used in the subject instrument have all been within the resistance tolerances of ± 0.5 ohms, cold.

35. The filaments are mounted onto the cell block with the bakelite button countersunk into the filament chamber as shown in Plate 9. There must be no leakage around this button and the most suitable material which has been found for cementing them in place has been a thermosetting bakelite cement, PG-1, made by the Dolph Corporation. The filaments must be positioned in their chamber so that the plane in which the filament loop lies is perpendicular to the side tubes through which the air enters. They must also be well centered. A terminal base with five contacts is fastened directly to the filament block and serves for making connections between the filaments and the rest of the electrical systems. (See Plate 5).

36. The Indicating Meter. The indicating meter which has been used in the subject instrument is a special microammeter used by the Wm. O. Hebler Company in its commercial thermal conductivity instruments. They were supplied by this company. They have a coil resistance of 28 ohms and a full scale range which varies somewhat from one instrument to another but averages about 300 microamperes. The company which makes these meters is not known.

37. The Electrical Network. Plate 3 shows the circuit diagram for the complete air flowmeter. Resistances R_5 , R_6 , R_7 , R_8 , are the filaments and are shown connected in the conventional bridge. R_7 and R_5 are the active legs, R_7 being the low temperature filament and accordingly being shunted with resistor R_3 . To maintain symmetry, R_8 is shunted with R_4 which has exactly the same resistance as R_3 . It has been found necessary to adjust

the value of this resistance for each instrument in order to obtain a linear calibration curve. Its value is critical, however, it will be in the neighborhood of 10 ohms for filament resistances of 20 ohms. These resistors should be wound of manganin.

38. Resistance R_2 is the bridge current shunt for the indicating microammeter. It is also of manganin and individually adjusted so that the potential across it will give a full scale reading on the meter at the desired bridge current. When the meter is switched to measure this potential, resistors R_1 and R_{10} are in series with it. R_{10} is of pure nickel wire and R_1 of manganin. It is seen that any change in the value of these resistors will alter the sensitivity of the meter to current through R_2 , and will consequently alter the bridge current which flows at a full scale reading. Thus by properly choosing the values of R_1 and R_{10} the normal temperature coefficient of the instrument is compensated for by an automatic change in bridge current (see paragraph 25).

39. The balance rheostat makes possible final adjustment of the bridge to zero potential at zero air flow by adjustment of the current through the two sides of the bridge. It should be of low resistance and smooth action and should have contacts which do not foul. Present instruments have been equipped with 4 ohm wire wound rheostats but this does not permit fine enough adjustment and it is necessary to shunt them with a resistor of about 1 ohm (R_{11}). It is believed that a type of 1 ohm single slide wire rheostat recently developed by the "Ohmite" Company may be more satisfactory.

40. The current rheostat should be about 25 ohms and also of smooth action. It has been found that the type P-58 wire wound resistor manufactured by the Clarostat Company is satisfactory.

41. Resistor R_9 of about 5 ohms was inserted in series with the external power terminals in order to make possible operation on 4 volts. By raising the value of this resistor, provision could be made for operation on 6 volts. In selecting the proper resistance for R_9 , it must be born in mind that sufficient reserve movement must be allowed in the current rheostat to provide the changes in bridge current called for by the temperature compensating resistor R_{10} .

42. The two switches used in the subject instrument, particularly the bridge current - balance selector switch must be of a type which has a constant contact resistance. It has appeared that silver plated wiping contact switches are satisfactory. Greater dependability in this respect is obtained if double-pole, double throw switches are used and the contacts ganged in pairs. Centralab switches No. 1458 are presently being used. This switch has the added advantage of having no open circuit position so that the indicating meter cannot be left with its coil unshorted when the meter is not in use or being transported.

43. All electrical contacts in the instrument must be soldered. Pressure contacts are generally not satisfactory.

44. Power Supply. In order to make the instrument self contained, an internal power supply of four "D" flashlight cells has been built into it. They are arranged in two parallel banks of two cells each, in series, giving a potential of three volts. They are connected into the network through the power supply selector switch.

45. Terminals are provided for the operation of the instrument on an external power supply. They are connected into the circuit network through the opposite side of the power supply selector switch. Four volts was chosen as the supply voltage since it is easily obtained from any two cells of a submarine storage battery. It should be noted that the voltage applied to these terminals has no significance; the only critical quantity is the bridge current. As long as this is accurately set at the proper point, the instrument will operate correctly and any range of voltages may be used within which this is possible.

46. Adjustment of Circuit Constants. Calibration of the instrument was, in all cases, carried out by drawing air through the flowtube at a known, constant rate. This was accomplished by means of a 5 cubic foot gas holder which was adjusted to either draw in or exhaust its contents at a constant rate throughout its run. It has been found that air flow so obtained is constant to a high degree and free from fluctuations.

47. In order to produce a linear calibration curve for the instrument the values of by-pass orifice diameter and shunt resistances must be carefully adjusted. This is done mainly by trial and error. The average value of these constants has been found to be about 0.028" orifice diameter and 10 ohms shunt resistance. These are usually taken as the starting values.

48. A copper plate is soldered onto the end of the orifice tube and a .028 hole drilled into it. Two decade resistance boxes, variable in steps of 0.1 ohms are connected into the electrical network in the position of resistors R_3 and R_4 . They are set at a starting value of 10 ohms. The instrument is then calibrated and from the shape of the resulting curve, corrections may be deduced and applied.

49. In order to do this it is desirable to consider the changes in the shape of the calibration curve which are brought about by small differences from the proper value of these calibration constants. It has been seen that the low temperature (shunted) filament has its maximum sensitivity in the initial part of the calibration curve and that the high temperature filament has its minimum sensitivity at this point. At the top end of the calibration curve the opposite is true. In general it may be said that the lower temperature filament controls the shape of

the lower end of the curve, and the high temperature filament controls the upper end. Thus if the initial calibration curve shows a hump or a sag at the lower end it may be straightened by decreasing or increasing respectively the effectiveness of the low temperature filament. This in turn is accomplished by decreasing or increasing the value of the shunt resistances.

50. Similarly, if the upper end of the curve is cupped either up or down, it can be straightened by controlling the effectiveness of the high temperature filament. This is, however, a little more difficult since the current through the high temperature filament can be changed only by changing the bridge current. This normally alters the current through the low temperature filament so that the net result is a change in range of the instrument with no appreciable change in shape of the calibration curve. The effectiveness of the high temperature filament is changed by varying the by-pass orifice size.

51. If the upper end of the curve is cupped downward, it indicates that too great a length of the normal hot wire calibration curve is being utilized by the high temperature filament. This must be corrected by decreasing the orifice size. Such a decrease will also result in an increase in the range of the instrument which may in turn be corrected by raising the bridge current. As a result of this it may then be necessary to decrease the shunt resistance on the low temperature filament. If the upper end of the curve is cupped upward, it may be corrected by corresponding changes in the opposite direction.

52. Instances may occur occasionally in which the initial resistance and orifice values are considerably in error. This will cause the entire curve to be cupped either up or down. In such cases the curve may be brought to linearity by successive adjustment of the upper and lower ends as described. In general it is better to adjust the lower end first since the operations are simpler and more easily made, and will affect a greater part of the curve. After the proper orifice size and shunt resistance have been determined, a gold orifice plate may be substituted for the copper one and fixed resistors for the two decade boxes.

53. It has been found that after experience has been obtained in the adjustment of these instruments an average time of approximately 1 hour per instrument is required for the operation. Satisfactory adjustment was regarded as obtained with instruments built at this Laboratory when departures of the calibration curve from a straight line did not exceed 0.1 c.f.m. at any point. After the calibration curve has been reduced to linearity, it will hold its shape over a fairly wide region of bridge currents. The instrument may be set to measure any range of air flows corresponding to a value of bridge current within this region.

54. If a single range instrument is desired the resistor R_2 may be set so that the proper bridge current produces any desired indication on the meter. On all instruments built at this Laboratory it was set to give full scale deflection since maximum accuracy is obtained at this point. During this adjustment it is necessary to make sure that the terminals of resistance R_2 are not heated while the calibration is being checked, as for example, from recent soldering. The indicating meter is sufficiently sensitive so that the resultant thermoelectric effects would cause considerable error, particularly if one of the terminals is joined to a metal other than copper.

55. Adjustment of the temperature compensation of the instrument consists of varying the relative values of the nickel resistor R_{10} , and the manganin resistor R_1 . Determination of the proper resistance values is by trial and error; in general a value of 30 ohms of nickel for R_{10} and 20 ohms of manganin for R_1 has been found to provide adequate compensation with the majority of instruments built at this Laboratory. Enough exceptions were obtained, however, to make necessary the checking of each one. Temperature compensation was checked by carrying out calibrations at temperatures of 35° and 100°F. Variations of calibration by not more than 0.15 c.f.m. at any point was regarded as satisfactory compensation.

56. In connection with the temperature compensation it must be borne in mind that the hot wire filament will be almost immediately responsive to the temperature of the air passing around them, whereas the compensation by the nickel resistor in the control unit must await attainment of temperature equilibrium by the entire instrument. For this reason the rate of attainment of temperature equilibrium should be speeded up as much as possible by using metal cases, or providing ventilation openings or both. For the same reason it is seen that for rapidly fluctuating ambient temperatures, or if the temperature is not uniform throughout a battery tank, the present type of compensation will not be valid. A more satisfactory arrangement would consist of two compensating coils, one mounted in the flowtube and placed in a spot conspicuous to the flowstream for compensating the coefficient of the hot wire bridge, and the other mounted in the control unit to compensate for the temperature coefficient of the indicating meter.

57. The Assembled Instrument. Plate 10 shows a photograph of the complete instrument as it has been produced at the Laboratory. It consists of the flowtube assembly, the control box and a carrying case (not shown).

CONCLUSIONS

A. Performance.

58. The first experimental models of the subject instrument to be put in service have been in use at the Portsmouth Navy Yard since August, 1943. They are very similar to the present instruments, the main exception being that they contain tungsten filaments instead of nickel and lack temperature compensation and directly calibrated scales. During this period they have undergone a total of about 200 hours operation. They have been inspected once by personnel of this Laboratory; were found to be in good condition and are still in use. It has not been possible to check their calibration but from reports received from the Portsmouth Navy Yard, it does not appear to have changed appreciably.

59. Present models as herein described incorporate many improvements designed to give the instrument greater ease of construction, dependability, and convenience of use. Particular attention has been paid to factors influencing the stability of the calibration. Due to the fact that almost all of the instruments which have been built have either been sent into service or torn down and rebuilt periodically to incorporate new improvements, it has not been possible to study the stability of the calibration for periods of more than a few months. At the present time it can be said that only one instance has been found in which the calibration has spontaneously changed after proper initial setting. As has been stated, however, accuracy of calibration is not essential to proper ventilation balancing. Of more importance is a minimum alteration of air flow when the instrument is placed on or removed from the cell. With the subject instrument the alteration is negligible as shown by the curves of Plate 11.

60. The instrument has been subjected to no formal shock test. Some idea of the shock resistance of the flowtube and cell assembly can be obtained however from the fact that they have been dropped from a height of 6 feet onto a concrete floor without damage or change of calibration. In view of the fact that the instrument has been intended for use by responsible specialized personnel rather than for general service with the fleet, extensive attempts to protect it from shock were not made. Indications have been obtained however since putting the instruments in service that the indicating meters are subject to damage. It is consequently deemed desirable to equip future instruments with suitable shock mounts for the indicating meter. In any case the instrument should be afforded the same care usually given precision electrical apparatus.

61. No attempt has been made to render the instrument insensitive to changes in barometric pressure since it appears that the difficulty of its accomplishment would be far out of proportion to the seriousness of the error involved. Fluctuations in barometric pressure generally take

place over a range of about 3% with occasional sharp rises or drops which widen this range to about 5%. As has been explained, the low temperature filament of the instrument is affected by barometric changes as the square root of the density of the atmosphere but the effect on the high temperature filament is unknown. In general, it is probably safe to assume that the overall calibration of the instrument varies directly as the density of the air. If this is correct the error from barometric changes would for the most part be within the range of $\pm 1-1/2\%$. It will be observed from a study of reference (d) that errors of the same magnitude are to be expected from both the Alnor velometer and the "Ower" vane anemometer in the range where it must be used for measurement of battery ventilation.

62. In considering the seriousness of this error, it must be borne in mind that changes in barometric pressure take place slowly and that the change which would normally be expected to take place while a battery is being equalized is very small. For this reason while the measurement of the actual flow through the cells may be slightly in error, the error in cell equalization would be negligible. It is also pointed out that changes in barometric pressure cause an inversely proportionate change in the volume of hydrogen evolved by a battery being charged at a given current. It is thus seen that if the instrument were used to control the airflow through a battery, the density error would act to reduce the volume of air which passed at a given reading proportionately with the reduction in volume of the hydrogen evolved.

B. Future Development.

63. The present mechanical form of the instrument has been strongly influenced by the problem of procurement. By keeping it in a form closely resembling certain instruments of an analogous nature which are in commercial production, it has been possible to secure much of the parts and labor through commercial channels. Some indication has been obtained, however, that this form is not the most efficient and that certain modifications will be worthy of future consideration.

64. It is believed possible that the main flowtube could be eliminated by mounting the cell block directly into a standard battery cap. This would eliminate a step in the construction of the instrument, produce a simpler and more compact unit and, more important, obviate the difficulty now encountered that the present flowtube will not fit into one particular cell of a submarine storage battery because of nearby structures. The calibration of such an instrument would, however, depend upon the dimensions of the cell intake vent. Consequently, unless these are normally held within the tolerances necessary to maintain the desired accuracy, such a modification would be unfeasible. If not, mounting the cell block in the cap and use of a shortened flowtube of about 4 inches in length would be indicated.

65. Changes in the construction of the cell block itself are also under consideration. Present cells provide a by-pass path which has a sharp 90° bend at the base of the filament loop. This was necessary in order to make possible the use of commercial loop type filaments. Such construction is, however, believed to render the range of the instrument and the shape of its calibration curve rather susceptible to the position of the filament in the filament chamber. Furthermore, it will tend to cause instability in the flowstream at this point which may be responsible for the slight fluctuation which the instrument exhibits. A much more ideal design for the by-pass system would consist of a linear flow path containing a linear filament centrally located. It is believed that cells of this type could be built with much more nearly identical characteristics than has been possible with the present type. It is also worthy of note that such cells could be more conveniently mounted in the cell cap than could the present type.

66. The meters which have been used with the subject instrument are not regarded as completely satisfactory. They are microammeters, 300 microamperes full scale and with a coil resistance of 28 ohms. The accuracy is rated at $\pm 2-1/2\%$. It has been found, however, that some of the movements tend to stick badly which makes it necessary that the instrument be strongly tapped before every reading. Also some tendency for the reading to creep has been noted.

67. Other meters are being considered, and suspension type galvanometers have been used. They have high sensitivity and accuracy and no tendency to stick or creep. Their main probable disadvantage lies in the fact that they are easily disturbed by vibration, but for most applications to which the subject instrument will be put this should not be a serious factor. Their resistance to shock is comparable to that of sensitive pivot type instruments. A photograph of one of the latest models of the instrument containing a galvanometer, manufactured by the "G-M Laboratories, Inc." series 2561 as the indicating unit is shown on Plate 12.

68. Some consideration has been given to the possibility of increasing the power output of the filament bridge so that a more rugged and less sensitive indicating meter could be used. The use of ratio meters which may to some extent decrease the sensitivity of the instrument to power supply voltage has been considered in this connection.

69. It has been pointed out in a previous section of this report that the linear calibration which the subject instrument possesses is obtained by careful adjustment of three constants, namely, the orifice size, the filament shunt resistances and the filament current, which must be done individually on each instrument. It is not certain that this linear calibration is necessary. If it is not and if the normal hot wire calibration curve would be satisfactory (see Plates 1 and 2) then it is possible that manufacture of the instruments could be somewhat facilitated by

elimination of the filament shunts R_3 and R_4 and the differential airflows in the two by-passes. When modified in this way, it is likely that all units produced by ordinary manufacturing methods would have calibration curves of identical shape. Final adjustment would then consist simply of adjusting the filament current setting to give the proper range, an operation which would require only a few minutes per instrument.

70. The calibration curves available would be as shown on Plates 1 or 2 (see paragraphs 14 and 15) namely with maximum sensitivity at the low end, maximum sensitivity at the high end or maximum sensitivity in the center. The one which is desired could be chosen merely by adjusting the rate of airflow through the by-pass. This would be a general adjustment and not one that would be different for each instrument. It would probably be more suitable with this construction to place both active filaments in a single by-pass.

C. Additional Applications.

71. The subject instrument was built for a highly specialized purpose and in its present form is not suited to any other use. At the present time, however, this Laboratory is engaged in the development of a portable modification for the measurement of flow rates in large ventilation ducts [Reference (g)].

72. Its use has also been proposed for the measurement of wind velocity, the high speed of response which it possesses, rendering it particularly suitable for the determination of gust velocity. Similarly, of course, the instrument could be used as an airspeed indicator. The principle of the hot wire anemometer combined with the by-pass arrangement under which the subject instrument operates possesses great versatility and can be adapted to a wide variety of uses in the measurement of low and high velocity gas flow. The electrical nature of the indication permits use with any of the common recording potentiometers thereby making possible continuous records of the phenomena under study.

D. Procurement.

73. Development of the subject instrument was carried out with the cooperation of Wm. O. Hebler Co. of Hillside, New Jersey. So far this company has supplied most of the parts and much of the labor required in building the units which have been placed in service, but has been unable to supply the nickel filaments or make the necessary final adjustments on the instruments before placing them in service. It is hoped that in the future it will be possible to place the manufacture completely in the hands of this or other commercial organizations. Until this is possible however, it is believed that all units of the subject instrument should be checked at this Laboratory before being put into service.

APPENDICES

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Photograph of Experimental Galvanometer Model	Plate 12

APPENDIX I

SPECIFICATIONS FOR AIR FLOW METER

1. The complete instrument shall consist of three main parts, namely: (1) the flow responsive unit, (2) the indicating and control unit which operates in conjunction with part (1), and (3) the case for storing and transporting parts (1) and (2).
2. Part (1) shall consist of a flowtube which shall be built in accordance with the enclosed plans and specifications (Plate 6) and upon which shall be mounted a by-pass system containing the flow sensitive elements.
3. The by-pass system shall consist of a brass filament block of approximately $3/4"$ x $3/4"$ x $5/6"$. It shall contain four filament chambers consisting of $0.20"$ holes symmetrically placed around its center and passing through it in such a way that they terminate in the $3/4"$ x $3/4"$ faces. Two adjacent holes of the block shall be countersunk in the bottom face to a depth of $1/32"$ and with a $1/4"$ diameter, and all holes shall be countersunk in the top face with a $1/4"$ diameter and to a depth of $3/32"$. All countersunk portions shall end with a square shoulder. The filament chambers, including the countersunk portions shall not be closer than $1/32"$ to any edge of the block.
4. Two holes $1/4"$ in diameter shall be drilled into one side of the filament block and through into the two adjacent filament chambers which have been countersunk in the bottom face. The centers of these holes shall be $1/4"$ from the top face of the block. A brass side tube $1-1/4"$ in length and $3/16"$ i.d. $1/4"$ o.d. shall be silver soldered into each and the outer end of one tube cut off at a 45° angle. In addition a hole $1/16"$ in diameter shall be drilled into each of the other two filament chambers from the side of the block opposite to that carrying the above two tubes. These holes shall be $1/16"$ from the bottom face of the block.
5. The filament block shall be mounted upon the flowtube by means of a base plate adapted to receive it. The base plate shall consist of a $1-1/4"$ x $3/4"$ x $1/8"$ brass plate carrying two holes into each of which has been soldered a length of $3/16"$ i.d. brass tubing. These tubes shall extend $1/32"$ from the face which is to receive the filament block and shall be so spaced and so arranged than when the filament block is in place with its two side tubes perpendicular to the long axis of the base plate, a male - female joint shall be formed between the tubes through the base plate and the two filament chambers which have been countersunk in the bottom face of the filament block.
6. The tubes through the base plate shall extend from the opposite face of the base plate so that when it is in place on the flowtube they shall extend through the wall of the flowtube and be flush with the inner surface.

7. The filament block and base plate shall be mounted onto the flowtube so that the center of the filament block shall be $3\frac{1}{8}$ " from the smaller end, and the side tubes shall be parallel with the flowtube and point toward its larger end. The base plate shall be retained to the flowtube by means of screws and cement so as to form a gas tight seal. The screws shall be in the four corners of the plate and shall be $\frac{1}{8}$ " from the edges which form the respective corners. Details of the filament block and base plate are shown in the enclosed drawing (Plate 7).

8. A terminal base shall be retained immediately above the filament block and spaced from it by not more than $\frac{1}{4}$ " or less than $\frac{1}{8}$ ". It shall carry five rigidly fastened soldering lugs of brass or copper. The terminal base, filament block and base plate shall be held together by a single machine screw which passes successively through the terminal base, through the spacers which separate the base from the filament block, through the center of the filament block and finally into a tapped hole in the base plate. The size of the screw shall be 8-32.

9. The filament block shall be equipped with four 20 ohm nickel filaments built as shown on Plate 9 and connected to the lugs of the terminal base to form a Wheatstone bridge as shown on Plate 3.

10. A cover shall be provided for the entire by-pass assembly. It shall be made of 25 gauge sheet steel and shall be of such size that at least $\frac{1}{4}$ " clearance is provided between any point on the inner surface and the nearest point of the assembly. An opening of not less than $\frac{1}{8}$ square inch or more than $\frac{1}{4}$ square inch shall be in the end nearest to the small end of the flowtube. The cover shall be secured to the flowtube by means of four screws of proper size and type.

11. The inner bore of the flowtube shall be finished as smooth as possible and shall contain no projection of any kind.

12. Part 2 consists of the indicating and control part of the instrument. It shall include a microammeter of suitable characteristics and the required switches, resistors and rheostats to produce the electrical network shown in the enclosed wiring diagram (Plate 3). The switches shall be of the silver plated wiping contact type, four pole double throw wired to give double pole, double throw with paralleled contacts. An example of a suitable type would be Centralab switch #1458. The characteristics of the various constituents of the circuit shall be as shown.

(a) The meter, rheostats, and switches shall be mounted upon a bakelite panel which shall form the top of the case of part 2. The panel shall be engraved with the proper labeling of the rheostats, the positions of the switches and with a serial number for each instrument.

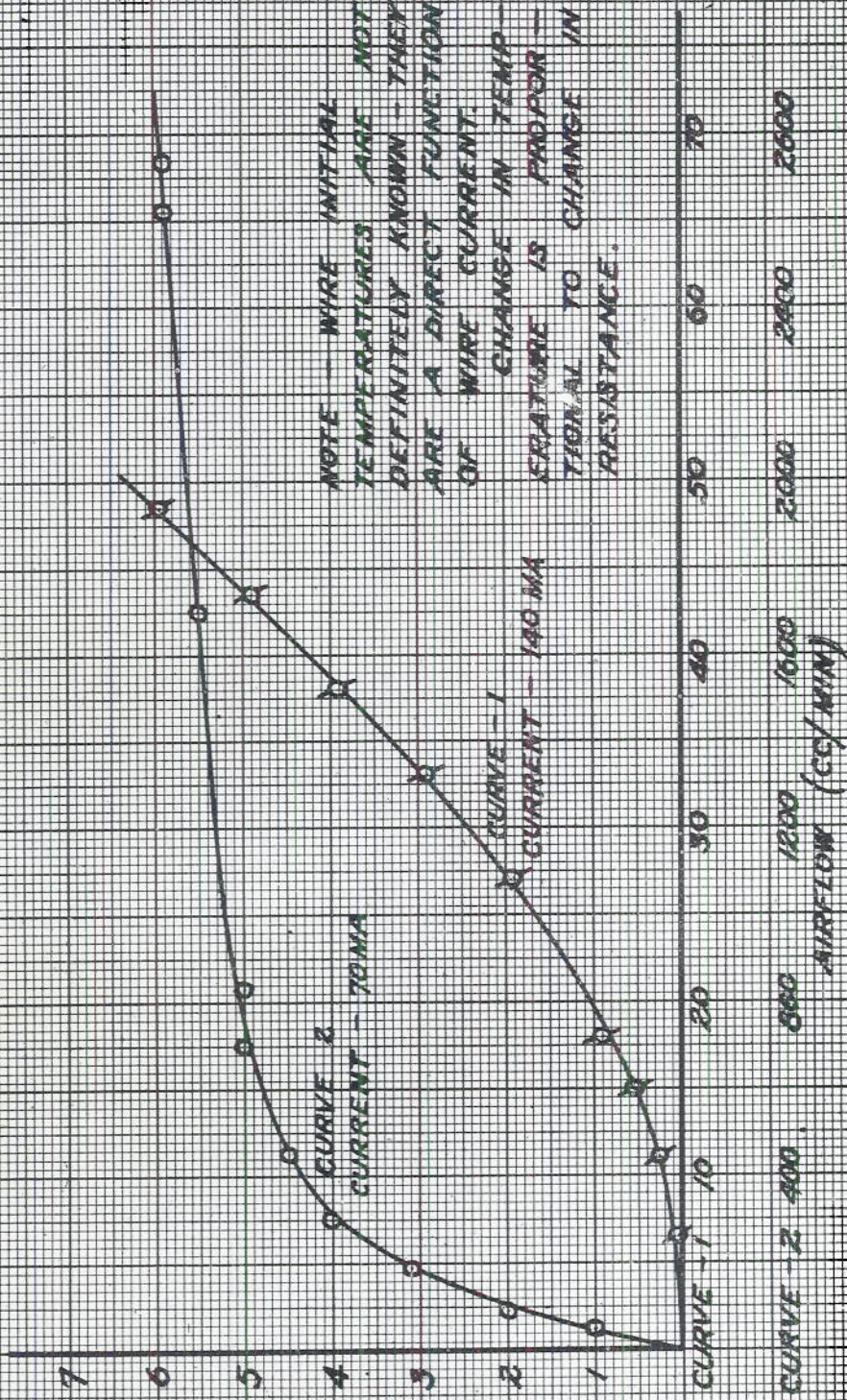
(b) Part 2 shall also include the power supply for the instrument which shall consist of 4 size "D" flashlight batteries. They shall be contained in a separate battery compartment of the case and their terminals shall be connected into the electrical system by means of unpainted brass or copper contacts which do not include the screws holding the cover to the battery compartment. The battery compartment shall be accessible for replacement of batteries from the outside and shall be closed by means of a suitable cover.

(c) Part 2 shall further be equipped with external connections and the necessary subsidiary internal circuit for operation of the instrument on 4 volts D. C. from an external source. The connections shall be placed in the upper right hand corner of the panel. Electrical connection between parts 1 and 2 shall be made by means of 5 conductor rubber covered cable. This cable shall be securely fastened by means of suitable cable clamps, at the points where it enters the case of part 2 and the cell cover of part 1. The conductors of the cable shall make connection with the electrical network of part 2 at the switch terminals and with the terminal base of part 1. Connection shall be as shown on Plate 3.

13. Part 3 shall consist of a storing and carrying case for the instrument and shall be of a form which provides simplicity of packing and protection against mechanical abuse likely to be encountered during transportation. At least one inch of longitudinal clearance shall be provided between the large end of the flowtube and the side of the case, and at least 1/4" clearance in all other directions.

CHANGE IN RESISTANCE (ARBITRARY UNITS)

COOLING OF A HOT WIRE BY CONVECTION
AT TWO DIFFERENT WIRE INITIAL
TEMPERATURES AND FLOW RANGES



NOTE - WIRE INITIAL
TEMPERATURES ARE NOT
DEFINITELY KNOWN - THEY
ARE A DIRECT FUNCTION
OF WIRE CURRENT
CHANGE IN TEMP -
TEMPERATURE IS PROPORTION-
AL TO CHANGE IN
RESISTANCE.

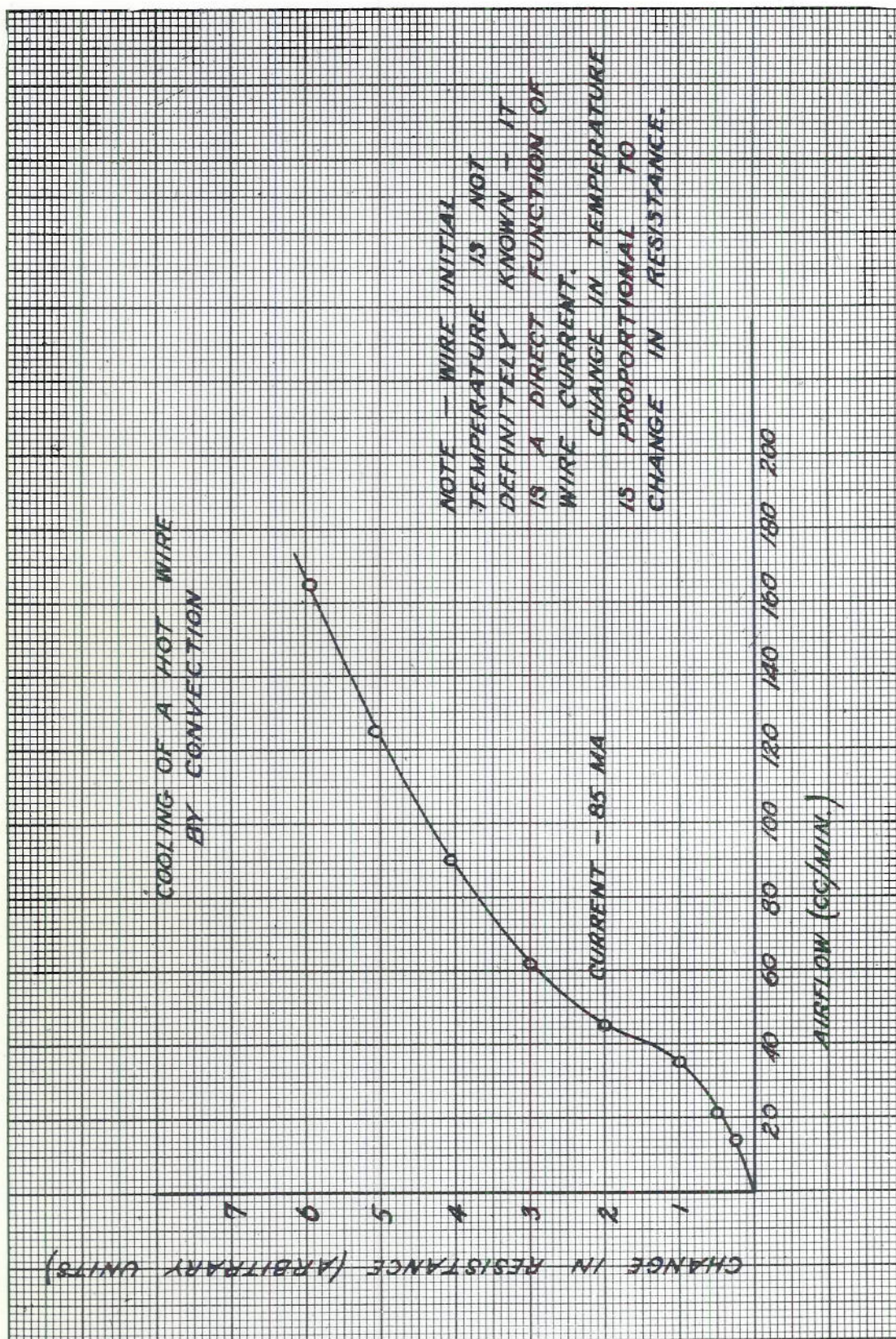
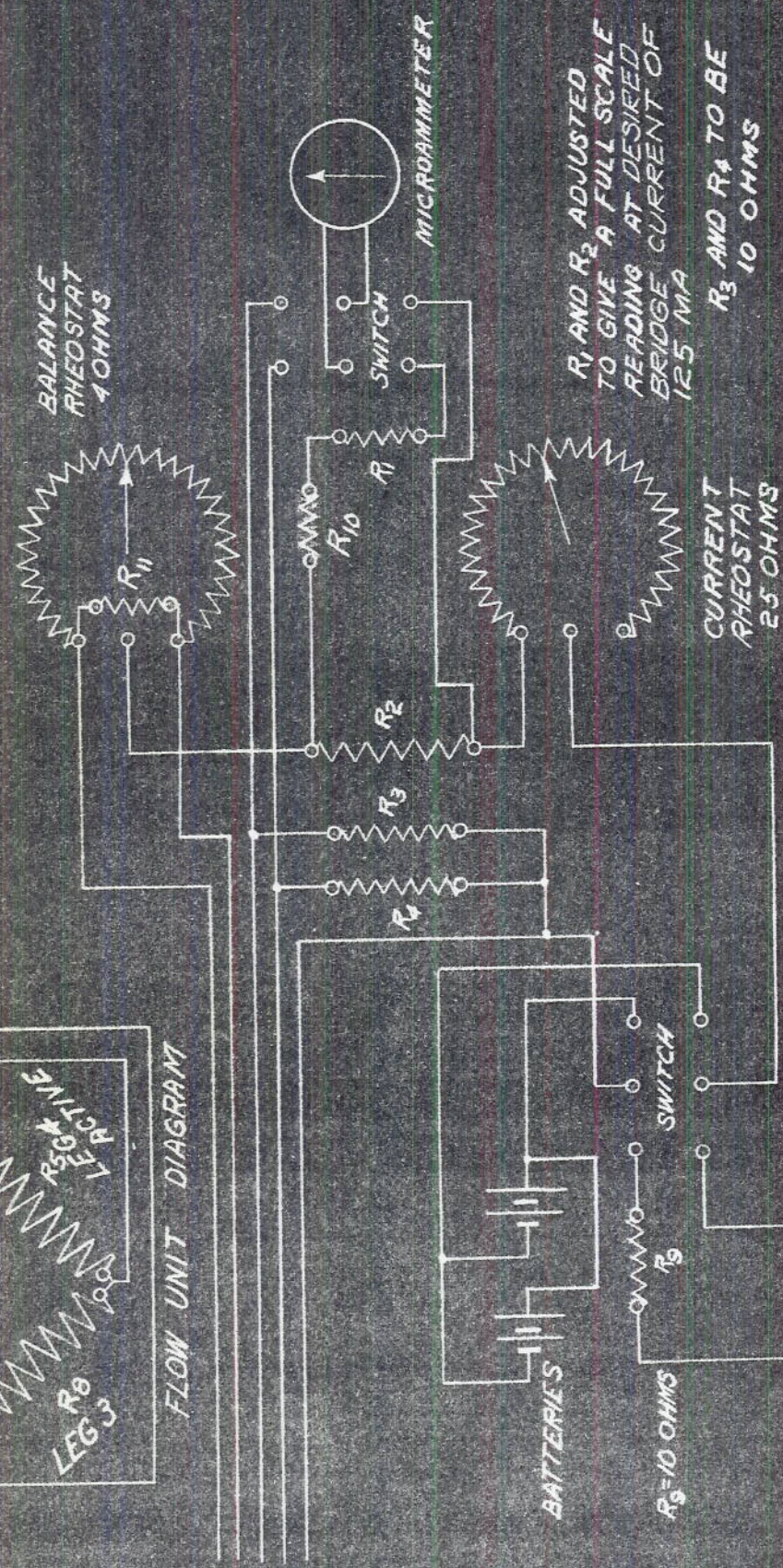
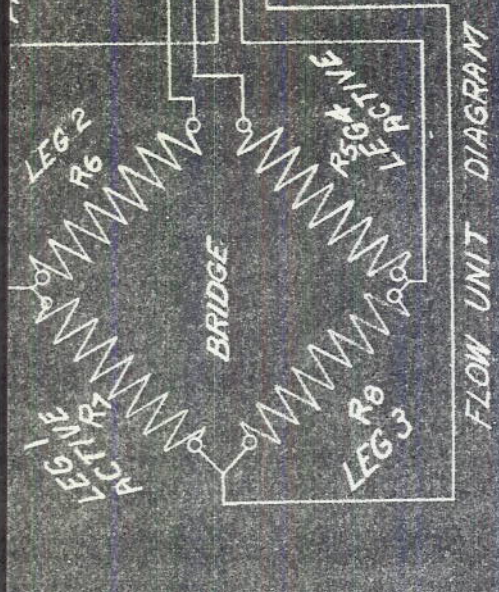


PLATE 2

$R_5 = R_6 = R_7 = R_8 (\pm 0.5\Omega)$ AND
 $R_9 = R_{10} = R_{11} (\pm 0.05\Omega)$
 TEMP - 25°C

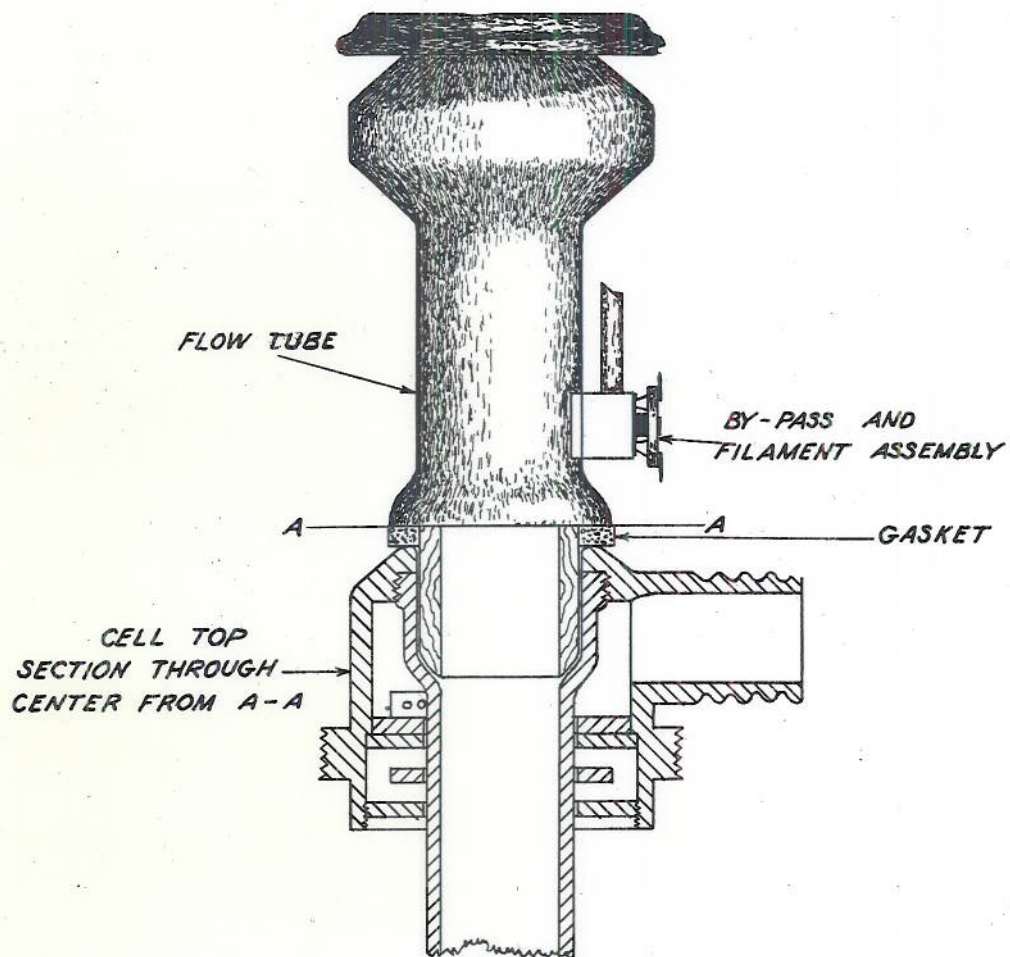


CONTROL UNIT DIAGRAM

TERMINALS FOR EXTERNAL POWER SOURCE

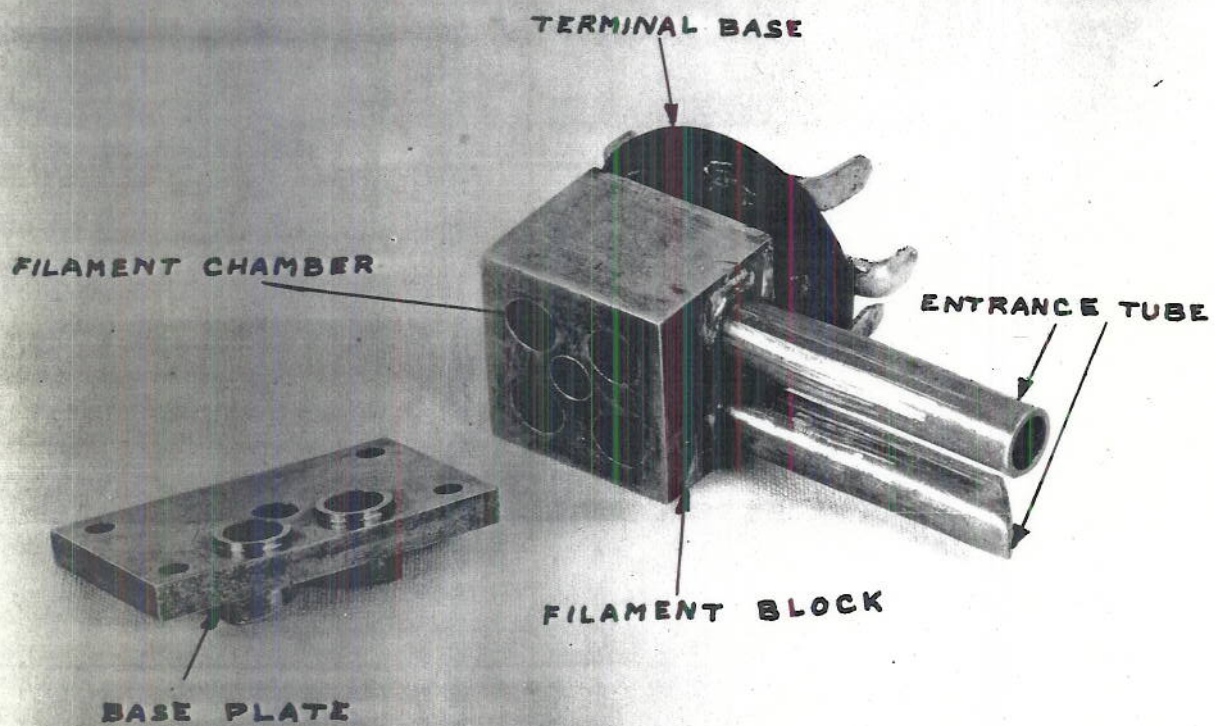
4 VOLTS D.C.

WIRING DIAGRAM - SUBMARINE MAIN
 STORAGE BATTERY VENTILATION
 INDICATOR
 MODEL N 3/16/44



SKETCH OF FLOW TUBE IN PLACE
ON CELL TOP
— THE FLOW TUBE FORMS AN
EXTENSION OF THE CELL VENT
WITHOUT ALTERING THE RESISTANCE.

PLATE 4



AIR FLOW TUBE
6-V-370
F.S. THOMAS

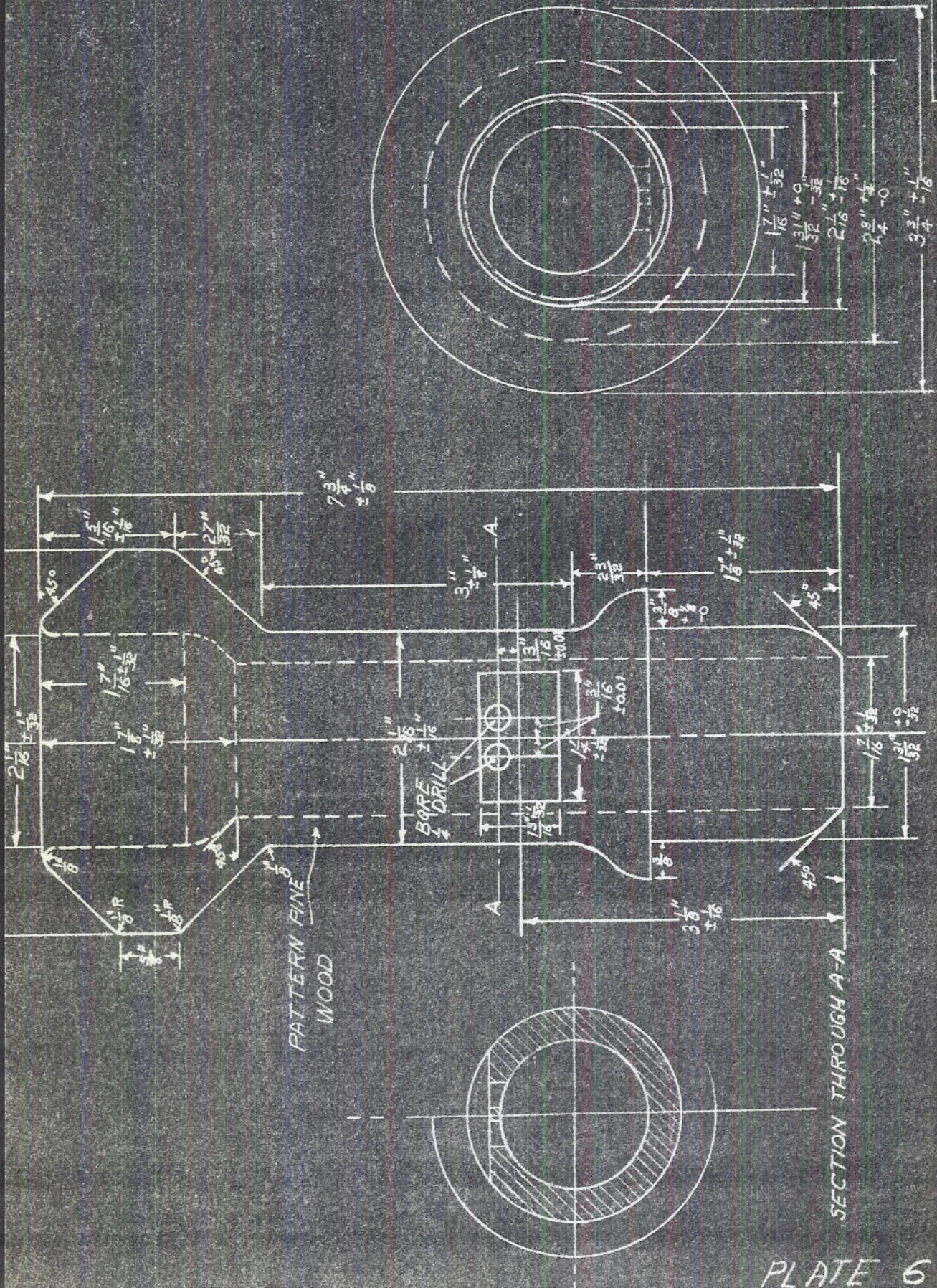
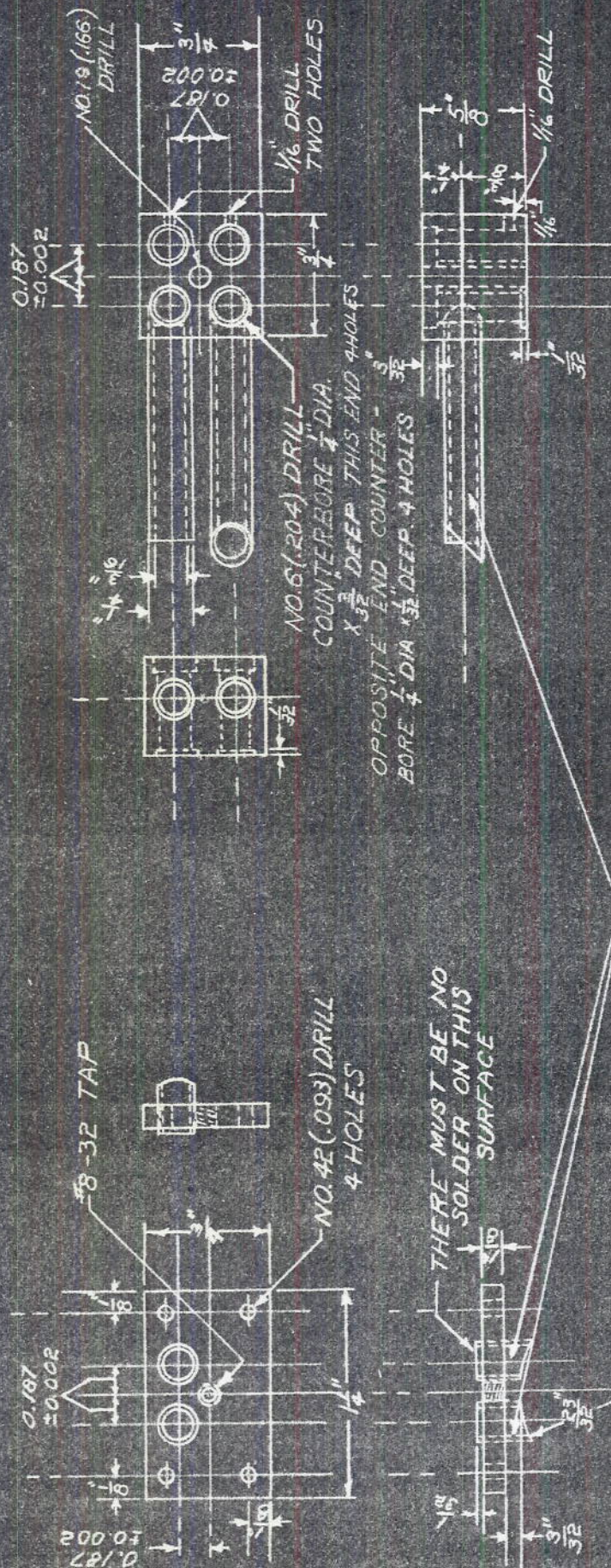


PLATE 6

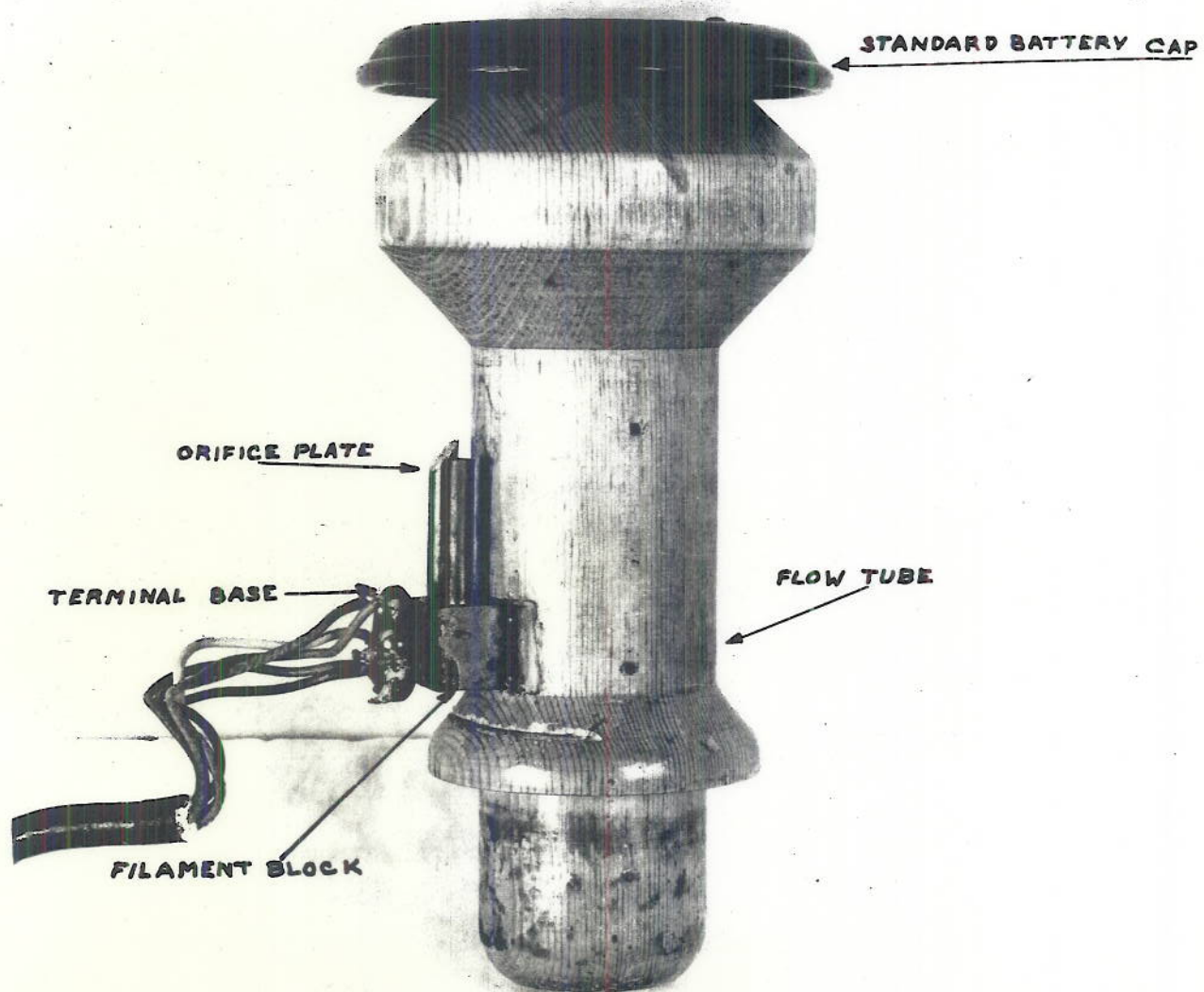


TUBES ARE $\frac{3}{16}$ I.D. $\frac{1}{4}$ O.D. BRASS
SILVER SOLDERED TO BLOCK

BASE PLATE
MATERIAL - BRASS

FILAMENT BLOCK
MATERIAL - BRASS

FILAMENT BLOCK AND BASE PLATE FOR
SUBMARINE MAIN STORAGE BATTERY
VENTILATION INDICATOR - MODEL N



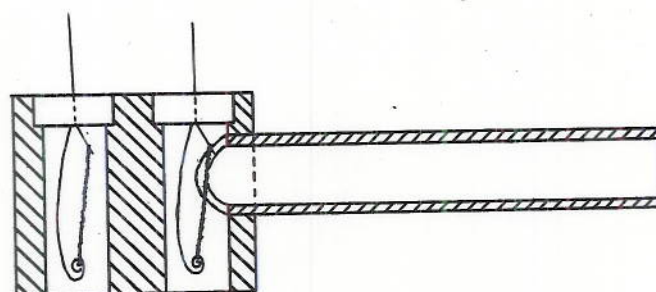
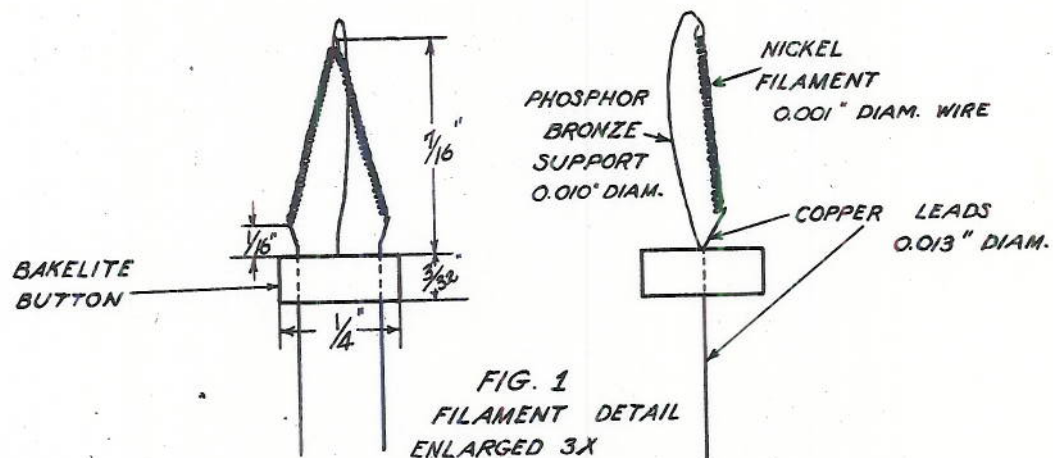


FIG. 2
POSITION OF FILAMENTS IN
FILAMENT BLOCK
ENLARGED 2X





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