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Title An Electrical Method For the Determination of,
Water Velocity

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(Major Professor)

The determination of the quantity, and hence the velocity, of water flowing in large penstocks and conduits of hydro-electric power installations is very difficult with present methods. This applies particularly to low-head installations having short penstocks.

The object of this research was to develop a new, practical, and easily applicable method for measuring water velocities which would be independent of any of the physical factors which limit the accuracy of present methods.

The basic principle upon which this method depends is a measured heat transfer of electrical energy to the water. A recognized electrical phenomenon is that the resistance of an electrical conductor will change with a change in the temperature of that conductor. By using a metal with a large temperature coefficient of resistivity, any small change in the temperature of the conductor may quite easily be determined.

Water is a very good convector but a very poor conductor of heat. Also, the amount of heat taken from a heated object at a constant temperature will vary almost directly with the difference in the temperatures of the object and the water. Therefore, by holding the temperature of a conductor of the proper design in water at such a value that the temperature difference is a constant, the amount of heat removed from the conductor should vary directly with the water velocity and by plotting a curve with the amount of heat removed in Btu per minute per degree of temperature difference as a function of the water velocity a straight line should result if no turbulence exists around the conductor.

Another type of curve could be obtained by holding the current input to the conductor, or element, constant and noting the change in element temperature and total heat given up to the water as a function of the watervvelocity.

These two tests, constant element temperature and constant element current, were investigated during this research. It was found for the constant element temperature tests that:

(1) A straight line relationship existed between the amount of heat

given up by the element in Btu per minute per degree of temperature difference and the numerical value of the water velocity.

(2) This straight line relationship gave the most accurate results for differences of water and element temperatures below about 40 degrees Centigrade. Discrepancies were noted at the higher element temperatures due to the vaporization of the layer of water next to the element and the resulting formation of air and water vapor bubbles.

(3) Because of reason number 2 the most accurate practical results may be expected by using a small and constant difference between element and water temperatures.

(4) The element effectively integrates the cross-section of water coming in contact with it as shown by the straight line relationship obtained between the heat removed per degree of temperature difference as a function of the water velocity.

For the constant element current tests two straight line curves were obtained, the greater proportional amount of heat being taken up by water velocities below two feet per second, thereby indicating that the type of elements tested would not yield accurate practical results for water velocities above two feet per second because of the low resistance of the element and the resulting difficulty of accurately measuring the low AC voltages encountered

The greatest single difficulty found in this series of tests was the accurate measurement of and accurate control of the voltage impressed across the test element. The voltage regulation of the source of power often made accurate determinations very difficult and many of the errors found are undoubtedly due to this cause. For this reason it is reccommended that for any practical useage, or for further laboratory tests a separate and easily controlled source of power be available. The source preferred being direct current because of the ease of measurement of low values of DC voltages.

A spot velocity element was designed and is now being built. This element should prove to be portable and easy to use in the field in much the same manner as present current meters, but when properly calibrated be more accurate. It is expected that this device will be ready for active use very soon.

AN ELECTRICAL METHOD FOR
THE DETERMINATION OF
WATER VELOCITY

by

JAMES KELLY MOORE

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I INTRODUCTION

Necessity For Accurate Water Velocity Measurements

Water is the most common substance with which humanity comes in contact. Hence, it would seem to follow, that when desired the measurement of large quantities of water such as those quantities encountered in power installations should be very exact. This situation is not met in many cases, however, as under different practical conditions the accurate measurement of large quantities of water is extremely difficult. That which follows will deal,with water which is considered to be flowing in closed and open channels, pipes, and penstocks, the accurate measurement of which is often very desireable but difficult to attain.

An example which shows the necessity for the accurate measurement of a large quantity of water is a newly-constructed hydro-electric plant. The only way in which the power input to the turbine may be measured, when its efficiency is unknown, is by determining the quantity of water flowing through and the head of the water on the turbine. Because the premiums paid the manufacturer are based on the guaranteed efficiency of a unit, costing in some instances millions of dollars, may depend upon a variation in the efficiency of the installation of a few tenths of one percent, the accurate determination of the power input, and hence the quantity of water flowing, is ver apparent.

The quantity of water flowing through any conduit may be expressed in terms of the mean velocity past any point multiplied by the cross-sectional area normal to the direction of flow at that point;,or, expressed symbolically;

$$Q = AV$$

in which Q is the quantity of water flowing in cubic feet per second, A is the cross-sectional area of the conduit in square feet, and V is the velocity of the water in linear feet per second. The area may be readily determined from the physical dimensions of the conduit and thus it is at once apparent that the limiting factor upon which the accuracy of the determination of the quantity of water flowing depends is the precision with which the velocity can be measured.

Available Methods For Determining Water Velocities

A brief resume of present methods of measuring water velocities would be desireable at this point. The better known methods include the orifice, the weir, and the venturi meter, all of which depend upon a difference in head as the base of determination. Of these, only the venturi meter is applicable to large power installations and, while quite accurate, is not feasible in many instances.

The current meter is a device suited primarily to open channel flow, the most accurate results being obtained in channels of comparatively small cross-section and whose water velocities are below 5 or 6 feet per second. This method, like the others mentioned, is not feasible for use with large power projects.

Perhaps one of the better known methods for determining water velocities in large power installations is the Salt Velocity Method developed by Prof. C.M. Allen of the Worchester Polytechnic Institute. This method depends upon the increased conductivity of the water due to the presence of a salt solution. The velocity is determined by placing two, or more,,pairs of electrodes at known intervals along the pipeline and measuring the time taken by the salt solution in the water to pass from one pair of electrodes to the next. With the distance between the electrodes known, the velocity may be readily calculated. The minimum accuracy of this method is placed at about one percent by Professor Allen.

The Color Velocity Method is similiar in principle to the above except that a strong dye is used in place of the salt solution. The dye is introduced into the pipeline and by observation the time required for it to pass between two known points is measured. The limiting factor in this instance is the ability to see the stream flow at critical points along the conduit. The accuracy of this method is good where its use is feasible.

The Chemical Method is used extensively where turbulent flow is encountered. In this instance a solution of known concentration, usually salt, is introduced into the streamflow at a known and uniform rate. Samples of water are then taken simultaneously at points upstream and a given distance downstream from the point of injection of the solution. It may readily be seen that the concentration of the downstream sample is a function of the velocity of the water. The relative concentration of the upstream and downstream samples is determined by titration, and with the linear distance between the point of injection and point of sampling known, the velocity of the water may readily be calculated. The limitations of this method are due to the lack of assurance that the mixing of the injected solution with the water at the point of sampling is uniform.

The Gibson Pressure Method of determining water velocities, as the name indicates, is dependent upon a pressure change. The gate at the foot of the penstock is closed slowly and the pressure rise at this point is recorded accurately along with the surge in the tank at the head of the penstock. According to theory the results obtained by the use of this method should be quite accurate although the computations are complicated. Difficulties in the accurate measurement of pressure, however, limit the probabilities of accuracy. This method is restricted to pipelines over 150 feet in length.

Need For a More Accurate Method of Measuring Water Velocities

The greatest single objection to all methods in use at the present is the requirement that a comparatively long penstock or conduit be available as all but the last-mentioned method require a thorough mixing of an injection and the water as well as an appreciable time interval between the points of measurement. A long penstock is also required for the Gibson Pressure Method.

Because many present hydro-electric installations have short penstocks, and because no present method will accurately determine the quantity of flow in these, it is evident that an accurate method for measuring the velocity of the flow of water in these is badly needed.

Reference may be made to a few present installations. For instance, in such plants as the Connowingo and Safe Harbor installations on the Susquehanna river in Maryland, the accurate determination of the flow of water through the turbines by present methods is extremely difficult. The Bonneville development, now in the process of construction, is another instance in which present water velocity measurement methods will be found inadequate due to the inherent construction of the intake conduits and the draft tubes which will discharge their contents directly into the river channel. Other examples could be readily found and called to the attention, but the above should be sufficient to show the present need of a more accurate and easily applicable method of determining the velocity of water flowing in open and closed channels.

Object of Research

The object of this research is to present an electrical method for measuring water velocity. This method, which depends primarily upon the amount of heat taken from an electrical element in the water as a function of the water velocity, was first investigated by Draper M Mason, CE '34 Oregon State College, and the author during the school year 1933-34. A summary of the results obtained from these preliminary tests will be presented later. The work upon which this paper is based is a refinement of previous results, and an attempt is made to develop an element and method of using it such that a linear relationship may be obtained between the water velocity and some other readily determined variable. This result was accomplished over a large range of water velocities by holding the temperature difference between the element and the water at a constant value and determining the change in heat input to the element per degree of temperature difference between the element and water temperatures.

As nearly as could be determined by a careful search of the available literature this is the first attempt to utilize this form of heat transfer characteristic for the purpose of measuring water velocities. The hot-wire anemometer for measuring air velocities, which operates upon a somewhat similiar principle, was developed approximately 20 years ago by Thomas, but the problems involved by the two methods are quite different due to the thermal properties of water as compared to those of air. The entire theory and results of this investigation were developed originally at this institution.

II THEORY

Basic Considerations

Water is a poor conductor of heat, its heat conductivity being 0.0013 as compared to approximately unity for copper at a temperature of 15 degrees Centigrade. The specific heatnof water at the same temperature is one and is essentially constant over the practical range of water temperatures encountered; that of copper is 0.093. Therefore, from a theoretical consideration, water is a poor conductor but a good convector of heat, and if this property is used for the determination of the quantity of water coming in contact with a heated surface as a function of the amount of heat carried away from the surface, a linear relationship should readily be found.

Other considerations should also effect the above simple theory. The first requirement that must be met is that the surface area of the heat emitting body be constant and in intimate contact with the water at all times. If this condition is not fulfilled it is obvious that the amount of heat carried away by the water will not vary as a direct function of the quantity of water coming in contact with the heated object.

The amount of heat taken away by water, with a constant quantity coming in contact with a unit area of the heated surface per unit of time, will vary with the temperature difference between the surface and the water. Therefore, it would be necessary to hold the temperature difference between the heated surface and the water constant as the quantity of water is varied in order to obtain a linear relationship between the amount of heat removed and the quantity of water flowing.

Practical Considerations

The basic theoretical considerations effecting the heat transfer from a heated object to water alond have been considered so far. Practical considerations must also be mentioned. For instance, it is much more practical to measure the velocity of the water past any given point than the total quantity flowing; the quantity being equal to the cross-sectional area at any point multiplied by the mean velocity past that point. Therefore, in all discussions that follow, the word "velocity" will be used in place of the word "quantity" and, as such, the subject of this research is referred to as a velocity rather than a quantitative or volumetric measurement.

The first practical problem to be considered, then, is the design of an element to insert in the stream flow; this design being as nearly as possible such that it will create no disturbance in the flow of the water. If the element causes a condition of turbulence to be set up around it at any water velocity being investigated, then it ismobvious that all the surface area of the element will not be uniformly covered by the water passing it, and therefore the amount of heat conducted away from the element will be greatly influenced by the presence of air pockets caused by the turbulence. These air pockets will vary in magnitude and position as the velocity is varied, and because of the difference in the convecting property of air as compared with that of water, it may be seen that the desired linear relationship between the water velocity and the amount of heat removed from the element by the water alone will be destroyed. .

To eliminate all turbulent conditions is obviously impractical if not impossible. However, by considering the important characteristics of compressibility and inertia of moving water, a shape can be so designed that it will produce a minimun of disturbance. To keep this disturbance a minimum, then, the cross-section of the element should be long and thin, any increase or decrease in the thickness being very gradula and composed of a smooth curve ratherthan a straight slope progressing directly to or from a sharp corner. In this manner any change in the direction of the flow of the water will be gradual, and its almost total lack of compressibility will cause the water to flow in intimate contact with the element at all points. For the higher velocities where the inertia of the Water as a moving mass will be an important factor, the gradual change from a minimum to a maximum thickness will not result in the water being unduly deflected away from the sides of the element, and the gradual decrease from a maximum thickess to a minimum will tend to overcome the inertia effect and allow the water to follow a more natural course in its flow, thereby adhering closely to the sides of the element.

The next problem to be considered is the matter of heat supply for the element. The fact that the temperature mustbe held constant has been mentioned but no method of holding it constant has been suggested. For instance, a thinnwall hollow pipe of the proper proportions and cross-section might be used with some heated liquid, for example water, being forced through it at a constant rate and temperature. The amount of heat conducted through the walls of the element and carried away by the water could be readily calculated from the measured temperature difference between the water flowing into and out of the hollow element. This method would be objectionable, however, because the temperature of the surface exposed to the flowing water would not be the same at any two points, but would progressively decrease as the heated fluid travelled through the element. Also, the temperature at any one point on the surface of the element would not be the same for any two different water velocities because each different velocity would result in a different amount of heat being carried away from the heated surface at every point, and the element temperature at that and all succeeding points would thereby be changed.

In order to hold the temperature at all points constant it is therefore obvious that some means must be provided whereby all parts of the element surface will be heated uniformly. The only practical means of accomplishing this result is by using the element as an electrical conductor and heating it by means of an electric current which passes through the element. To insure a uniform heating effet the cross-sectional area of the element must be constant. In order for the water to take away an equal amount of heat per unit of length, the surface area of the element must be the same at all points. From this it immediately follows that in order to satisfy and combine the above two conditions, the thickness of the element must be constant. When the above-mentioned dimensional requirements are satisfied, the amount of heat taken away from the element by the water should essentially be a linear function over the practical range of water velocities if the surface of the element is maintained at a constant temperature difference with respect to the water.

Factors Influencing the Design of the Element Used

The amount of heat which is required to maintain a constant tempereture difference between a heated object immersed in water and the water is a direct function of the surface area of the object, other factors remaining constant. It has been shown that the surface area exposed to the water should be a maximum. In order to obtain this condition the volume of the conductor should be as small as possible in order to obtain a high element resistance, and the surface area sufficiently large that it would be consistent with obtaining accurate results. If the electrical conductor itself is designed to meet these conditions, it is readily seen that it would not be sufficiently strong mechanically to withstand the force which would be exerted upon it by a flowing stream of water. To overcome this difficulty a core may be designed upon which a thin strip of metal can be mounted. The dimensions of such a core are sketched in the apparatus section, the core itself being constructed of bakelite, which is a non-conductor of electricity, and so designed that a minimum of turbulence will be set up in the stream flow due to its presence. By this method both sufficient mechanical strength and the desireable electrical characteristics may be obtained; the element core being so built that the conductor material will cover the leading edge of the core only and such that it may be replaced by other conductors of different thickness and width.

The fact the the element temperature difference between the element and water must be held constant at a known value at once imposes a known condition with respect to electrical measurements. If the temperature of a metal is constant its resistance must also be constant and, conversely, if the resistance is either constant or known, the temperature may readily be determined from known resistance characteristics of the metal. To measure a changing temperature most accurately be electrical means the test metal should have a high temperature coefficient of resistivity so that any small variation in the temperature may readily be noticeable because of a resistance change and so be accurately corrected. The pure metals with the highest temperature coefficient of resistivity are nickel and iron. Of these two nickel was selected as the material for the tests because its temperature coefficient of resistivity remains constant over a much wider range of temperatures than thatnof iron. Also, nickel is not as subject to deterioration due to oxidation, or rust, when exposed to water and high temperatures as is iron. The temperature coefficient of resistivity of pure nickel is 0.0062 (as listed by various handbook tables; the nickel used in this research had a temperature coefficient of resistivity of 0.005 specified by the manufacturer); that of copper is 0.00393 so it is seen from these comparisons that nickel should posess quite satifactory characteristics as its resistance per unit of length is approximately five times that of copper and the temperature coefficient of resistivity one and one-half times as great.

Electrical and Heat Measurements

The resistance of the conducting element may accurately be determined at a known temperature by means of a standard resistance bridge. From this determination the resistance may be calculated for any temperature by the equation:

$$R_t = R_o(1 + at) \qquad (1)$$

where R_t is the resistance at the known temperature,

R_o the resistance at zero degrees Centigrade,

t the change in temperature in degrees Centigrade,

and a the temperature coefficient of resistivity.

From equation 1 it can be seen that the simplest reference temperature to use in calculations is that of zero degrees Centigrade. The resistance at this temperature may be found from resistance bridge measurements at a known temperature by changing equation 1 into the following form:

$$R_o = R_t/(1 + at) \qquad (2)$$

where R_t is the resistance measured by the bridge,

and t is the temperature of the element at this resistance.

To determine the temperature of the element at any known resistance, as determined by the element voltage drop and current input relations obtained from test data, equation 1 may be converted to:

$$T = m(R_t - R_o)/R_o a \tag{3}$$

where T is the temperature of the element at the test resistance.

The heat input to the element may be determined by converting the product of the current through the element multiplied by the voltage drop across it into Btu per minute as indicated by the following:

$$1 \text{ KWH} = 3412.3 \text{ Btu} \tag{4}$$

$$1 \text{ KW Min.} = 3412.3/60$$

$$= 56.87 \text{ Btu per minute} \tag{5}$$

To determine the rate of heat absorption per degree of temperature difference between the element and water temperatures:

$$\text{Temperature difference} = T - t \tag{6}$$

where T is the element temperature in degrees Centigrade, and t is the water temperature in degrees Centigrade. The rate of heat absorption in Btu per minute per degree of temperature difference will be equal to:

$$(\Delta H)/(\Delta T) = (\text{Btu/Min.})/(T-t) \tag{7}$$

The average amount of heat conducted away from the element per square inch of exposed surface area per degree of temperature difference between the element and water temperatures may be found from:

$$A = LB \tag{8}$$

where A is the total exposed surface area of the element to the water in square inches, L is the effective length of the element in in.,

and B the effective width of the element in inches.

Then:

$$h = (\Delta H)/(\Delta T)/(A) \qquad (9)$$

where h is equal to the average amount of heat taken away from the element per degree of temperature difference per square inch of element surface area exposed to the water.

An interesting calculation is the determination of the thickness of the heated layer of water next to the element surface. This may be made under two conditions: First, by assuming that all the layer is raised to the same temperature as the element and, second, by assuming that the average temperature of the layermis raised one-half of the temperature difference between the element and water temperatures. These thicknesses may be found by converting the temperature difference to degrees Fahrenheit and finding the number of pounds of water whose temperature would be raised the specified amount. Knowing the width of the element and the water velocity, the thickness of the layer can be determined by the following:

$$t = (w \times 1728)/(62.4 \times L \times V) \qquad (10)$$

where t is the thickness of the layer of the water in inches,

w is the weight of the water in pounds that would be raised in temperature by the given amount of heat,

and V is the water velocity in inches per minute.

Hydraulic Measurements

The most accurate means of determining water velocities is by the displacement-time method when the quantities involved are such that its use is feasible. This method was used for this series of tests. The water was weighed, the time recorded for a given weight of water to collect, and the velocity determined from these measurements by the following equation:

$$V = W/62.4\,TA \qquad (11)$$

where V is the mean water velocity in feet per second,

W the total weight of water collected in pounds,

T the time in seconds for that weight to be collected,

A the cross-sectional area of the conduit in sq. ft., which in these tests is equal to 0.4,

and 62.4 is the weight of one cubic foot of water. Substituting the value of A in equation 11, the velocity becomes equal to:

$$V = 0.0405\,W/T \qquad (12)$$

Types of Laboratory Tests

Four types of laboratory tests are possible, in each of which the value of one or more variables can be determined with reference to the changing water velocity. These tests and the conditions which would be held constant are:

1. Constant temperature difference between the element and water temperatures.
2. Constant current input to the element.
3. Constant heat input to the element.
4. Constant element voltage drop.

The constant temperature difference test, as brought out in the section "Theoretical Considerations", should give the closest approach to a linear relationship of heat input per degree of temperature difference between the element and water temperatures of any of the above tests.

When the current input to the element is held constant no linear relationship should be expected because, with the water taking different amounts of heat away from the element, the element temperature cannot remain constant as the water velocity is varied. The amount of heat removed should be found to vary both with the water velocity and the temperature difference between the element and the water. That this actually occurs is shown by a typical constant current input curve in a later section. This method should be quite practical, however, where extreme accuracy is not necessary because, by holding the current constant as the water velocity is varied, a voltmeter could easily be calibrated to read the water velocity directly, thereby producing a simple and relatively accurate device for field use.

A constant heat input test should not give a linear relationship between any variable and the water velocity for much the same reasons as those suggested for the constant current test. The practical variable in this instance would be the element temperature, and because the amount of heat removed by the water, which is held constant, does not vary directly with the difference between the element and water temperatures, a direct relationship should not be expexted between the water velocity and any other variable.

A constant element voltage drop should produce much the same results as those produced by a constant current input, the fundemental heat transfer phenomena being essentially the same because the amount of heat transferred from the element to the water is determined directly from the product of the current multiplied by the voltage drop across the element. This method, also, would present one disadvantage for high velocity measurements and under turbulent conditions of stream flow because of the danger of burning out the element due to the combination of air pockets and the high values of current that would be necessary to hold the voltage drop constant as the velocity is increased.

III SUMMARY OF PRELIMINARY TEST RESULTS

The preliminary tests conducted last year were practically all constant current and constant heat input investigations. That is, either the current input to the element or the heat input in Btu per minute were held constant and the water velocity calibrated against the resulting element temperature change. A typical element temperature curve for these two types of conditions is shown by Fig. 1 on the following page. This curve is used to indicate the characteristic trend of the results obtained and the numerical values apply only to the particular element used.

From this curve it may be noted that two distinct conditions are present, and that the change in slope of the t two curves occurs quite sharply at a water velocity between 2.00 and 2.25 feet per second. The core of the element for this and other previous tests was of tear-drop design, the type used extensively for theoretically perfect stream lining for air conditions. The cores were wound with number 26 nickel wire of different parallel combinations which gave elements of different resistance and current-carrying capacity. The abrupt change in the slope of the curve is due to three separate causes: First, the amount of heat conducted away from a heated body in a still liquid does not vary directly with, but as some power of, the temperature difference between the liquid and the heated

FIG. 1

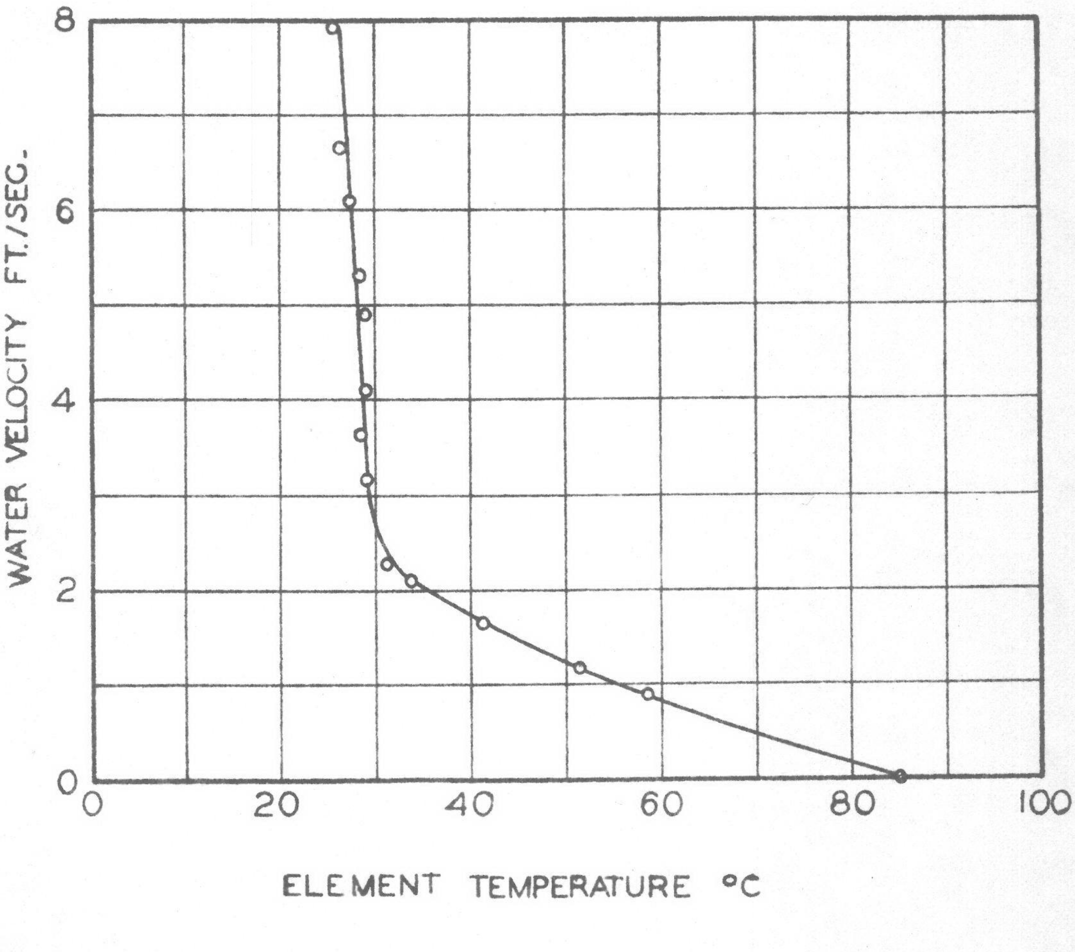
TYPICAL CONSTANT CURRENT CURVE

SHOWING

WATER VELOCITY - ELEMENT TEMPERATURE

RELATIONS

FOR NICKEL WIRE ELEMENT
R= 0.8020 OHMS AT 0°C
I = 30 AMP.
t= 18°C



body. That this effect should be noticeable at low velocities is self-evident; a slight change in temperature difference being produced by a small change in water velocity would result in a large change in the amount of heat removed from the element due to convection currents. This, in turn, would be directly reflected in the resulting element temperature as determined from current and voltage relationships obtained from test data.

Second: The critical velocity of the water with respect to all elements tested occurred between 1.5 and 3.0 feet per second for all tests. Above these values a more turbulent condition was set up around the element which resulted in less heat being removed per unit quantity of water flowing past the element. As less heat was removed from the element per unit change of water velocity above this critical point a smaller change of element temperature was noted.

Third: The elements, with one exception, were all wound with wire at a spacing of approximately 1/16 of an inch. The wire was wound at a slight angle with the direction of stream flow and as a result a turbulent condition existed on the downstream side of the wire at the higher water velocities and so the water was not in intimate contace with all the wire surfaces. The close spacing of the wires also introduced a condition of localized turbulence, small air bubbles being formed between the wires due to the vaporization of the water and liberation of absorbed gasses from the water caused by the wire temperature, these bubbles continuously progressing downstream between the wires from the point of formation.

The combination of the above mentioned three factors being directly additive offers a probable cause for the observed change in the slope of the curves. However, it may also be noted that these curves would give a quite accurate and practical means of measurement for water velocities below two feet per second because of the large temperature change found in this region and the ease of its determination. For a given element and a standard constant current input, a voltmeter scale could be calibrated to read the water velocity directly in feet per second, thereby eliminating several calculations.

A single no. 26 nickel wire stretched normal to the direction of stream flow was alsomused as a test element. This element did not give satisfactory results because: (1) The voltage change was so slight that it was extremely difficult to measure accurately. (2) The wire being round caused a turbulent condition to be present on the downstream side and therefore the water was not in intimate contact with all the surface at all times, thus effecting the heat transfer characteristics. (3) The wire consistently broke at the point of contact with the current lead-in, or support, after a short period of useage; probably being due to fatigue stresses induced by vibrations set up in the wire by the force of the water coming in contact with it.

The results of these previous tests proved conclusively that this method of water velocity measurement was feasible; pointed out the fact that the greater the surface area of the element exposed to the water flow the more dependable would be the results obtained; that a small cross-section with a large surface area was most desireable; and that the greater the resistance of the element, especially for constant current test conditions, the greater would be the measureable voltage change and therefore the higher the accuracy of the method.

IV APPARATUS

Arrangement and Use of Hydraulic Equipment

The major part of the work for this research was carried on in the Hydraulics Laboratory at Oregon State College. The water circulation diagram of the following page, Fig. 2, indicates the general set-up of the hydraulic equipment. A large storage pool is located beneath the first floor and the water drawn from this by two centrifugal pumps pumps connected in series as shown. These pumps are capable of delivering approximately 1400 gallons per minute against all heads used for these tests, this quantity producing a water velocity of approximately 8 feet per second in the test conduit.

The water velocity was regulated by a combination of two schemes. Back-pressure plates having different outlet areas were constructed to fit in the bottom of the test pipe. These plates served two functions; the first to provide sufficient back-pressure to limit the amount of air that would be entrained in the water due to turbulence at the entrance to the pipe, and second to provide varying outlet areas to assist in the regulation of the water velocity in the pipe. Different water velocities for each back-pressure plate were obtained by varying the head in the tank on the second, or laboratory, floor. This was done with the head control valve shown and the head was

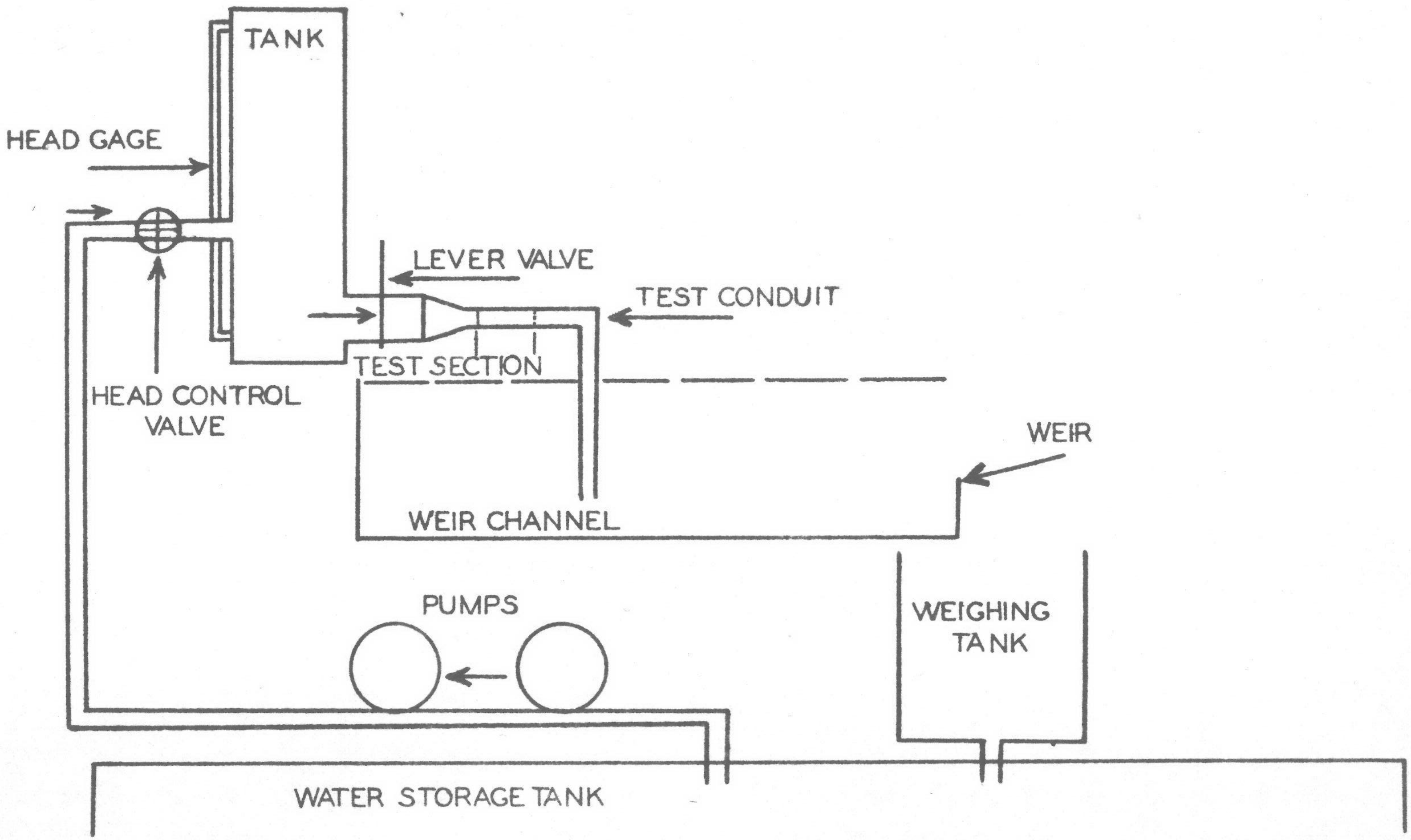


FIG. 2

WATER CIRCULATION DIAGRAM

read directly upon the glass gage located along the length of the tank.

The conduit in which the water velocity measurements were taken is shown by the sketch of Fig.3 and the photograph, Fig. 4. The intake was made larger than the main body of the pipe in order to eliminate turbulent flow at entrance as much as possible. The cross-sectional area of the conduit was 0.4 square feet at the test point. Pyralin plates were placed in the sides of the conduit above and below the element so that any effect it might have in producing turbulence in the stream flow could be observed.

A brush was placed on a brass rod, which operated through a hard grease packing in such a way that the element could be cleaned of any dirt or waste that might be collected from the water supply. This brush was located on the downstream side of the element and a pocket was provided in the side of the pipe in which the brush could be stored when not in use without creating an obstruction to the stream flow.

Guide vanes were placed in the bend of the pipe to promote a more gradual change in the direction of the water flow at this point so that much of themturbulence that would ordinarily result from a sharp-angle turn in a rectangular pipe would be eliminated.

A thermometer for reading the water temperature was located two feet ahead of the element. The thermometer

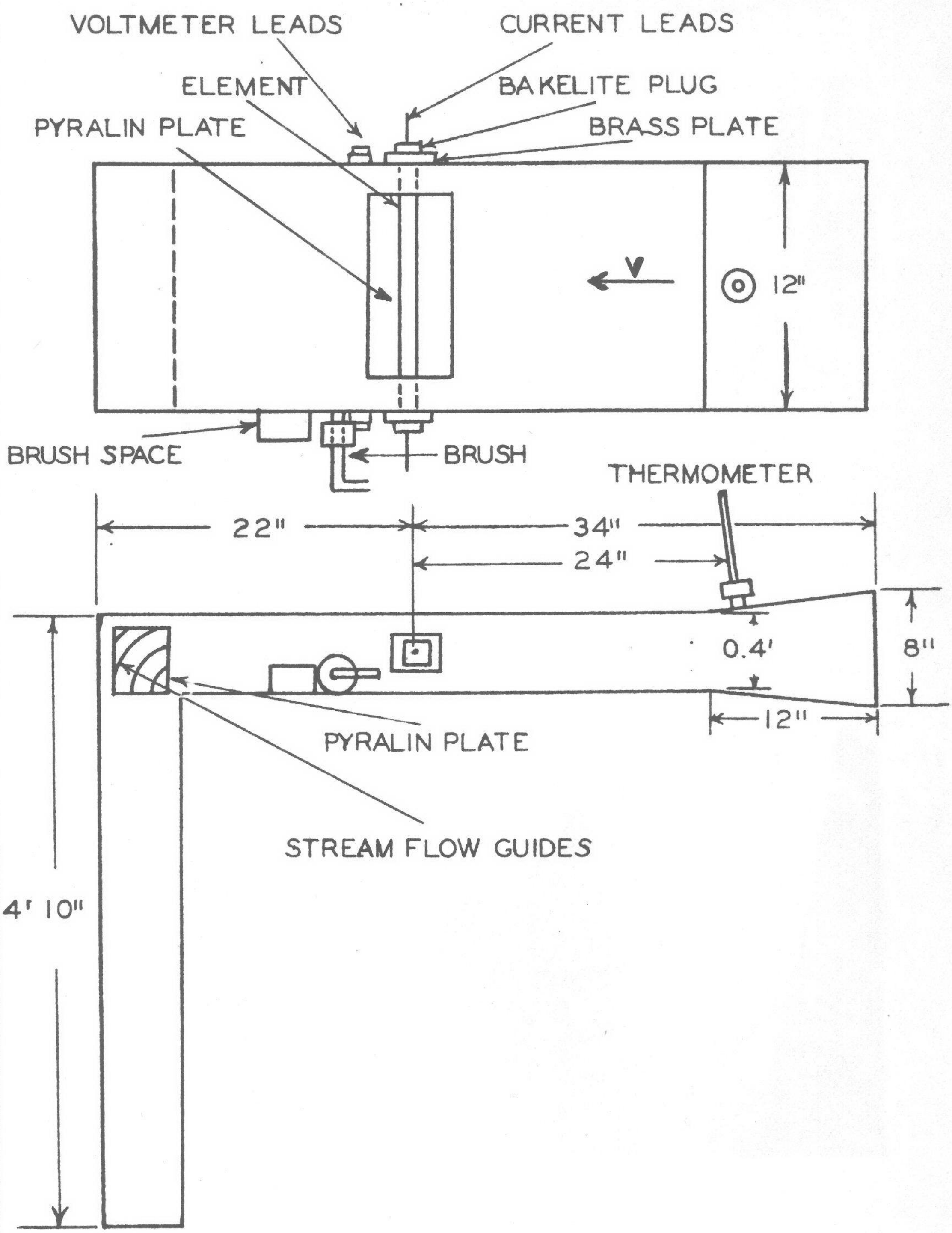


FIG. 3

TEST CONDUIT

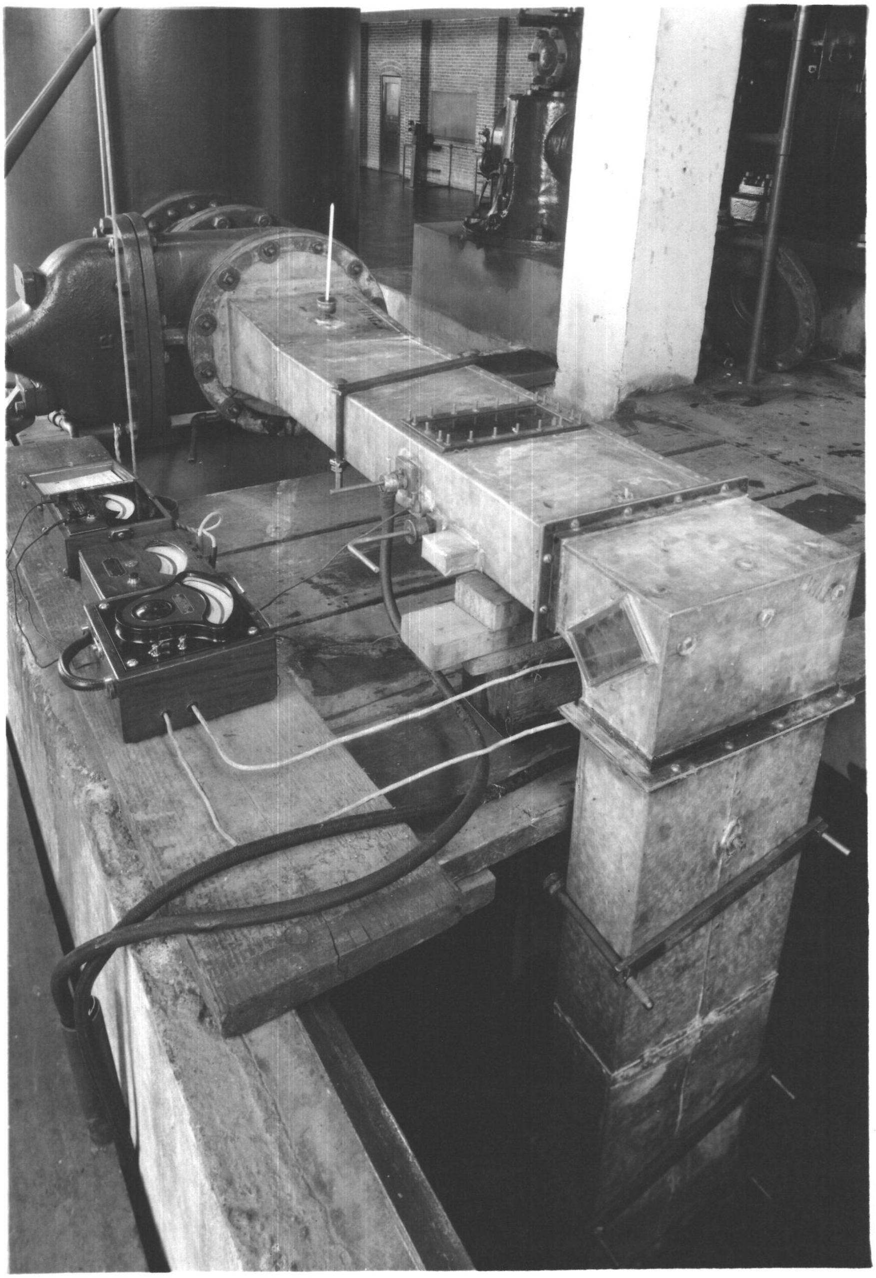


Fig. 4

General View of Test Apparatus

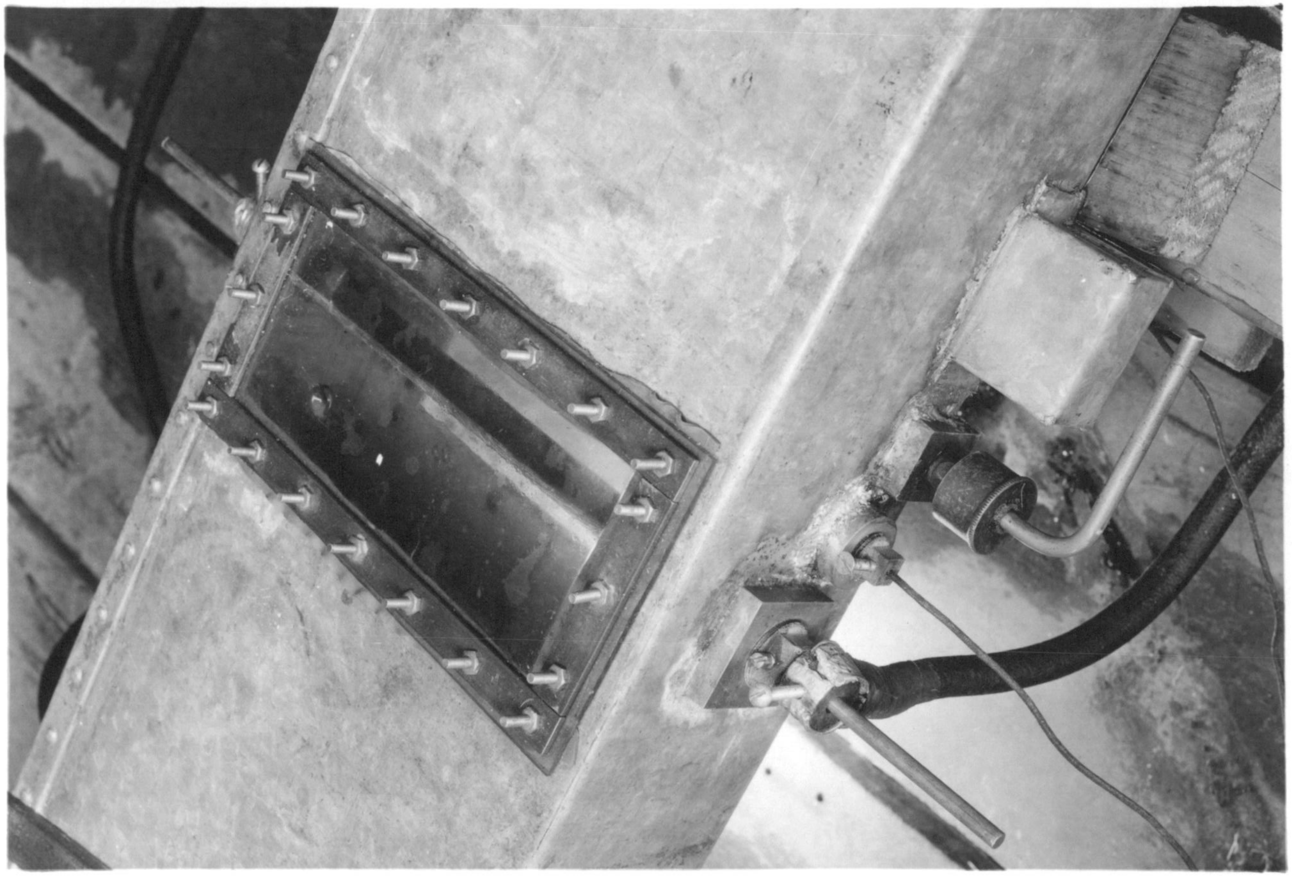


Fig. 5

Top View of Test Section
Showing Element in Place

was mounted in a hard grease packing in such a way that only the bulb was introduced into the inside of the pipe and at that point would produce no turbulence to effect the element. The thermometer was located ahead of the element so that the water temperature as determined would not be effected by any heating of the water due to the presence of the heated element conductor.

Electrical Equipment

The wiring diagram for the circuit used is shown by Fig. 6. Alternating current was used to heat the element, the supply voltage being 220 volts nominal. This was connected through a cutout switch to a 5 KV-A auto-transformer and switches S_1 and S_2 so arranged that either 220 volts or 110 volts could be selected for energizing the remainder of the circuit. Since current values as high as 1000 amperes at 15 volts should be available, a high-current transformer having a transformation ratio of 10:1 was used to supply the power to the element. The voltage across the primary of this transformer could be varied from about 20 volts to the maximum of 220 volts in small increments by suitable combinations of the resistances shown and the different circuit voltages provided by switches S_1 and S_2. Switch S_3 was used to short-circuit the resistance R_2 when desired. Switch S_4 was placed in the

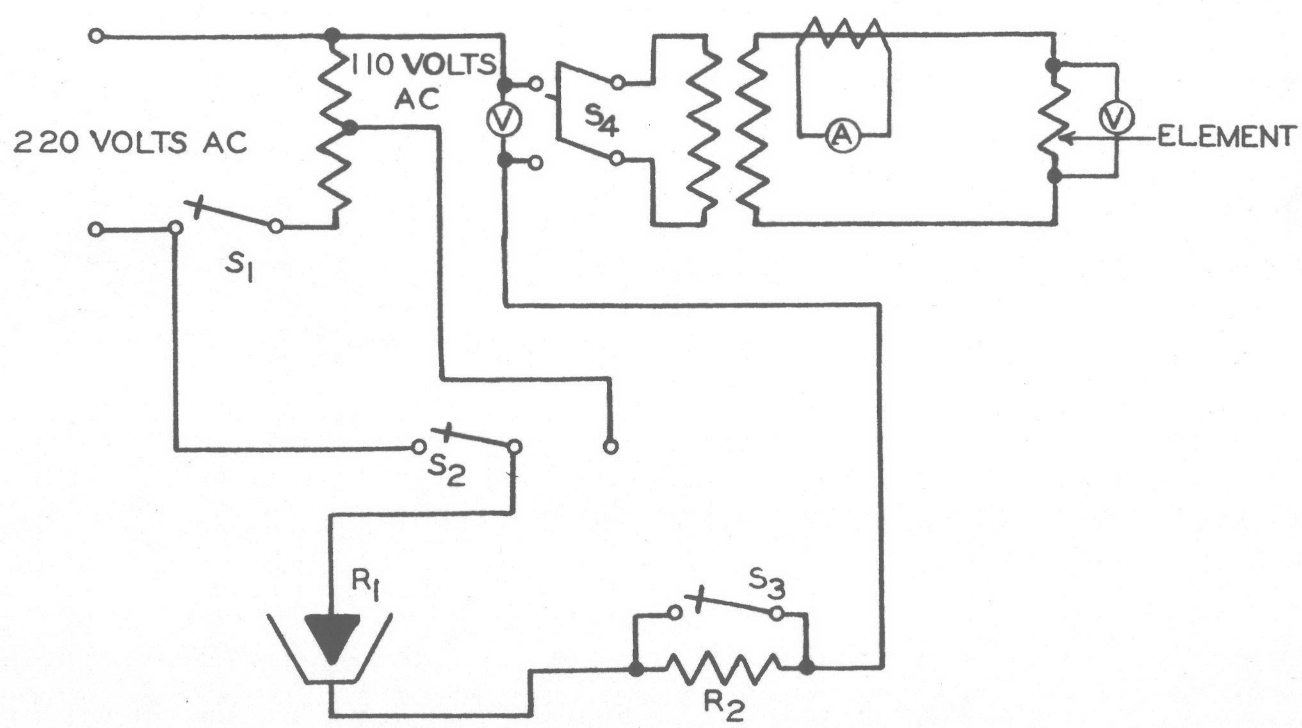


FIG. 6

WIRING DIAGRAM

primary circuit of the high-current transformer so thatbthe energy supply for the element circuit could be controlled at that point. Instruments were placed in the circuit as indicated; a voltmeter for checking the voltage across the primary of the high-cutrent transformer before energizing the element circuit. This voltmeter also indicated voltage variations due to the voltage regulation of the source. The other voltmeter was connected, by drop leads from inside the conduit, across the element to determine the voltage changes due to different water velocities and element currents. An ammeter was connected to a current transformer to determine the value of the current supplied the element circuit.

The voltmeter measuring the voltage drop across the element and the ammeter were carefully calibrated against accurate laboratory standards before they were used and all necessary corrections indicated by calibration curves were made during the tests. By doing this the highest possible acdurac of instrument readings was assured.

Due to the difficulty of accuratelt measuring very low values of alterhating current voltages with laboratory instruments, a vacuum thermocouple with a resistance in series with the heater was calibrated so that the microammeter readings of the output circuit of the thermocouple could readily be converted to the necessary voltage values with the aid of a calibration curve. This method of measuring voltage values was unsatisfactory for these tests however due to the time lag introduced by the thermocouple. Because any change in the element current will result in a rapid change in the voltage drop across the element, any type of vacuum thermocouple instrument will be found unsatisfactory for such tests as these because it the registers a value determined by the average value of the heater current and by so doing introduces a time lag and voltage error that is too large for this type of work where the voltage may fluctuate rapidly.

Description of Elements Used.

The design of the core for the test elements is indicated by the sketch of Fig. 7A. The core was constructed of bakelite and the nickel strips which served as the heating elements were folded over the leading edge of the core, as shown by Fig. 7B, and cemented to it.Voltage drop leads were taken from the ends of the active part of the element and brought out of the test conduit separately so that any small voltage drop in the current lead-in conductors would not effect the measured results. A picture of element D is shown by Fig. 8.

The characteristic resistance data of the elements follow:

Element A: 0.5 inches wide by 0.005 inches thick. A flat nickel strip stretched edgewise and normal to the

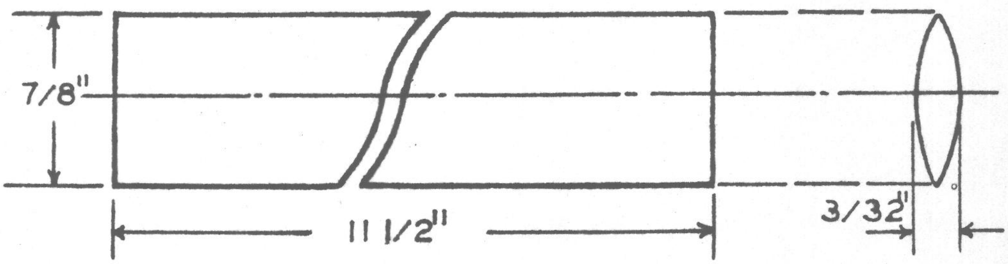


FIG. 7A

ELEMENT CORE

ELEMENT A
FLAT NICKEL STRIP
0.5" X 0.005"

ELEMENT B
FOLDED NICKEL STRIP
1.0" X 0.005"

ELEMENTS C&D
FOLDED NICKEL STRIP
0.5" X 0.005"

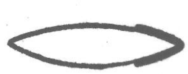


FIG. 7B

ELEMENT CROSS-SECTIONS

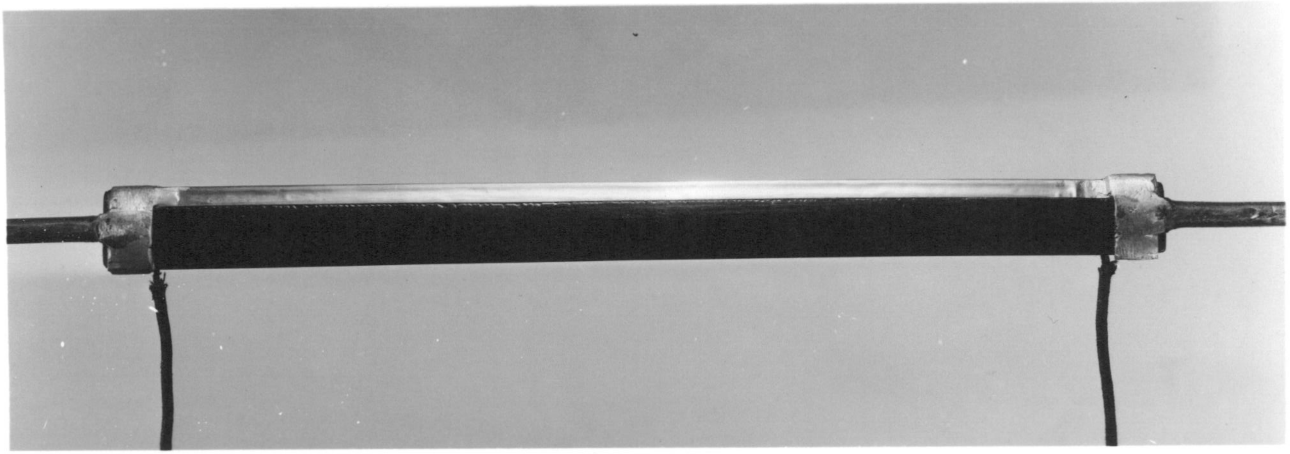


Fig. 8

Element D

direction of stream flow. Resistance of 0.01413 ohms at zero degrees Centigrade.

Element B: 1.0 inches wide by 0.005 inches thick nickel strip folded over leading edge of bakelite core. Resistance of 0.006745 ohms at zero degrees Centigrade.

Element C: 0.5 inches wide by 0.005 inches thick nickel strip folded over leading edge of bakelite core. Resistance of 0.01377 ohms at zero degrees Centigrade.

Element D: 0.5 inches wide by 0.005 inches thick nickel strip folded over leading edge of bakelite core. Resistance of 0.01442 ohms at zero degrees Centigrade.

V DISCUSSION OF TESTS ON DIFFERENT ELEMENTS

Test Procedure

After the construction of an element the first test made was the determination of the resistance of the element at a known temperature. A low resistance Kelvin bridge was used for this measurement, the accuracy of which extended to 0.00001 of an ohm. A thermometer was placed in contact with the metal strip of the element and the resulting temperature carefully noted. The resistance was measured several times and the resulting resistance value corrected by the use of equation 2 to the equivalent resistance at zero degrees Centigrade and the average resistance at this temperature used as the basis for determining resistances for different element temperatures. The desired resistances for the test temperatures were calculated by the use of equation 1. A sample calculation is shown in the appendix.

During a test in the laboratory the velocity was regulated as previously indicated, the head on the tank being held constant which, for a given back-pressure plate, held the velocity constant at approximately the desired value. The actual value of the water velocity was determined by allowing a known weight of the water to collect and noting the time taken to collect this quantity. From these known factors the velocity of the water past the test element was calculated by equation 12 and checked several times before being accepted.

The resistance of the element, and therefore the temperature also, was held constant at the desired value by adjusting the ratio of the voltage drop across the element to the current input. A slide rule was used for this purpose, the end of the C scale being set on the D scale at a point equal to the numerical value of the desired resistance. The numbers on the C scale then represented the current values and directly below each current value the corresponding value of voltage to produce the desired resistance was shown on the D scale. A value of current was then allowed to flow through the element. If the voltage as read by the voltmeter across the element was too low as compared to the value indicated by the slide rule for the same value of current, it was immediately known that the current had to be increased to raise the element resistance to the desired value. This adjustment was repeated for every different water velocity until the desired resistance was obtained. The values of water velocity, current, and voltage required wre then recorded together with the water temperature and the velocity changed to another value and the process repeated.

In the first parts of this paper much reference is made to a constant difference of temperature between the water and element temperatures, and it is pointed out that this is the desireable test condition to maintain. For the tests conducted during this research, however, the element temperature instead of the temperature difference was held constant. This was done because the water in the laboratory would vary a few degrees during a test and because the method of measuring the water temperature was not as accurate as the measurements obtained from the electrical instrumaents used. Much additional time would also be involved for each individual test run, so no direct attempt was made to hold the temperature difference constant. Some of the experimental points on the various curves may be in error due to this cause, particularly those points which are in error and taken at different water temperatures than the points immediately preceeding and following the point in error.

Tests on Element A

Element A, as indicated by the descriptive data on on elements in the apparatus section, was a flat strip stretched horizontally normal and edgewise to the direction of stream flow. Two tests were made on this element: A constant current test, the current being equal to 250 amperes, and a test at a constant element temperature of 95 degrees Centigrade. The constant current curve obtained, Fig. 9, was a straight line over the velocity range investigated, indicating that in this instance the total heat input to the element per degree difference between element

FIG. 9

WATER VELOCITY - HEAT RELATIONS

FOR

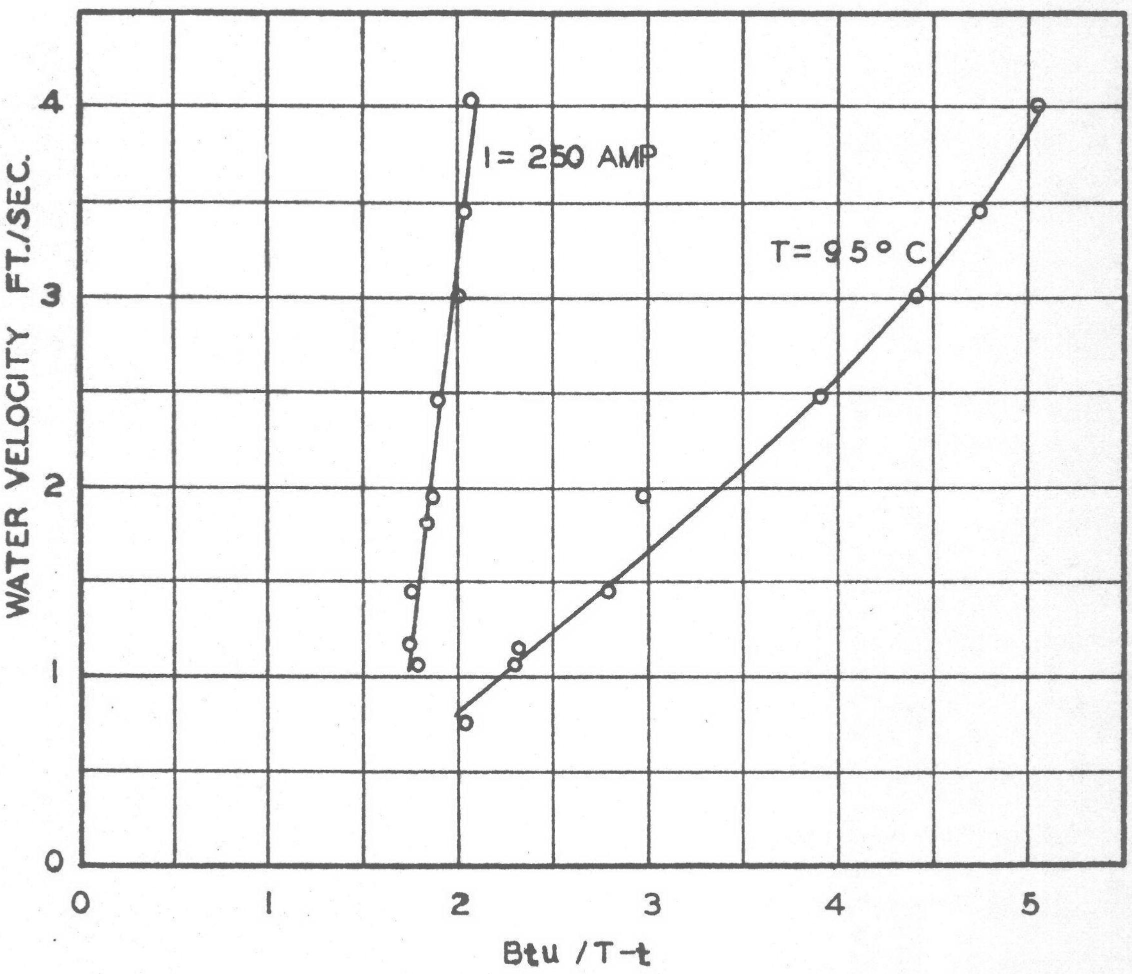
CONSTANT ELEMENT TEMPERATURE

AND

CONSTANT ELEMENT CURRENT

ELEMENT A

t= 15.5°C



and water temperatures varied in a direct relation with the water velocity. It may be noted, however, that in comparison to the constant element temperature curve for the same element the change in heat input per degree of temperature difference for the constant current case is quite small, the curve being very nearly a vertical line. This would indicate that for practical useage the accuracy of this type of test with a flat element of this resistance would not be as high as that obtained from a constant temperature difference relationship.

The constant temperature curve, Fig. 9, for element A as it is plotted is practically a 45-degree line with a slight curvature, intersecting the axis of abscissa at about 0.9 Btu/T-t when extended. This would indicate that the heat change for this particular test varied in almost a direct ratio with the water velocity which would make it a very desireable type of element to use for tests of this kind. It may be noted, also, that several of the points do not fall directly on the curve. This discrepancy may be due to one, or both, of two causes in addition to the slight change in water temperature during the test. The first being the continuous waving of the element in the water which would tend to create a slight amount of turbulence around it, and the other that the voltage impressed across the first transformer varied slightly at all times. Fluctuations of the test instruments were so rapid that average readings had to be taken most of the time.

The element failed at a water velocity slightly above four feet per second, apparently due to fatigue at the point of contact with the rigid current lead-in. This fatigue, due to the waving of the element in the water, cracked the metal across part of the surface, the remainder of the cross-section being fused by the high concentration of current at that point. From this test it is evident that a flat strip, without support in addition to that at the extreme ends, is not suitable for average tests because if it were to be made mechanically strong enough to resist the waving action due to the water, the current requirements for a suitable element temperature would be excessive and, also, due to the thickness that would accompany the change in design, trouble due to turbulence would undoubtedly be encountered.

Tests on Element B

Element B was the first element constructed using a folded nickel strip on the leading edge of the bakelite core. Two different constant element temperature tests were made on this element, the first at a temperature of 29 degrees Centigrade and the second at a temperature of 61 degrees Centigrade.

The results of the first tests are shown graphically by the curve of Fig. 10, all points below a water velocity

FIG, 10

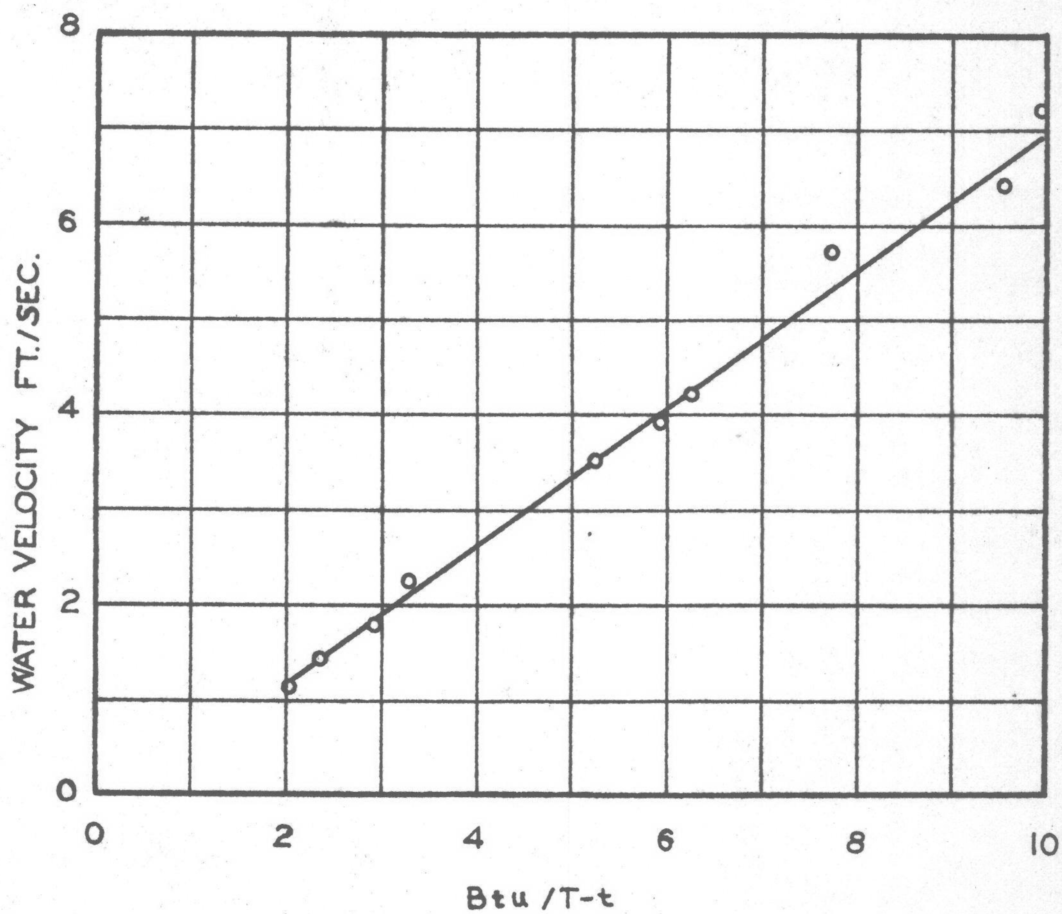
WATER VELOCITY - HEAT RELATIONS

FOR

CONSTANT ELEMENT TEMPERATURE

ELEMENT B

T=29°C
t=15.2°C



of 4.5 feet per second forming a distinct straight line. The points above this velocity vary slightly from the curve; these variations most probably being due to the combined effect of voltage source fluctuations as reflected by the larger values of current necessitated by the higher velocities and because a calibrated vacuum thermocouple was used as a voltmeter. This type of voltmeter tends to average all small voltage fluctuations, thereby increasing the possibility of incuttring slight errors.

The curve for a constant elementtemperature of 61 degrees Centigrade is shown by Fig. 11. The points for this curve appear quite erratic as compared to the curve of Fig. 10 for the same element. The vacuum thermocouple voltmeter was again used for this test and an additional voltmeter placted across the supply source. It was noted that the voltage of the source fluctuated considerably all during the test, and this fact alone is the most probable cause of the discrepancies present. Another factor that would greatly increase any error present was that due to the higher element temperature the current requirements for this test were approximately twice those for the previous test. Because the heating value varies as the square of the current it is obvious that a small error in the instrument readings due to voltage fluctuations would be greatly magnified in the final results.

This element failed by fusion at the beginning of a

FIG. 11

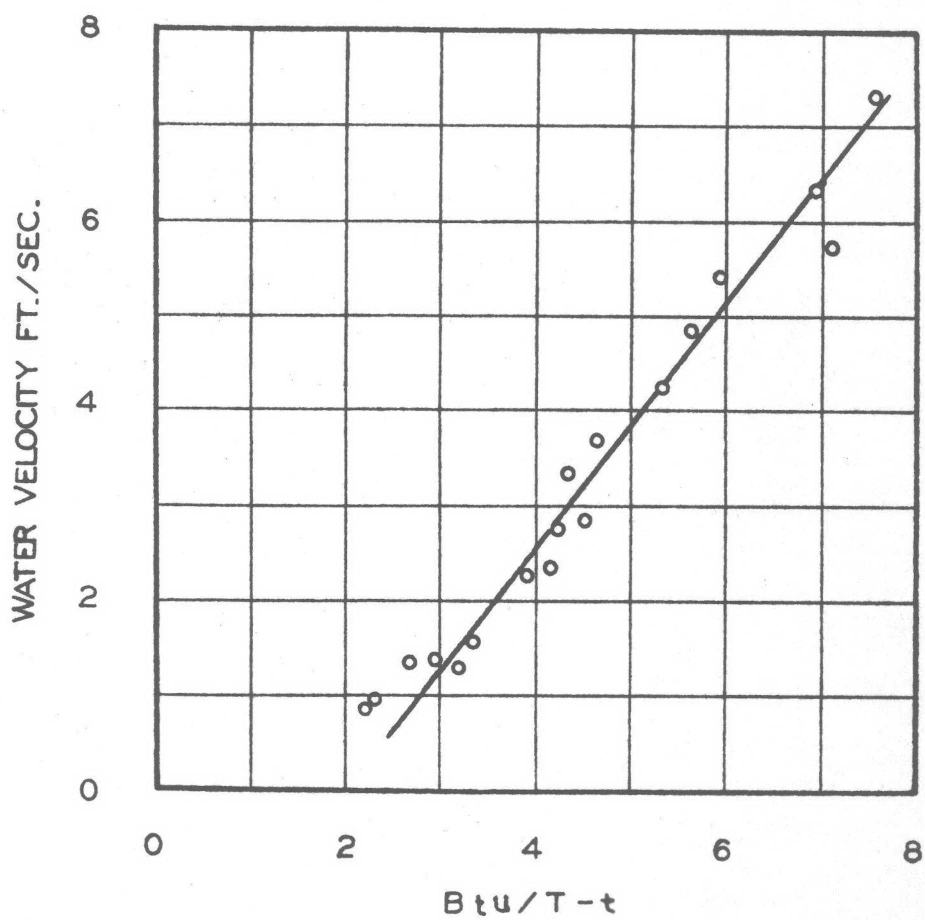
WATER VELOCITY - HEAT RELATIONS

FOR

CONSTANT ELEMENT TEMPERATURE

ELEMENT B

T = 61° C
t = 16.3° C



later test at a higher value of element temperature. The failure occurred about 1.5 inches from the side of the conduit, being caused by a momentary condition of turbulence and the presence of a large amount of entrained air in the water supply at the time. The water velocity was approximately 1.5 feet per second.

The greatest objection to the use of this element was the high value of current required to maintain it at a satisfactory temperature. The natural line voltage fluctuations had such an effect on the element current supply and, because of this, the voltage drop across the element that it was very difficult to get highly accurate instrument readings. For this reason an element having a conductor but half the width of that of element B was constructed and used, the current requirements being cut in half for the same values of element temperature and voltage drop.

Tests on Element C

Element C was constructed with a 0.5 by 0.005 inch nickel strip folded over the leading edge of the bakelite core. This type of element, as mentioned above, requires but half the value of current to raise its temperature to approximately the same point as for element A. Two tests were made on this element; one for a constant element temperature of 80 degrees Centigrade as shown by Fig. 12 and the second for a constant element current condition of 200

FIG.12

WATER VELOCITY- HEAT RELATIONS

FOR

CONSTANT ELEMENT TEMPERATURE

ELEMENT C

T= 80° C
t=16.2° C

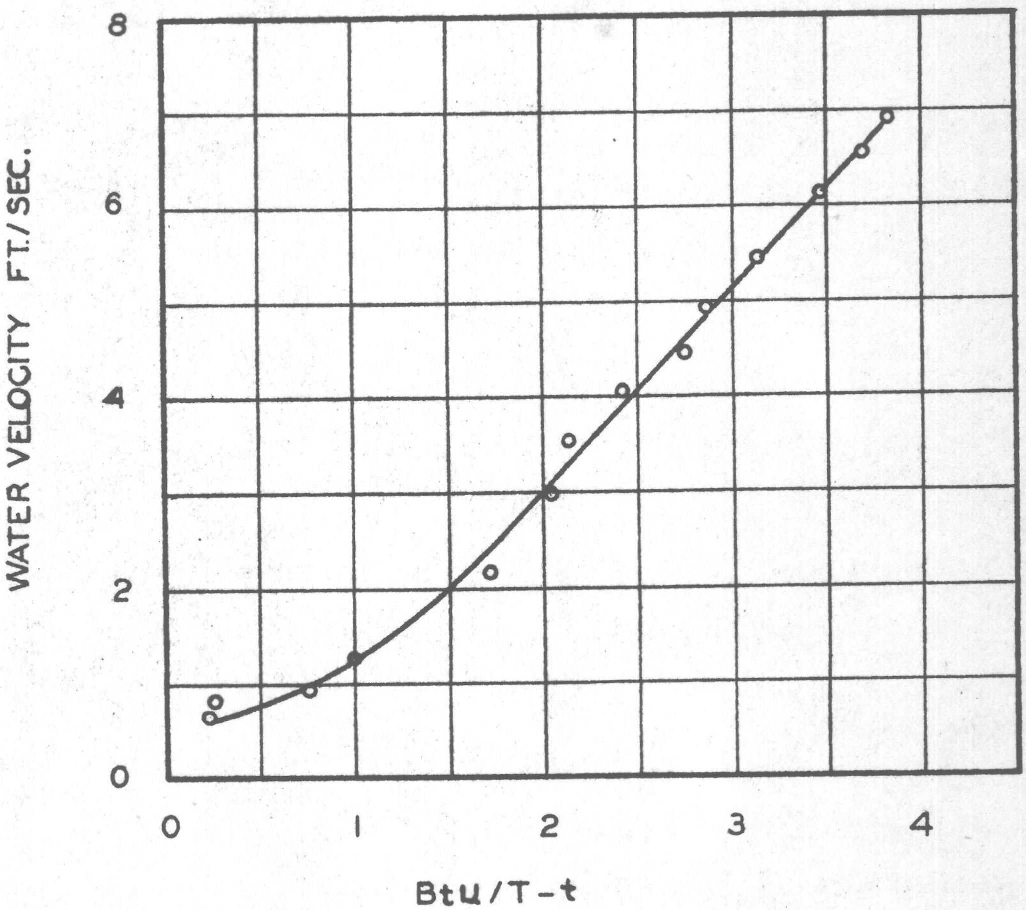


FIG. 13

WATER VELOCITY-HEAT RELATIONS

FOR

CONSTANT ELEMENT CURRENT

ELEMENT C

I = 200 AMP.
t = 16.2 °C

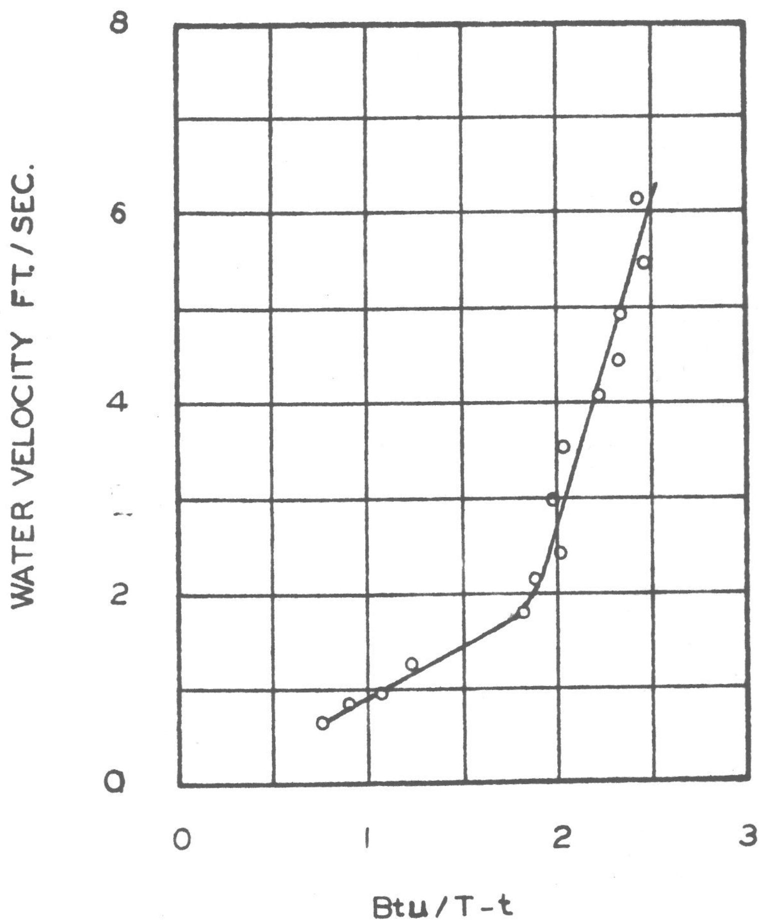


FIG. 13B

WATER VELOCITY

ELEMENT TEMPERATURE RELATIONS

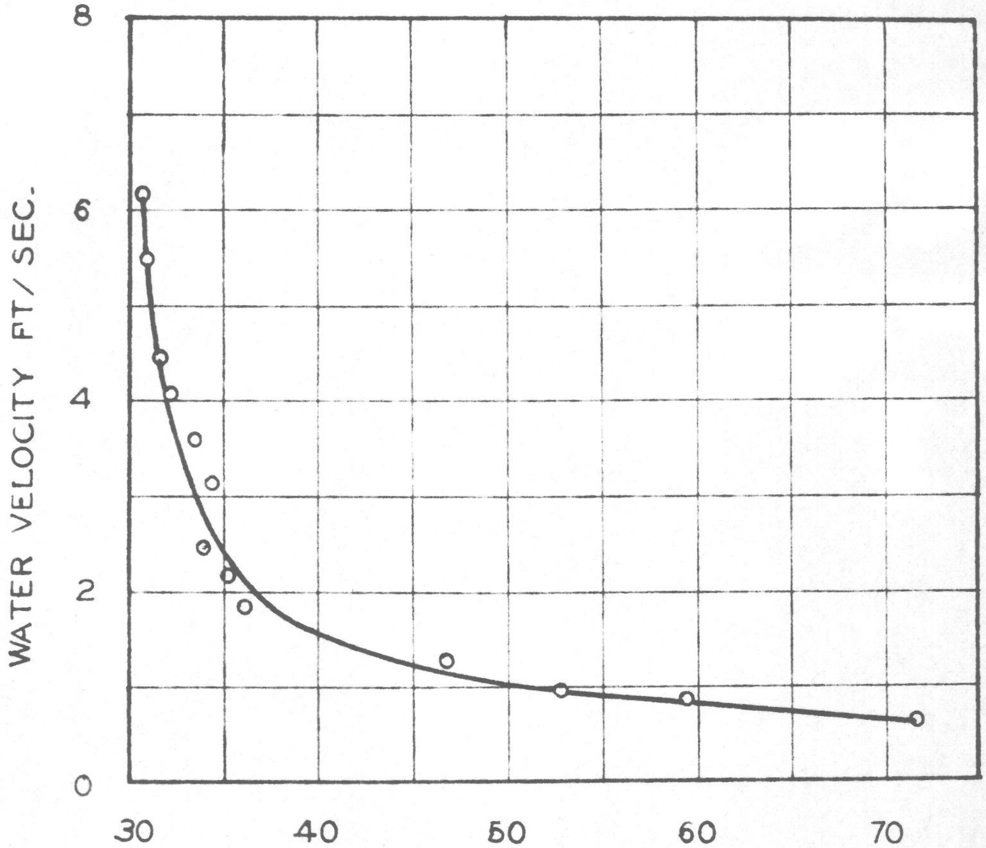
FOR

A CONSTANT ELEMENT CURRENT

I = 200 AMP.

t = 16° C

ELEMENT C



amperes as shown by the curves of Figs. 13 and 13B. These two sets of data were obtained during the first test run, the only variations necessary being the adjustment of the element temperature for the first and the input current for the second.

The constant element temperature test for element C shows the same straight line relationship as the curves of element B over the same range. It may be noted here that the minimum water velocity shown by the tests on element B was slightly less than 1.2 feet per second. Below this value the curve of element C tends to become more horizontal, indicating that over the velocity range of 0.7 t0 1.2 feet per second the water is taking a greater amount of heat away from the element in proportion to its velocity than is the case for the remainder of the curve. The probable reason for this is that atbthe lower water velocities the large temperature difference between the element and water temperatures tends to cause more heat to be removed from the element due to conduction and pure convection currents set up independent of the water velocity. At the higher water velocities this phenomenon does not have an opportunity to occur because the water does not remain in contact with the element long enough to establish a convection component in the water velocity.

The constant current test curve for element C shows much the same characteristics as those shown by the constant temperature test curve for the same element. Two outstanding differences are apparent however. The first is that the slope of the constant current curve is much steeper, which indicates that the water is taking less heat away per degree of temperature difference between the element and water temperatures. The second point that should be noted is that below a water velocity of 2.4 feet per second the curve is no longer the same straight line.

The reason for the constant current heat transfer as a function of the water velocity curve having a steeper slope may be ascribed to two conditions. The first that the element temperature decreases as the water velocity increases, as indicated by the typical constant current curve for such test conditions as shown by Fig. 1 and also as shown by Fig. 13B for this element. The temperature decrease bears a direct relation to the water velocity and tends to keep the curve straight, while the decreased total heat input to the element as compared to the total heat input for the constant temperature condition of Fig. 12 accounts for the distinct change in slope. Below two feet per second, as also indicated by Figs. 1 and 13B, the element temperature undergoes its most rapid rate of change. Therefore the temperature difference between the element and water temperatures is changing at its most rapid rate which causes the amount of heat taken away by the water to change in almost a direct ratio. The only other possible influence is that due to pure convection currents set up by the difference between the element and water temperatures which is not as high in this instance as for the curve of Fig. 12.

The above discussion alsomindicates the reasons for the shape of the element temperature curve for Fig. 13B. This curve has the same characteristics as those temperature curves for previous constant element current tests which indicates that the practical results to be obtained from constant element current test conditions would be sufficiently accurate only for the lower water velocities.

This element failed at a water velocity of about 7.0 feet per second. It evidently failed by fusion as the failure was quite narrow, indicating that it occurred very suddenly as the bakelite core was not appreciably charred as in the instance of the failure of element B. A quite turbulent condition of water flow along the left side of the pipe where the failure occurred was noted at this velocity, and it is probable that a large and narrow slug of air was suddenly accumulated which allowed the element to fuse. Under any other conditions much more charring of the bakelite core should have been noted due to the accumulative formation of air pockets and a resulting longer time to fuse the metal.

Tests on Element D

Element D is essentially the same as element C, the only difference being that the resistance is about 5 per-cent higher. Two tests were made on this element, one at a constant element temperature of 60 degrees Centigrade as indicated by Fig. 14 and the other at a constant element temperature of 40 degrees Centigrade as shown by Fig. 15.

The curve for a constant element temperature of 60 degrees Centigrade is seen to be two practically parallel straight lines with a transition period in the water velocity region of 2.5 to 3,8 feet per second. A comparison of this curve with that of Fig 12, constant element temperature of 80 degrees with element C, would indicate that the same transition period is the same in both curves, but being raised from a maximum water velocity of 1.2 feet per second for Fig.,12 to a maximum of about 3, 8 feet per second for Fig. 14. Whether this transition actually occurs or not cannot be stated definitely, although it is the author's opinion that if sufficient experimental data for Fig. 12 could have been obtained the curve for that condition would have again changed slope and intersected the axis of abscissa at a value of heat transfer per degree of temperature difference slightly above zero, perhaps being so small that it would be difficult to plot accurately. That this surmise is reasonable may be ascertained by a closer examination of Fig. 12. If this curve is allowed to follow its trend as plotted, it will intersect the axis of ordinates at a water velocity of about 0.1 feet per second.

FIG. 14

WATER VELOCITY - HEAT RELATIONS

FOR

CONSTANT ELEMENT TEMPERATURE

ELEMENT D

T = 60°C
t = 17.0 °C

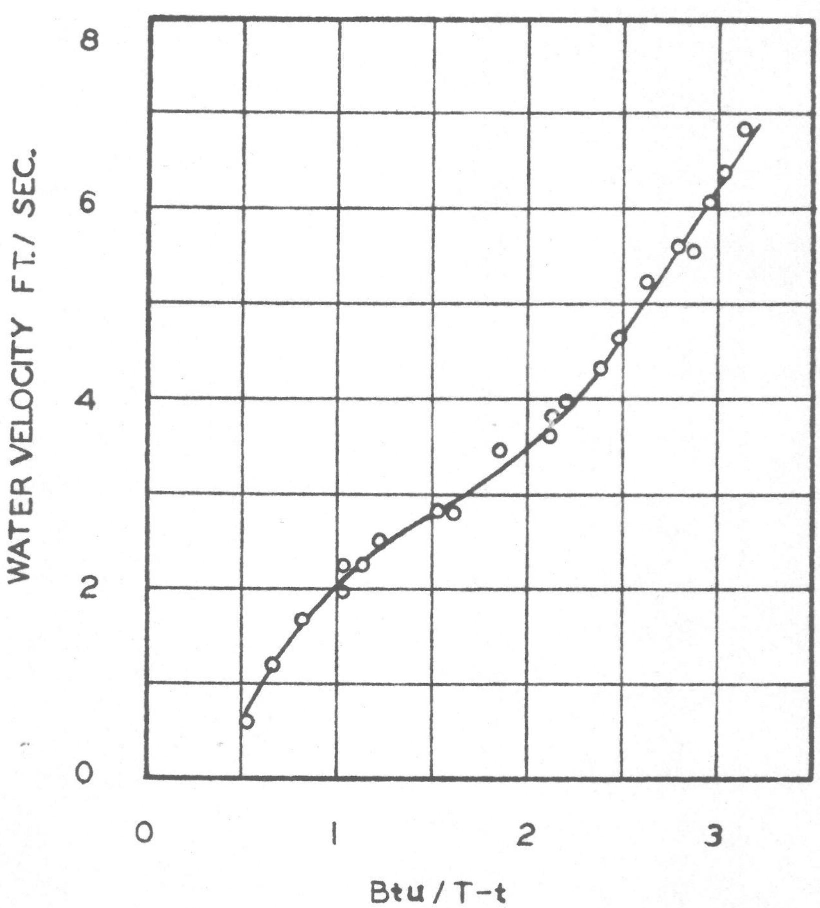


FIG. 15

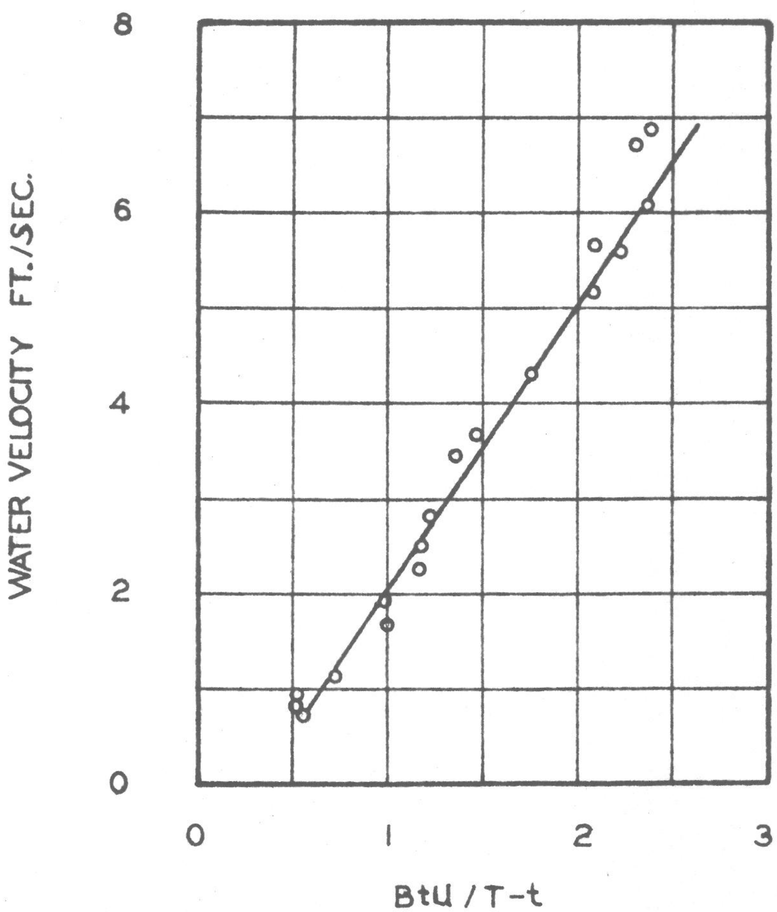
WATER VELOCITY-HEAT RELATIONS

FOR

CONSTANT ELEMENT TEMPERATURE

ELEMENT D

T= 40°C
t= 16.6°C



This would be physically impossible to obtain experimentally because if such an intersection occurred, the curve of Fig. 12 would intersect the axis of abscissa at an appreciably negative value of heat removed from the element per degree of temperature difference. In other words, if this occurred the water would be giving up heat to an object with a temperature over 60 degrees Centigrade higher than itself. The impossibility of this occurring is readily recognized and, therefore, the only logical path for the curve of Fig. 12 to follow is one similiar to that of Fig. 14, thereby showing the transition period to be moved higher with respect to the water velocity as the element temperature is decreased from 80 degrees to 60 degrees Centigrade.

The most probable cause for the transition period and its change in position with respect to the element temperature is the formation of minute air bubbles on the surface of the element due to the vaporization of the water. An examination of the curve of Fig. 14 will show that if the lower portion of the curve were extended as a straight line it would be parallel to the upper portion of the curve, but over 0,6 Btu/T-t less at every point. This indicates quite definitely that for some reason the water below a velocity of two feet per second is not taking as much heat from the element in proportion to its velocity as is being removed atbthe higher velocities. The only probable reason for this is the formation of the above-mentioned minute air bubbles. The shape of the curve during the transition period also substantiates this line of reasoning because the change is quite rapid at first. This rapid change is due to more and more air bubbles being removed as the velocity is increased and thus the percentage of element surface intimately exposed to the water increases rapidly at first and then more slowly until the element surface is uniformly covered with water. From this point on the curve again assumes a linear relationship, but at a higher rate of heat removal because water and not vapor is in direct contact with the element to convect away the heat.

The constant element temperature curve for 40 degrees Centigrade for element D, Fig. 15, produces a straight line relationship through all experimentally determined points and is quite similiar in its characteristics to the curve of Fig. 10 for element B at a constant element temperature of 29 degrees Centigrade. The similiarity in these two straight line curves and the irregularities noted in other curves for higher element temperatures tends to advance the supposition that the most accurate results may be obtained with the lower element temperature curves. The most probable reason for the lower element constant temperature curves having no marked irregularities over the expreimental range is that small bubbles due to water vapor and absorbed air are not formed because of the low temperature of the element and, therefore, while the total quantities of heat involved are much smaller, the results as determined are more reliable. The only factor which would appear to limit the dependability of results obtained with low values of constant element temperature tests is the accuracy with which the current and voltage changes can be measured. However, with the proper instruments, which can be obtained, this limiting condition may be largely removed.

Heat Transfer Per Square Inch of Element Surface

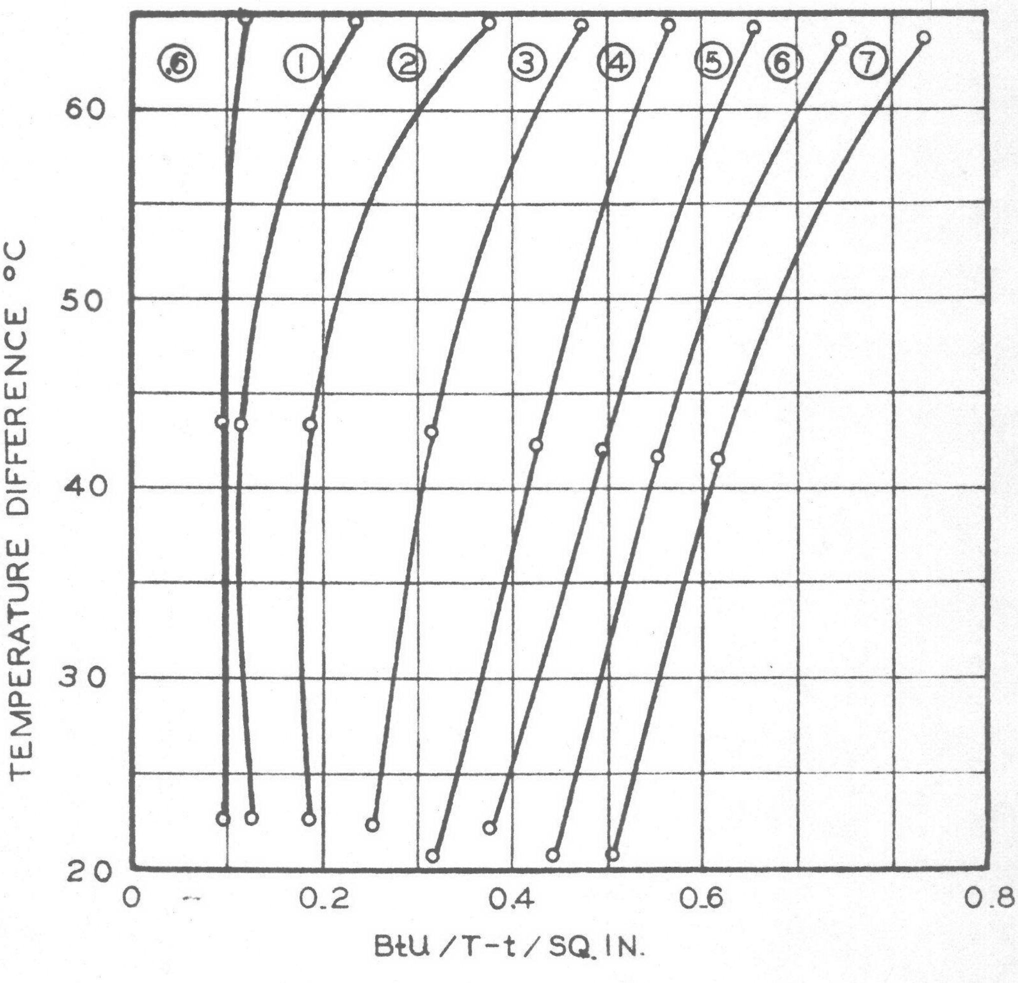
This set of curves, as shown by Fig. 16, is constructed from the curves of Figs. 12, 14, and 15. The results are interesting, and, also, to be expected because of the shape of the curves for the above figures. For all water velocities above 4 feet per second, the amount of heat removed per square inch of element surface increases by the same amount for every unit increase of element temperature and water velocity. For water velocities below 4 feet per second, the increase in heat removed per square inch of element surface area is practically constant for the temperature differences up to 40 degrees Centigrade. At all higher temperatures, however, the increase is different, the greatest increase being noted for a temperature difference between 55 and 65 degrees for an increase in water velocity from 2 to 3 feet per second. By following the explanation offered for the erratic behavior for the curve of Fig. 14 in the water velocity region indicated, a ready explanation is obtained. The reason that the increase in heat removed per unit of surface area is more uniform for the higher temperature differences of about 55 to 65 degrees Centigrade is most probably that the amount of heat given off at the element surface produces more of a boiling action along the surface and the bubbles of vapor thus formed are forced off by this action rather than being pulled off by the water flowing past the element surface. As each individual bubble is forced off the surface a cold particle of water takes its place, thus producing a momentary localized cooling action. Because of the large number of minute bubbles being given off, a uniform condition is set up, and as the water velocity is increased the bubbles are removed faster until a velocity is reached at which the bubbles, due to the combined action of their internal pressure and the pull of the water flowing, are removed instantaneously. From this point on, at a water velocity slightly over one foot per second, the amount of heat removed will vary directly with the water velocity.

This set of curves brings out more forcibly the statement made previously that it appears that the most accurate practical measurement of water velocities will be obtained from elements designed to operate at a constant temperature difference below 40 degrees Centigrade because in this temperature the amount of heat removed per unit of surface area varies by a constant amount with each unit increase

FIG. 16

HEAT TRANSFER PER UNIT AREA OF ELEMENT SURFACE AS A FUNCTION OF TEMPERATURE DIFFERENCE AND WATER VELOCITY FOR ELEMENTS C & D

CURVE NUMBER INDICATE WATER VELOCITY IN FT./SEC.



in water velocity, and the only limiting condition that should be encountered is the ease with which the change in the amount of heat conducted away from the element can be measured.

The thickness of the film of water which was warmed by the heat given off by the element was determined for element C when used at a constant element temperature of 80 degrees Centigrade. This thickness was found in the manner indicated on page 17 of the Electrical and Heat Measurements section. It was found that if the heat given off was assumed to raise the whole layer to the temperature of the element, the thickness of the film of water would be 0.00211 inches for a water velocity of 0.96 feet per second and 0.00103 inches thick for a water velocity of 6.14 feet per second. If it is assumed that the temperature gradient of this layer of warmed water is a straight line function, the temperature of the layer decreasing from a value equal to the element temperature on one side to a value equal to the water temperature on the other, it is found that for a water velocity of 0.96 feet per second the thickness of the layer is equal to 0.00422 inches and for a water velocity of 6.14 feet per second 0.00206 inches. These values give a relative idea of the extreme thinness of the layer of water effected by the heat given off by the element. For other tests on elements C and D the thickness would be approximately directly proportional to the test temperatures as compared to the results given here, these figures representing the results from the highest element temperatures used for elements C and D.

General Summary of Experimental Results

The curves submitted in the foregoing parts of this paper show conclusively that it is possible to construct and calibrate an element which will accurately determine water velocities in any practical installation free from excessive turbulence. A straight line relationship was found to be the base for all curves, small variations being induced at the higher element temperatures due to the formation of air bubbles on the surface of the element. Thus, the object of this research was accomplished; namely, that a straight line relationship between an easily determined variable and a variable water velocity was developed.

The straight line function of the heat input per degree of temperature difference between element and water temperatures as a function of the water velocity proved another point that has not yet been mentioned. This is that if each part of the cross-section of water coming in contact with the heated element surface takes away a proportionally greater amount of heat per unit increase of water velocity, then the total amount of heat taken away from the element by the water should increase directly with an increase in the water velocity. If this is done, the element will be shown to be effectively integrating the cross-section of the test conduit and adding each infinitesmal change of heat value directly. Because each of these small changes is a direct function of the water velocity at every point and because the addition of all points gives a straight line relationship, it is proven that the cross-section of the conduit is integrated by the element when the heat relationships are plotted as a function of the water velocity.

The greatest single difficulty encountered in this investigation was the difficulty of making sufficiently accurate measurements. This difficulty was caused primarily by the voltage fluctuations of the source of power. Some difficulty was also encountered in accurately measuring alternating current voltages below four volts. It is reccommended that for any future investigations or practical installations direct current be used as the source of power for the element when possible because of the ease of measurement of direct current voltages and the accurate and exact control of power that would be afforded by this source.

Proposed Spot Velocity Element

A type of element to replace such devices as current meters and the pitot tube is being constructed at the present. A sketch of this proposed element is shown in Fig. 17. The resistance of the element if wound with a 1/8 inch wide and 0.002 inch thisc nickel strip will be approximately one ohm. This is an element resistance over 70 times that of any element used in the investigation just completed. The maximum current requirement will be approximately 50 amperes, and the maximum voltage drop across the element will be about 50 volts. Under these conditions the element should give very satisfactory results for either constant element temperature tests or for constant current input tests because of the comparatively large and easily measured voltage changes that will be introduced by the higher element resistance. It is probable that this element will be calibrated with a voltmeter whose scale will read the water velocity directly so that it may be used in the field as a constant current input device. In this manner it may be used by anyone for determining water velocities without the necessity for making calculations and referring to calibration curves for the final determinations. While no data on this element are available at the present, this device should be completed and ready for active use in the very near future.

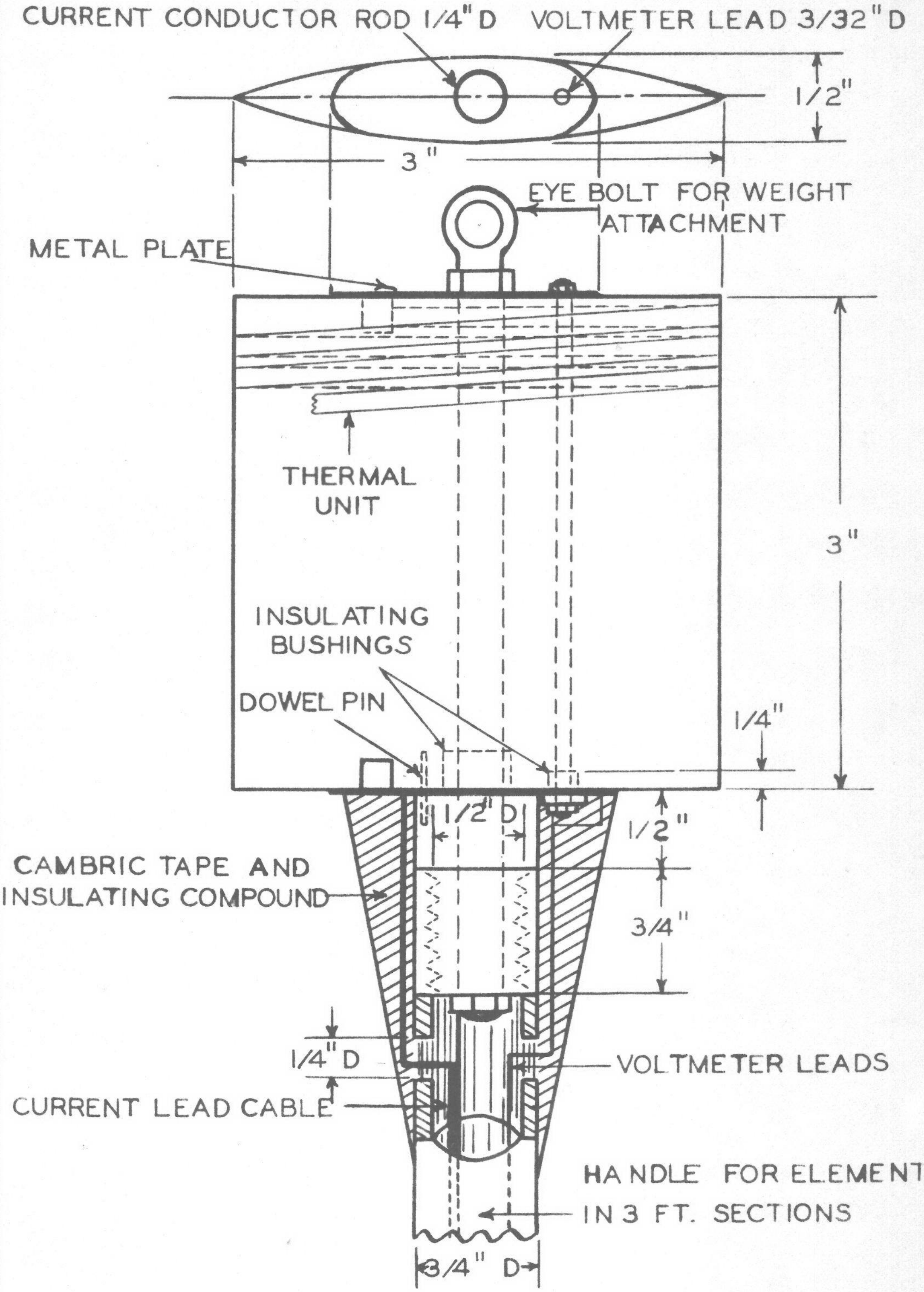


FIG. 17

SPOT VELOCITY ELEMENT

VI CONCLUSIONS

A straight line relationship between water velocity and the heat input to the element per degree of temperature difference between the element and water temperatures exists if the difference between the element and water temperatures is held constant.

The straight line relationship between the heat input per degree of temperature difference between element and water temperatures as a function of the water velocity proves that for a constant temperature difference the element effectively integrates and sums up the results of the many small heat transfer points along its surface.

The constant element temperature test is a very reliable means of determining water velocities if used below the value of temperature difference between element and water temperatures at which bubbles will form on the element surface.

With the proper apparatus an element of this type can be made to a large scale and calibrated so that the resulting velocity determinations will be very dependable.

A dependable spot velocity element, suitable for use by the general technical world, was designed and will be calibrated and ready for practical use in the near future.

VII APPENDIX

SYMBOL SHEET

Symbol	Meaning
V	Water velocity Ft./Sec.
E	Voltage drop across element volts
I	Current input to element Amperes
R_0	Resistance of element at 0°C ohms
R_t	Resistance of element at any temperature T ohms
T	Temperature of element in degrees Centigrade
t	Temperature of water in degrees Centigrade
A	Unit of area
H	Heat input to element in Btu/minute
$\Delta H/\Delta T$	Heat unit of Btu/Min. per degree of temperature difference between element and water temperatures
h	Average amount of heat in Btu/Min./T-t taken from the element by the water per square inch of exposed element surface area.

SAMPLE CALCULATIONS

Using element D:
Measured resistance at 23.1 °C = 0.016084 ohms

Resistance at 0 °C:

$R_0 = (0.016084)/(1 + 0.005 \times 23.1)$ (Eq.2)
$= 0.01442$ ohms

Resistance at 60 °C:

$R_t = (0.01442)(1 + 0.005 \times 60)$ (Eq.1)
$= 0.018746$ ohms

From test data for a constant element temperature of 60 °C for element D:

Given:

Water velocity 1.20 Ft./Sec
Current input 165 amperes
Element voltage drop 3.09 volts
Water temperature 16.0 °C

Calculations:

Element resistance:

$R = E/I = 3.09/165 = 0.01873$ ohms

Element temperature:

$T = (0.01873 - 0.01442)/(0.01442 \times 0.005)$ (Eq.3)
$= 59.8$ °C

Temperature difference:

$T-t = 59.8 - 16.0$ (Eq.6)
$= 43.8$ °C

Power input:

$P = EI = 165 \times 3.09 = 0.510$ KW

Heat input:

$H = 0.510 \times 56.87$ (Eq.5)
$= 29.0$ Btu/ Min.

Rate of heat removal:

$\Delta H/\Delta T = 29.0/43.8 = 0.662$ Btu/T-t (Eq.8)

Heat removed per unit area of element surface:

$h = 0.662/5.25$ (Eq.9)
$= 0.1261$ Btu/T-t/Sq. In.

TABLE I
WATER VELOCITY - HEAT RELATIONS
FOR
ELEMENT A

Water Velocity Ft./Sec.	Element Voltage Drop	Element Current Amperes	Element Temp. °C	Water Temp. °C	Temp. Diff. °C	Btu per Min.	Btu per T-t
Constant element current of 250 amperes							
1.06	4.42	250	50.5	15.3	35.2	62.9	1.787
1.16	4.40	250	49.2	15.3	35.9	62.5	1.741
1.45	4.44	250	51.1	15.4	35.7	63.0	1.767
1.80	4.41	250	49.7	15.7	34.0	62.8	1.848
1.95	4.39	250	48.7	15.3	33.4	62.4	1.868
2.45	4.39	250	48.7	15.7	33.0	62.3	1.888
3.00	4.35	250	46.4	15.4	31.0	61.9	1.998
3.45	4.34	250	45.9	15.5	30.4	61.6	2.025
4.03	4.33	250	45.0	15.4	29.6	61.5	2.078
Constant element temperature of 95 °C							
0.73	7.70	370	94.5	15.3	79.2	161.8	2.040
1.06	8.20	394	94.5	15.3	79.2	183.6	2.308
1.16	8.24	396	94.5	15.3	79.2	185.1	2.340
1.41	8.75	420	94.6	15.4	79.2	208.5	2.635
1.45	9.00	432	94.5	15.4	79.1	221.0	2.795
1.95	9.18	448	94.5	15.3	79.2	236.3	2.985
2.45	10.58	510	94.5	15.7	78.8	307.3	3.900
3.00	11.19	540	93.8	15.8	78.0	343.5	4.400
3.45	11.60	560	93.4	15.6	77.8	369.2	4.740
4.03	12.00	578	93.8	15.4	78.4	394.5	5.040

TABLE II
WATER VELOCITY-HEAT RELATIONS
FOR
ELEMENT B

Water Velocity Ft./Sec.	Element Voltage Drop	Element Current Amperes	Element Temp. °C	Water Temp. °C	Temp. Diff. °C	Btu per Mim.	Btu per T-t
Constant element temperature of 29 °C							
1.17	1.95	246	28.7	15.2	13.5	27.3	2.025
1.43	2.08	262	28.7	15.4	13.3	31.0	2.330
1.79	2.25	285	27.8	15.4	12.4	36.5	2.940
2.22	2.34	297	27.6	15.6	12.0	39.5	3.290
3.55	3.14	398	28.5	15.0	13.5	71.3	5.280
3.94	3.34	422	28.3	14.8	13.5	80.4	5.950
4.24	3.41	430	28.5	15.2	13.3	83.4	6.260
5.74	3.78	476	28.5	15.2	13.3	102.3	7.710
6.45	4.30	542	28.7	14.8	13.9	132.6	9.540
7.22	4.36	550	28.7	14.8	13.9	136.3	9.920
Constant element temperature of 61 °C							
0.87	4.06	436	61.4	16.6	44.8	101.2	2.260
0.91	4.11	442	61.1	16.4	44.7	103.4	2.213
1.31	4.81	518	60.7	16.4	44.3	141.6	3.197
1.37	4.48	480	61.9	16.6	45.3	122.3	2.700
1.39	4.67	502	61.2	16.4	44.8	133.3	2.975
1.59	5.08	542	62.9	16.3	46.6	156.6	3.360
2.25	5.39	579	61.5	16.2	45.3	177.5	3.920
2.37	5.49	592	60.5	16.2	44.3	184.9	4.172
2.74	5.58	600	61.1	16.6	45.0	190.6	4.238
2.84	5.72	618	60.1	16.1	44.0	201.1	4.560
3.35	5.71	612	61.8	16.1	45.7	198.7	4.350
3.71	5.79	624	60.6	16.0	44.6	205.0	4.610
4.23	6.29	676	61.2	16.0	45.2	242.0	5.360
4.87	6.41	690	60.7	15.9	44.8	251.7	5.620
5.41	6.60	710	61.0	15.9	45.1	266.5	5.910
6.35	7.05	760	60.5	16.0	44.5	309.0	6.945
7.37	7.43	800	60.7	16.0	44.3	338.2	7.530

TABLE III
WATER VELOCITY - HEAT RELATIONS
FOR
ELEMENT C

Water Velocity Ft./Sec.	Element Voltage Drop	Element Current Amperes	Element Temp. °C	Water Temp. °C	Temp. Diff. °C	Btu per Min.	Btu per T-t
Constant element temperature of 80 °C							
0.63	4.05	210	80.4	15.6	64.8	48.4	0.746
0.85	4.15	214	80.4	15.7	64.7	50.2	0.776
0.96	5.26	273	80.4	15.8	64.6	81.6	1.262
1.29	5.85	303	80.4	15.8	64.6	100.6	1.508
2.16	7.06	364	81.8	15.9	65.9	146.0	2.220
3.02	7.45	386	80.4	16.0	64.4	163.2	2.540
3.54	7.60	394	80.4	16.0	64.4	170.1	2.645
4.06	8.00	414	80.9	16.0	64.9	188.4	2.910
4.45	8.42	436	80.4	16.1	64.3	208.6	3.250
4.94	8.57	444	80.4	16.2	64.2	215.5	3.355
5.49	8.84	458	80.4	16.2	6312	230.0	3.640
6.59	9.45	490	79.8	16.8	63.0	263.0	4.180
6.92	9.65	500	80.4	16.8	63.6	274.0	4.310
Constant element current of 200 amperes							
0.63	3.74	200	71.7	15.6	56.1	42.5	0.758
0.85	3.57	200	59.3	15.4	44.9	40.5	0.903
0.96	3.48	200	52.8	15.8	37.0	39.6	1.070
1.29	3.40	200	46.9	15.8	31.1	38.6	1.240
1.80	3.25	200	36.1	15.9	20.2	36.9	1.830
2.16	3.24	200	35.3	15.9	19.4	36.8	1.986
2.42	3.22	200	33.9	15.8	18.1	36.5	2.015
3.02	3.23	200	34.6	16.0	18.6	36.7	1.970
3.54	3.22	200	33.9	16.0	17.9	36.5	2.040
4.06	3.20	200	32.4	16.0	16.4	36.4	2.220
4.45	3.19	200	31.7	16.1	15.6	36.3	2.330
4.94	3.19	200	31.7	16.2	15.5	36.3	2.340
5.49	3.18	200	30.9	16.2	14.7	36.2	2.460

TABLE IV
WATER VELOCITY - HEAT RELATIONS
FOR
ELEMENT D

Water Velocity Ft./Sec.	Element Voltage Drop	Element Current Amperes	Element Temp. °C	Water Temp. °C	Temp. Diff. °C	Btu per Min.	Btu per T-t
Constant element temperature of 60 °C							
0.60	2.75	147	59.4	16.0	43.4	23.0	0.530
0.85	2.80	150	59.4	16.0	43.4	23.9	0.551
0.91	2.84	152	59.4	16.0	43.4	24.6	0.568
1.20	3.09	165	59.8	16.0	43.8	29.0	0.662
1.67	3.46	185	59.4	16.0	43.4	36.5	0.842
1.98	3.83	205	59.4	16.0	43.4	44.7	1.032
2.24	4.04	216	59.4	16.0	43.4	49.6	1.143
2.28	3.84	206	59.4	16.0	44.9	44.9	1.036
2.50	4.16	223	59.4	16.2	43.2	52.9	1.223
2.82	4.56	245	58.4	16.3	42.1	63.5	1.510
3.44	5.15	275	59.7	16.0	43.7	80.6	1.844
3.60	5.39	288	59.4	18.0	88.3	88.3	2.130
3.84	5.44	291	59.4	16.9	42.5	90.0	2.120
4.02	5.54	296	59.4	17.0	42.4	93.2	2.200
4.31	5.70	305	59.4	18.0	41.4	99.0	2.390
4.62	5.80	310	59.4	18.0	41.4	102.3	2.480
5.20	6.05	323	59.8	17.4	42.4	111.1	2.630
5.58	6.22	333	59.4	18.0	41.4	118.0	2.860
5.60	6.17	330	59.4	17.0	41.6	116.0	2.790
6.08	6.38	341	59.4	17.8	41.6	123.7	2.970
6.36	6.44	344	59.4	18.0	41.4	126.0	3.040
6.83	6.55	350	59.4	17.9	41.5	130.2	3.140

TABLE V
WATER VELOCITY - HEAT RELATIONS
FOR
ELEMENT D

Water Velocity Ft./Sec.	Element Voltage Drop	Element Current Amperes	Element Temp. °C	Water Temp. °C	Temp. Diff. °C	Btu per Min.	Btu per T-t
Constant element temperature of 40 °C							
0.60	1.80	105	38.5	16.0	22.5	11.7	0.522
0.79	1.98	115	38.5	16.0	22.5	13.0	0.578
0.85	1.90	110	38.5	16.0	22.5	11.9	0.529
0.91	1.90	110	38.5	16.0	22.5	11.9	0.529
1.16	2.23	130	38.1	16.0	22.1	16.5	0.747
1.70	2.57	150	37.6	16.0	21.6	21.9	1.013
1.98	2.66	155	38.5	16.0	22.5	23.4	1.040
2.28	2.84	165	38.5	16.0	22.5	26.7	1.183
2.50	2.84	165	38.5	16.1	22.4	26.7	1.192
2.82	2.89	168	38.5	16.2	22.3	27.6	1.328
3.48	3.02	176	38.1	16.0	22.1	30.2	1.367
3.58	3.01	175	38.5	18.0	20.5	30.0	1.463
4.31	3.26	190	38.1	18.0	20.1	35.2	1.750
5.19	3.65	213	37.6	16.4	21.2	44.2	2.090
5.60	3.75	218	38.5	17.6	20.9	46.5	2.225
6.08	3.84	223	38.5	17.8	20.7	48.7	2.355
6.76	3.80	221	38.5	17.9	20.6	47.8	2.320
6.85	3.85	224	38.5	17.9	20.6	49.1	2.380

TABLE VI
HEAT TRANSFER PER UNIT AREA OF ELEMENT SURFACE
AS A FUNCTION OF
TEMPERATURE DIFFERENCE AND WATER VELOCITY
FOR
ELEMENTS C & D

Water Velocity Ft./Sec.	T - t for element temperatures of:			Btu/T-t/Sq. In. for element temperatures of:		
	40°	60°	80°	40°	60°	80°
0.6	22.5	43.4	64.8	0.096	0.095	0.120
1.0	22.5	43.4	64.6	0.126	0.114	0.238
2.0	22.5	43.4	64.5	0.189	0.189	0.378
3.0	22.3	43.0	64.4	0.252	0.318	0.471
4.0	20.5	42.4	64.3	0.315	0.427	0.562
5.0	22.1	42.0	64.2	0.378	0.494	0.653
6.3	20.6	41.6	63.6	0.442	0.554	0.745
7.0	20.6	41.5	63.6	0.507	0.619	0.839