U.M.

THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report
of
Committee on Examination

This is to certify that we the undersigned, as a committee of the Graduate School, have given Fredrik Waldemar Hvoslef final oral examination for the degree of Master of Science . We recommend that the degree of Master of Science be conferred upon the candidate.

Minneapolis, Minnesota
May 31 1919

John R Allen
Chairman
Frank B Rowley
WE Brooke.

THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report
of
Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Fredrik Waldemar Hvoslef for the degree of Master of Science.
They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science.

John R. Allen
Chairman
Frank B. Rowley.
W E Brooke

May 31 1919

A STUDY OF THE
TRANSMISSION OF HEAT THRU GLASS

A THESIS SUBMITTED TO
THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA

by

F. W. HVOSLEF

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE.

JUNE, 1919.

A STUDY OF HEAT LOSSES THRU GLASS.

The physical definition of heat is that it is a form of energy. The most familiar source of this energy is the combustion of fuels, and when thus obtained is used either in a converted form as power or in its original form as heat for numerous familiar purposes, among them, the heating of buildings. To the average house holder and to the business man who have homes and buildings to heat fuel is a great source of expense, and it is in this connection that the heating and ventilating engineer is mainly interested. Whenever it is possible to alter construction in such a manner that heat is conserved it is his aim to find and use that method. For this purpose the present investigation has been undertaken in respect to glass, in order that its insulating properties may be more exactly determined.

Heat is lost in three ways, namely, conduction, convection, and radiation. In passing from a warm room to a lower outside temperature the heat approaches the inner surface by convection and radiation, passes thru the wall by conduction, and leaves the outer surface by conduction and radiation. The quantity of heat passing thru a wall by conduction in a given time depends on the difference in temperature of the surface and upon the nature of the material, and is given by the formula

$$Q = hKA\ (t_1 - t_2),$$

in which h = time in hours

A = area in Sq. Feet

t_1 = temperature of inner face

t_2 = temperature of outer face

K = heat per Sq. Ft. per hour per degree difference in temperature, and is the co-efficient of conduction.

Transposing, $K = \frac{Q}{ah\ (t_1 - t_2)}$

The coefficients of convection and radiation are less definite and quite difficult to separate. The heat removed by convection depends upon the velocity of the air, and according to * Carpenter, it is thought to vary with the square root of the velocity. He gives the loss by convection as

$$A = .552\ K'\ t^{1.233} \text{ in metric units}$$

where K depends on the surface form and condition.

For vertical planes of height "h" in quiet air

$$K = 1.764 + \frac{.636}{\sqrt{H.}}$$

Carpenter further states that the rate of cooling due to radiation is the same for all bodies, but its absolute value varies with the conditions of the surface. It is represented by the formula

$$V = m\ a^{\Theta}(\ a^{t} - 1\ ),$$

in which m depends on the surface condition.

a = constant = .233° Fahrenheit.

Θ = temperature of surrounding air

t = excess of body temperature over that of the air.

The formula for radiation losses given in " Elements of

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* " Heating and Ventilating of Buildings", Carpenter.

Heat Power Engineering" by Barnard and Hirschfield is

$$\Delta Q_{RN} = K T_1^4 - K T_2^4,$$

which is known as Stefan's Law, T_1 and T_2 being absolute temperatures.

From this it is seen that radiation losses vary with the fourth power of the temperature of the bodies considered. It is to be noted that radiation losses differ under various circumstances depending on what kind of a surface the radiation surface "sees". Thus a window facing a white wall may radiate less heat than one facing some other surface. Under normal conditions, however, these differences are very small.

Péclet gives the general formula for heat transmission as

$$M = \frac{1}{2} (T - \theta) (K + K')$$

in which T = room temperature

θ = air temperature

K = coefficient for radiation

K' = coefficient for convection.

K' varies with the height

K = 291 in metric units.

The three forms of heat transfer as considered above never exist separately in engineering problems, and usually all three

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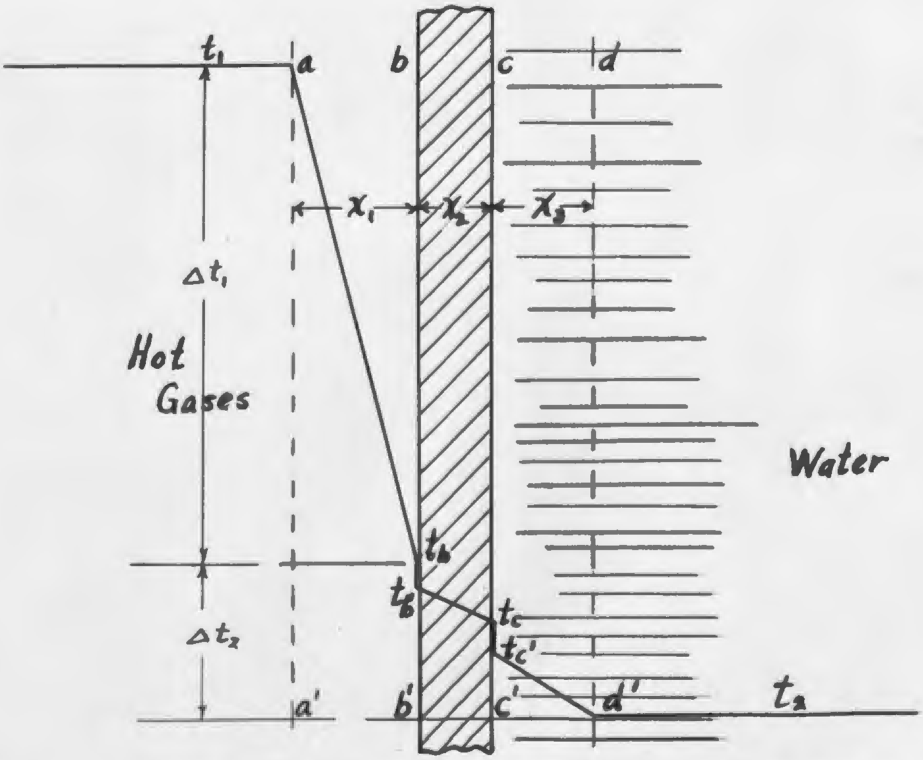
Numerous references for studies of radiation losses are given by:
Dalby in " Heat Transmission", British Inst. M. E. 1909.
Also see Bulletin No. 2, U. S. Bureau of Standards,
Bulletin No. 18, U. S. Bureau of Mines.

are found in combination. Moreover, in practical work, heat is seldom being transmitted thru one substance alone, but rather thru a succession of various substances. As examples of this we may take the boiler with hot gases on one side, and water on the other, or an ordinary wall with air on both sides. The latter case will be considered more fully hereafter in the study of heat transmission thru glass.

A diagrammatic representation of the temperature gradient from the hot gases of a furnace to the water of the boiler is given in the chapter on heat transfer by Hirschfield and Barnard in their book, and is reproduced below in Fig. 1.



Here X_1, X_2, and X_3 represent a column of hot gas, a column of steel, and one of hot water, respectively. As the temperature gradient approaches the plate thru X_1, it drops very rapidly to a point which represents the temperature of the outside of the surface. Heat cannot enter the surface until there is a drop thru the surface, and this drop is represented by T_b $T_{b'}$, which is that drop necessary to overcome the surface resistance. $T_{b'}$ T_c is the drop between the inner surfaces of the plate. Then again the surface resistance drop and the drop thru X_3 to the water temperature.

Considering now the formula for the coefficient of conductivity

$$K = \frac{Q}{ah\,(t_1 - t_2)}$$

it is evident that there might be three coefficients in the diagram shown

$$1.\quad K_1 = \frac{Q}{ah\,(t_{b'} - t_c)}$$

which is the coefficient per inch of thickness inside of the metal. A large number of values of K_1 have been determined by physicists.

$$2.\quad K_2 = \frac{Q}{ah\,(t_b - t_{c'})}$$

representing the coefficient per inch of thickness between the two surfaces of the metal, and which equals K_1 plus some value involving a constant depending on the surface condition and also involving a radiation constant. $K_2 - K_1$ might be termed the resistance due to surface conditions.

$$3.\quad K_3 = \frac{Q}{ah\,(t_1 - t_2)}$$

which we will denote by K and call combined coefficient of conductivity. It is evident that the combined coefficient is the coefficient of the three columns shown in the diagram and will necessarily be much less than K_1 or K_2 , depending on the nature of the surrounding media.

Turning again to the diagram we see that the quantity of heat passing thru any plane parallel to the surface must be the same as that passing thru any other plane and must equal

$$Q = K (t_1 - t_2) = \frac{K_1}{X_1} (t_1 - t_b) = a_1 (t_b - t_{b'}) = \frac{k_2}{x_2} (t_{b'} - t_c) = a_2 (t_c - t_{c'}) = \frac{K_3}{X_3} (t_c - t_2) .$$

Here K_1, K_2, and K_3 represent the coefficients for the materials corresponding to X_1, X_2, and X_3. a_1 and a_2 are the surface coefficients of radiation and convection. All other values are as shown in the diagram. * Solving we get:

$$K = \frac{1}{\frac{x_1}{k_1} + \frac{1}{a_1} + \frac{x_2}{k_2} + \frac{1}{a_2} + \frac{x_3}{k_3}} .$$

This formula for K can be extended to apply to any combination of materials such as are found in hollow walls of buildings, refrig-

* Solution $t_1 - t_b = \frac{\Delta Q \, x_1}{K_1}$, $t_b - t_{b'} = \frac{\Delta Q}{a_1}$, $t_{b'} - t_c = \frac{\Delta Q \, x_2}{K_2}$, $t_c - t_{c'} = \frac{\Delta Q}{a_2}$, $t_c - t_2 = \frac{\Delta Q \, x_3}{K_3}$ $\therefore$ $t_1 - t_2 = \sum (t_a - t_b) = \Delta Q \left(\frac{x_1}{K_1} + \frac{1}{a_1} + \frac{x_2}{K_2} + \frac{1}{a_2} + \frac{x_3}{K_3} \right)$, $K = \frac{\Delta Q}{t_1 - t_2} =$

$$\frac{1}{\left(\frac{x_1}{k_1} + \frac{1}{a_1} + \frac{x_2}{k_2} + \frac{1}{a_2} + \frac{x_3}{K_3} \right)}$$

erators, and other common examples, and it is merely necessary to add terms for the surface resistance and conductivity of each additional layer. In order to apply this formula to any compound wall it is necessary to know the values of K_1, and a_1 and a_2 for the various substances composing the wall. * A large number of these values have been determined by various experimenters and the list is continually increasing.

In the case of a very thin wall such as glass x is so small that $\frac{x}{c}$ may be neglected. Likewise in very thick walls $\frac{1}{a}$ may be disregarded.

OTHER INVESTIGATIONS.

Among the earlier experimenters in this subject were Péclet and Tredgold, many of whose contributions are now in practical use. Rietschel+ and Grashof+ under the German government have also contributed.

Among American investigators may be mentioned Professor C. L. Norton of the Massachusetts Institute of Technology, the Armstrong Cork Company Laboratory, and Professor Moyer of Pennsylvania State College. Dean Allen of the University of Minnesota conducted tests on glass while at Michigan and the present investigations are being conducted under his guidance.

* See Allen " Heating and Ventilation."
Harding and Willard, " M. Eq. of Buildings."
H. & V. Magazine 1918.

+ See page 15 Illinois Bulletin on Heat Transmission by Willard and Lichty.

THE PRESENT INVESTIGATION.

The heat transmission tests at the University of Minnesota during the first half of the year 1919 were devoted to a study of the resisting qualities of glass. In carrying out these tests several objects were kept in mind; first, to determine the combined coefficient K for ordinary double strength rolled window glass and for plate glass; second, to determine the effect of wind on this coefficient, and third, to find what effect the intensity of the heat at the heating element might have on the constant.

The first item is of interest in view of the fact that many people have contended that the use of plate glass removes the necessity for double windows; the second also has a bearing on the question of double windows, and more will be said of this matter later. The third item is of interest because of the recent discussions as to the situation of direct radiators and the relative merits of direct and indirect radiation.

Description of Apparatus.

The method chosen to determine the constants was that in general use at the present time, consisting of applying heat inside of a heavily insulated box with a removable front. The temperature inside of the box being higher than that outside, these temperatures being known, and the quantity of heat entering being known, means were at hand for determining the coefficient.

The box was located in a room on the west side of the experimental laboratory, having four windows. All the sashes were

PHOTOGRAPH SHOWING MEANS OF SUPPORTING BOX ON TRUNNIONS.

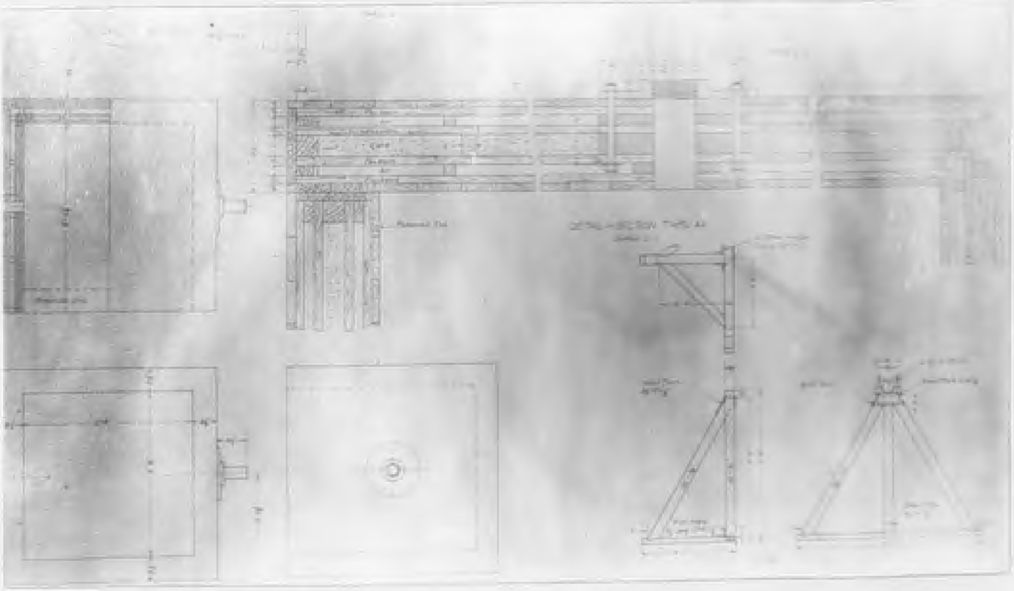
Note single multiple-strand cable for lights, thermometers, and thermostat.

removed from the windows and at first the openings were covered with cloth to reduce air circulation. This made it difficult to get the temperature of the room low enough, so the cloth was removed and the room left open to free circulation. The box was mounted on trunions as shown in the photograph, so that the open face might be used as floor, wall, or skylight, the axis of rotation being perpendicular to the outside wall of the room, thus preventing the open side from facing directly to the open windows. This fact may be of some importance due to the effect of radiation losses to different types of surfaces.

The inside dimensions of the box were 5 ft. x 5 ft. x 5½ ft., and the walls were 10" thick. The photograph shows the construction and dimensions. Here we see a cross section showing 6" matched pine boards on the inside and outside, separated by four layers of flax board, which in turn were separated by two air spaces and one layer of thick cork board. The idea of this unusually heavy insulation is of course to reduce the conductivity of the box to a minimum, thus decreasing the possible percentage of error in the calculation of K. The removable front used for calibrating the box for its coefficient was of the same construction as the rest of the walls.

Source of Heat.

Heat was supplied to the box by means of ten incandescant lamps on 110 volt A. C. circuit. These were suspended from a bar



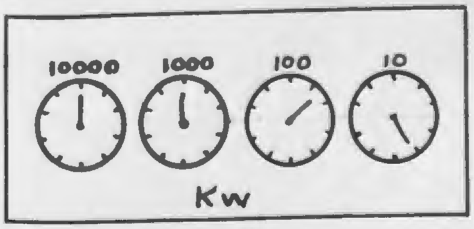
PHOTOGRAPH OF DRAWING

SHOWING DETAILS OF BOX-CONSTRUCTION.

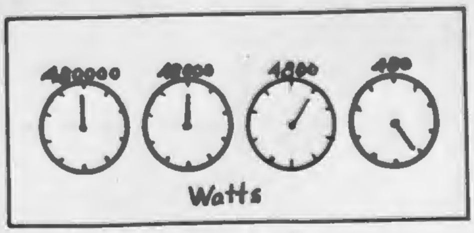
close to the axis of rotation of the box in such a way that they were always at the bottom. During the calibration, when the heat losses were very small, twenty watt lamps were used, and during the glass tests seventy-five watt Mazda lamps were used. 750 W. was barely sufficient and if -20^0 had been experienced would not have kept the box warm. Each lamp was controlled by an individual double-throw switch at the switch board, making it possible to cut out as many lamps as necessary to maintain the temperature nearly constant, the remainder of the lamps being controlled by the thermostat for the final regulation. See diagram of wiring. During tests it was always our aim to balance the lamps so that the arrangement of lamps operating was symmetrical with the center.

Measurement of Current.

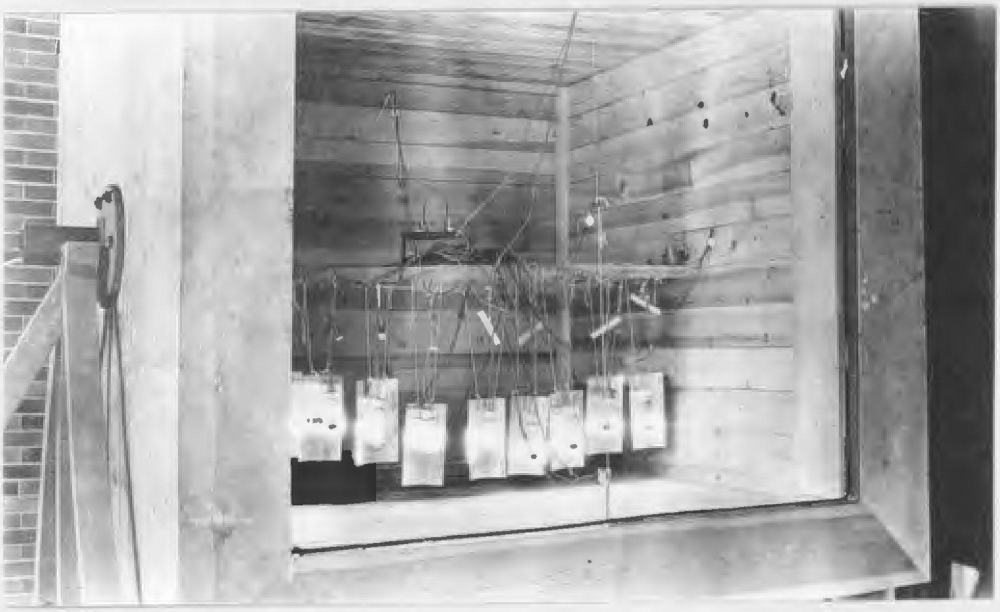
The quantity of heat entering the box was obtained by metering the current to the lamps and converting the electrical units to heat units. The meter used was an ordinary General-Electric watt-hour meter such as is used in commercial practise. In order to obtain close readings on this instrument, it was necessary to alter the gear-train from the rotor to the indicating dials by removing two gears. The effect of this was to multiply the movement to such an entent that one killowatt hour on the dial was equivalent to forty-eight watt hours.



Original



Adjusted



PHOTOGRAPH SHOWING INTERIOR ARRANGEMENT OF BOX WITH REFLECTORS IN PLACE.

Blocks over reflectors are for suspending collars.

In order to cut out from the meter reading the line losses between the meter and the lights, the potential terminals of the meter were not connected directly to the line terminals but by a separate pair of wires to the terminals of the first lamp in the box. (See wiring diagram.) The drop in this pair of wires was then very small and could be safely neglected. This method of connection necessitated the constant use of lamp No. 1, as without it the meter ceased to operate.

The meter was calibrated by inserting a standard indicating watt meter in the circuit in such a manner that it showed the true wattage to the lamps. The meters were then compared for every load from one to ten lamps. The exact reading of the watt-hour meter was obtained by timing a certain number of revolutions of the rotor with a stop watch. Thus if

True watts = 74

Meter constant = .6 watts per revolution

10 revolutions = 4.38 minutes.

Then

$$\text{Indicated meter reading} = \frac{60}{4.38} \times .6 = 82.2$$

Plot $x = 82.2$ $y = 74.$

Plotting this indicated meter reading against the true power to the box we get the curve shown in ~~Figure~~ blue print which can be used to correct the meter readings obtained.

Temperature Control.

The temperature inside the box was controlled by means of a bow thermostat with an automatic solenoid switch. The bow was composed

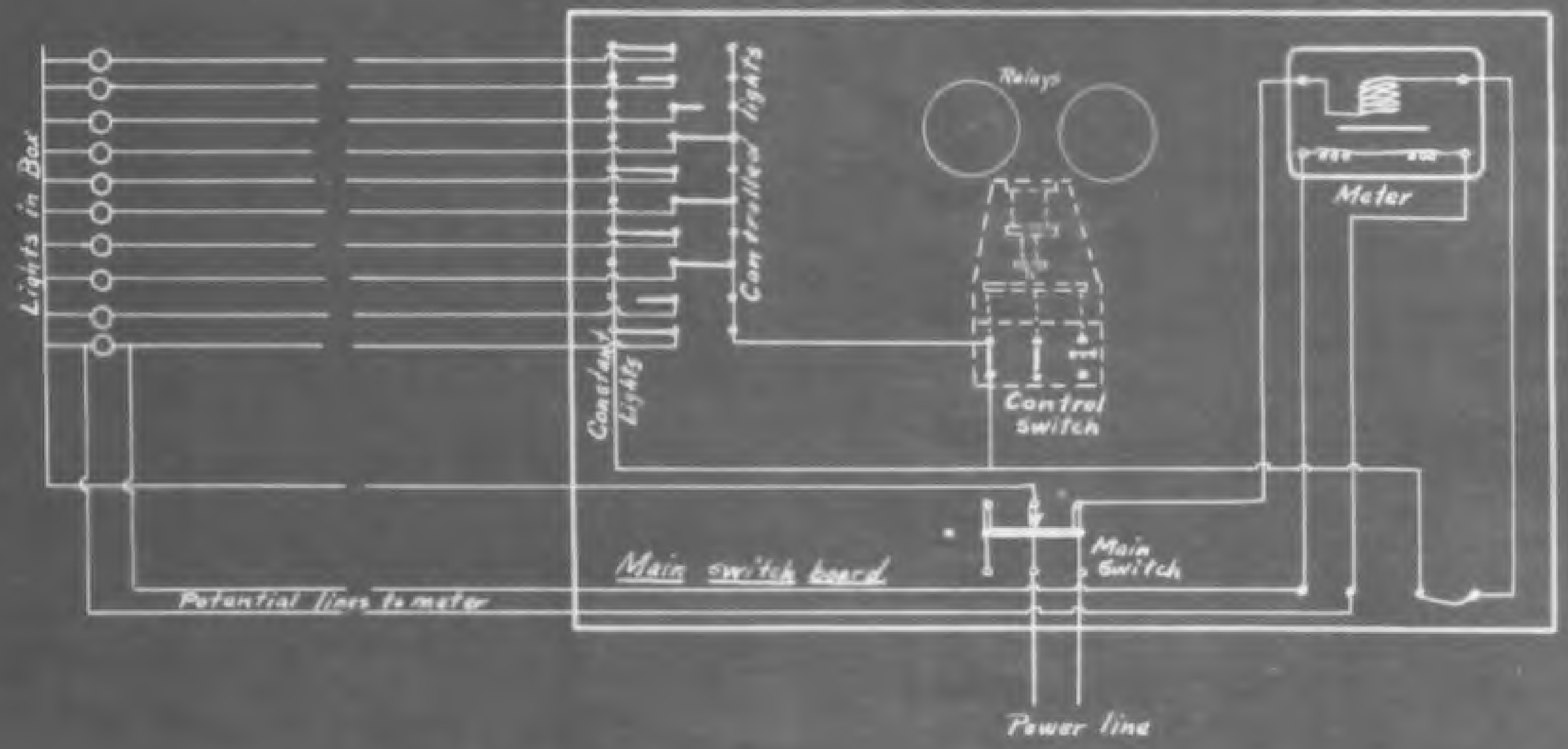
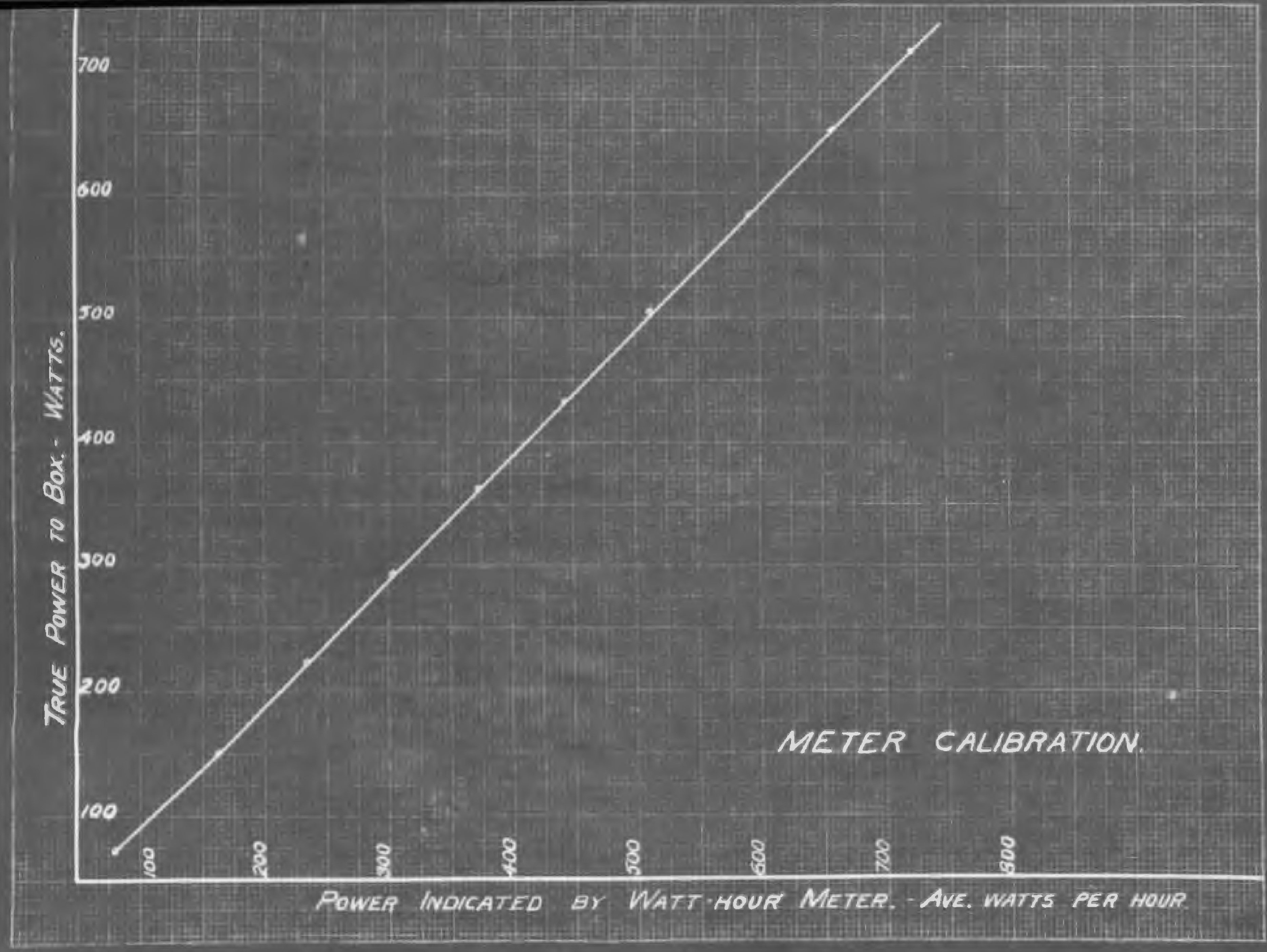


DIAGRAM OF POWER CIRCUIT.


METER CALIBRATION.
TRUE POWER TO BOX. - WATTS.
700
600
500
400
300
200
100
100
200
300
400
500
600
700
800
POWER INDICATED BY WATT-HOUR METER. - AVE. WATTS PER HOUR

of brass and nickel steel bent to a two inch radius. The diagram shows the wiring for the temperature control system. The photograph shows the construction and setting of the control element.

The switch consists of three pull-chain switches pulled simultaneously by the magnet in the solenoid. The first switch, marked A, is the power switch and turns the controlled lights off and on. The double throw switches for each lamp were arranged so each lamp might either be constant or be controlled by the regulator.

The second and third switches, marked B and C, are storage battery switches and act to reverse the wires to the solenoid. Thus when the temperature in the box rises to the point for which the adjusting screws are set a contact is made which allows a small current to pass thru the solenoid. This actuates one of the relays, which one, depending on whether the lights are on or off. When the relay closes the points represented by arrow heads come together allowing a heavy current to pass thru the solenoid. This pulls up the magnet and simultaneously pulls the three switches. The power switch goes off ~~and~~ or on and the other two switches are reversed so that when the box cools to the minimum temperature desired the process will be repeated. This control was effective to keep the temperature constant within one half degree.

Temperature Measurement.

The temperature was measured by means of Leeds & Northrup resistance bulbs and a Wheatstone bridge graduated directly to Fahrenheit degrees. Temperature bulbs were located at seven points inside

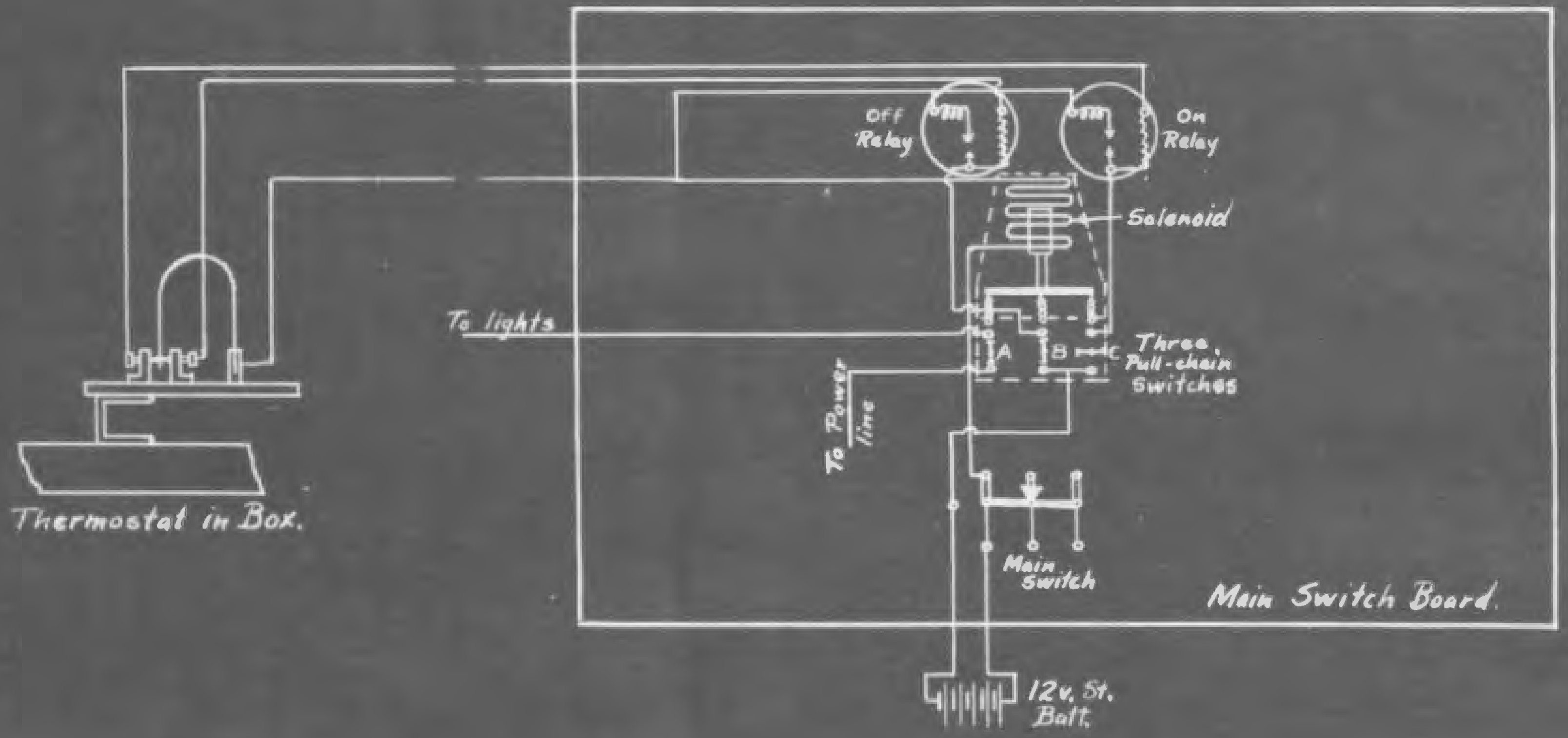
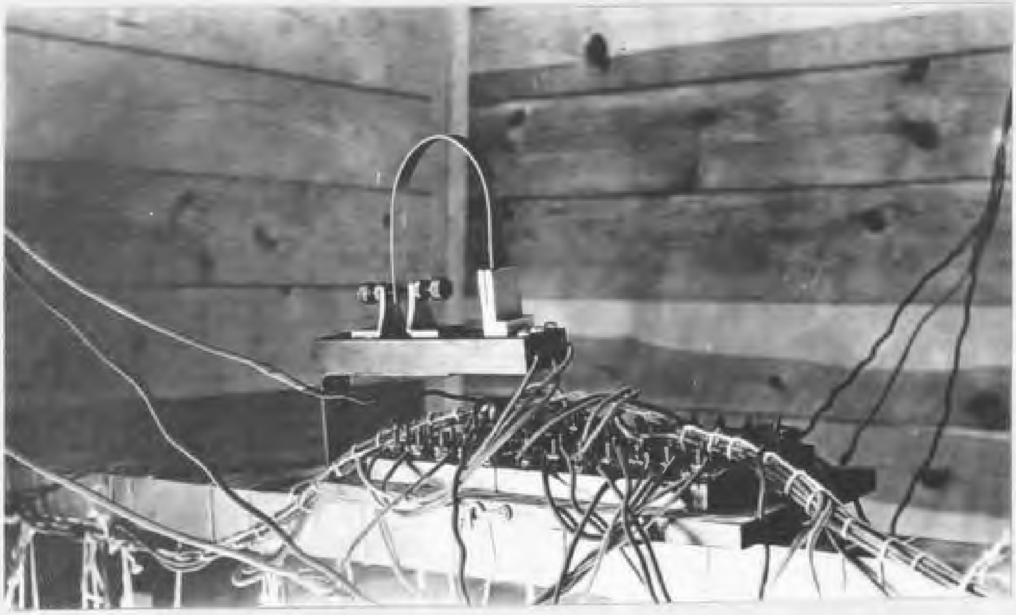


DIAGRAM OF TEMPERATURE CONTROL



PHOTOGRAPH SHOWING THERMOSTATIC ELEMENT AND METHOD OF LOCATING ALL WIRES.

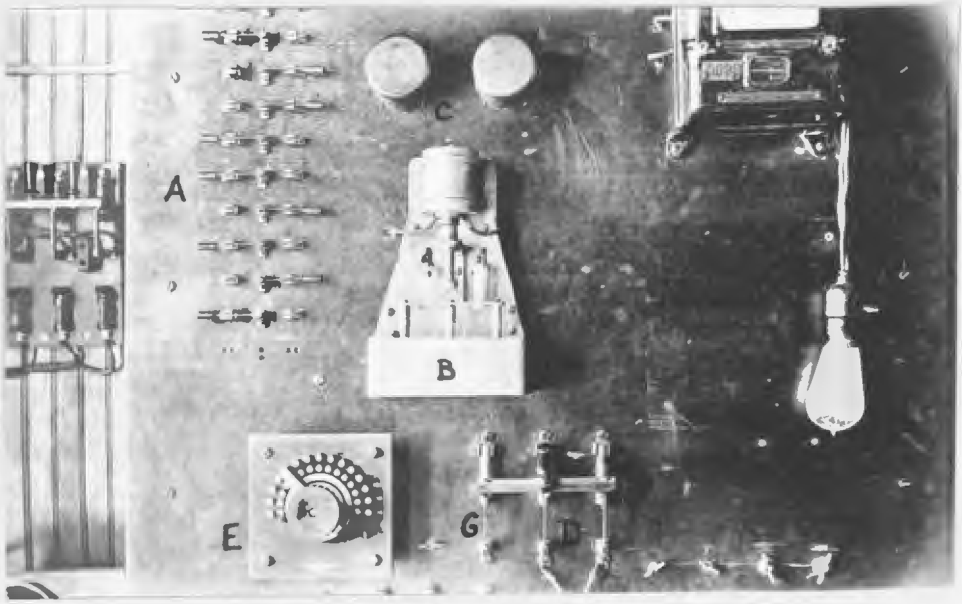
the box and five points outside. These were connected to the bridge and galvanometer by a multiple point switch, shown at left on the photograph of the switchboard. All thermometers were calibrated with a standard and correction curves plotted for each.

At first the resistance thermometers were installed without soldered joints and this fact together with the misplacing of one wire just previous to the glass tests was a source of great loss of time and work as the thermometers were very inaccurate. When the cause was finally discovered the error was corrected and all joints soldered, which immediately corrected the thermometers. All the results of our early work were made practically worthless by this error and for this reason most of them, except such as could be corrected by checking, were discarded.

In addition to the resistance thermometers a recording thermometer was used for the outside temperatures in order that a check might be available and the night temperatures might be recorded.

The switchboard was located in the room adjoining the cold room and it was unnecessary to enter the cold room to take temperatures and meter readings. The photograph of the switchboard shows the individual light switches in the upper left hand corner. Below these is the multiple point thermometer switch. At the top in the center are the two relays and below them the automatic control switch. On the right is shown the meter.

The diagrams show in elementary form the system of wiring on the switchboard.



PHOTOGRAPH SHOWING ARRANGEMENT OF SWITCHBOARD.

A: Individual Light Switches.

B: Automatic Control Switch.

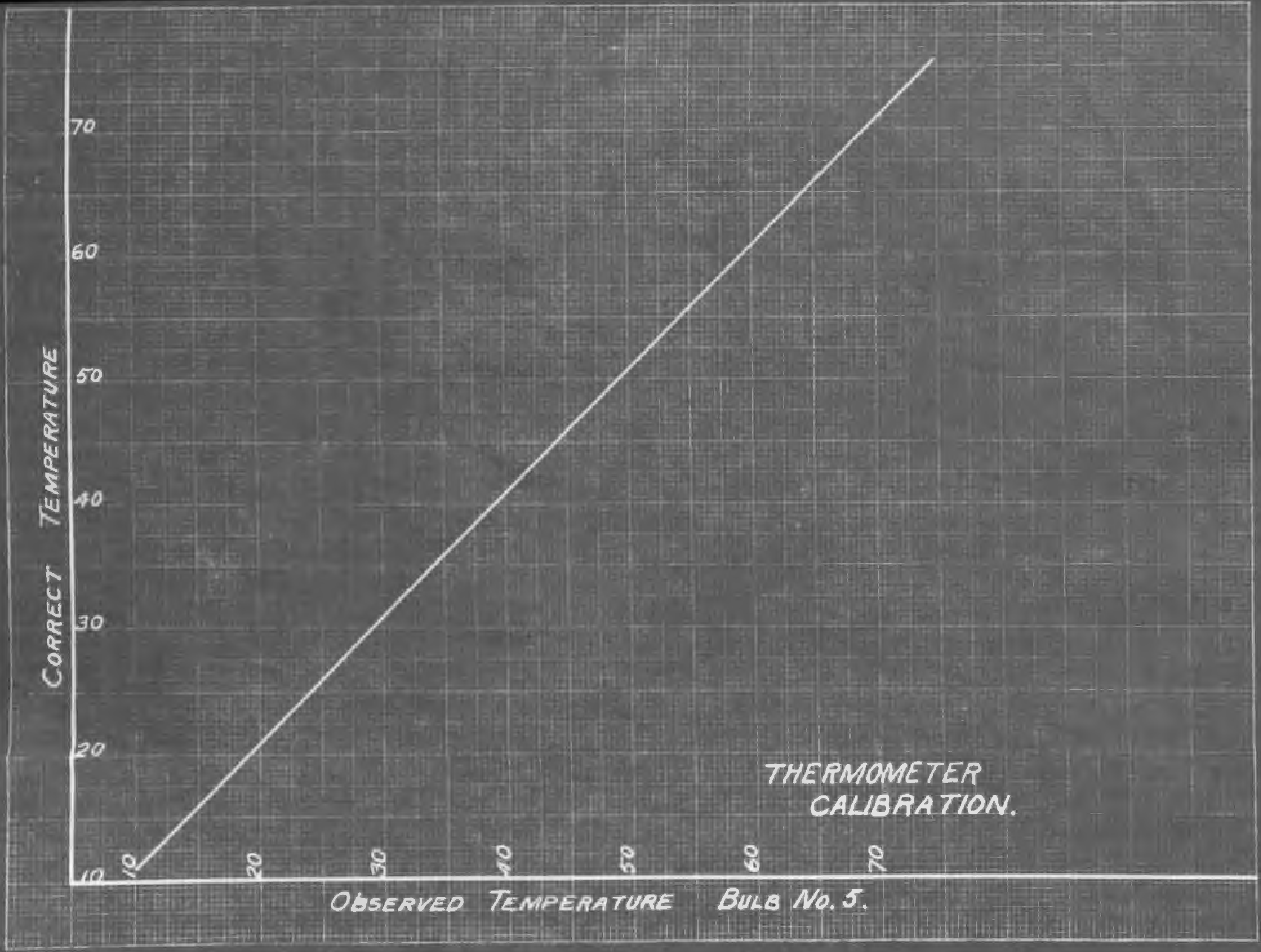
C: Control Relays.

D: Main Power Switch.

E: Multiple Point Thermometer Switch.

F: Electric Meter.

G: Storage Battery Switch.



THERMOMETER
CALIBRATION.

Source of Wind.

In those tests in which there was wind on one side of the glass the air was forced over the face of the glass by means of a No. 3 Buffalo blower driven by a three horse-power motor. The blower exhausted into a plenum chamber, shown at the top of the box in the photograph, from which it escaped downward over the face of the glass. In order to get even distribution the air was confined under a sheet of heavy black pasteboard extending nearly to the bottom of the glass.

This blower was running at constant speed and no effort was made to control the velocity of the wind.

Method of Procedure.

With the apparatus as described the first step in the procedure was to adjust the thermostat to the desired temperature which was 70° during the colder weather. As the season advanced it became desirable to increase the higher temperature and in March the thermostat was set for 80° and later to 90°. After the thermostat was set the box front was inserted and caulked tightly with flax packing.

The thermostatic element is very delicate and for this reason it is necessary that the temperature of the box be nearly at the point required when adjusting the points. After the points are once set the temperature must not be allowed to rise or fall more than ten degrees from the point set, as this will immediately bend the element and change the adjustment.

PHOTOGRAPH SHOWING ARRANGEMENT FOR TESTS WITH WIND.

A: Plenum Chamber.

B: Black Pasteboard Cover over Glass. Wind flows between cover and glass.

C: Wires to Resistance Thermometers under cover.

The temperatures in the box were then observed until they became constant, at which moment the test began. An effort was made to take all readings every two hours from eight in the morning until ten at night. The data included the following:

1. Date and hour.
2. Meter reading.
3. Temperature readings on all thermometers.

When the calibration was finished the box front was removed and the glass inserted for the test. The procedure with the glass tests was the same as for the calibration.

DATA AND RESULTS -- CALIBRATION.

With the data obtained the value of K for the box walls was determined from the formula

$$K = \frac{Q}{A\,h\,(t_1 - t_2)}$$

In this formula A is taken as the average area between the inside and outside surfaces of the box. h is the number of hours of the test, the period being selected from the total run for stretches of time in which the outside temperature was nearly constant. Periods of less than ten degree variations in temperature might frequently run for twenty four hours. Q is the corrected heat consumption. To obtain this the indicated consumption from the meter was divided by h, the value obtained was corrected from the calibration chart, and again multiplied by h. t_1 and t_2 are averages for the period chosen. The first calibration run was made in the early winter and the results obtained were as follows:

DATE	HOURS	t_1	t_2	B.T.U.	A	K
1-11-19	19¼	71.1	30.2	6440	216	.0379
1-12-19	30.6	71.1	30.4	9400	216	.035
1-15-19	47	70.5	37.9	14430	216	.0434
1-17-19	21.5	70.5	40.7	5870	216	.0424
1-20-19	72.5	71.8	38.9	19070	216	.0373

Because of the variation in K obtained in the first run it was decided to check the results later in the season. Results of other tests led to the belief that the variation in K was caused by air circulation in the room. In view of this belief the check calibration was conducted on a day when there was very little wind. After running for forty-eight hours under these conditions the blower used for the wind tests was started and allowed to exhaust directly into the room, thus causing a gentle circulation around the box. A calibration run was then taken. The results bore out the previous belief, being as follows:

	DATE	HOURS	t_1	t_2	A	B.T.U.	K.
Quiet Air.							
	4-2-19	23¾	87	46.5	216	8000	.0384
	4-3-19	17½	87	47.6	216	5590	.0376
Moving Air.							
	4-3-19	8	87	50.1	216	2660	.0417

The average area of the walls with glass inserted in the open face was 196 square feet. Using the constant .0384 this gave a box constant of 7½ B.T.U. per degree difference per hour. As it was never possible to know the exact condition of the air in the room this box constant was used under all conditions and the error resulting from thus using it is neglible.

DATA AND RESULTS -- GLASS.

The first glass test was conducted on plate glass under quiet air conditions. The plate was one quarter inch thick and filled the open side of the box completely, having an area of 26.7 square feet. In the first test the heating elements were painted black and left uncovered, but the temperatures varied too much over the face of the glass under these conditions, so the lamps were later covered with paper collars. The collars had the effect of chimneys and set up a circulation which distributed the heat more evenly; they also absorbed most of the radiant heat thus preventing it from reaching the glass as such.

Under these conditions the following results were obtained for plate glass:

DATE	HOURS	t_1	t_2.	A	B.T.U.	K
2-6-19	16	68.1	16	26.7	17750	.799
3-4-19	12¼	69	15.5	"	11650	.665
3-19-19	16	82.5	45.	"	14300	.894
3-20-19	8¼	82.3	36.1		6830	.67
3-21-19	8	80.6	39.3	"	6610	.719
3-29-19	21¾	84.3	49.8	"	14120	.697
3-30-19	23½	84	43	"	18550	.72
3-31-19	24	84	42	"	20020	.745

The calculation of the value of K for glass involves the subtraction of the heat loss thru the walls of the box. The formula used is the same as before but an additional step is necessary to find the value of Q. In this case

$$K = \frac{3.415\ M - h\ k_b\ (\ t_1 - t_2\ )}{A\ h\ (\ t_1 - t_2\ )}$$

M = corrected meter reading.

h = hours of test

k_b = box constant = 7.5

A = area of glass = 26.7

1 Watt = 3.415 B.T.U.

Exactly the same process was followed with the rolled window glass and the results were as follows:

DATE	HOURS	t_1	t_2	B.T.U.	K
2-25-19	12	67.8	10	14000	.758
3-21-19	15¼	79.7	39.5	12100	.742
3-22-19	11	80.2	47.2	7645	.787
3-23-19	14¼	80.4	46	9930	.758
3-24-19	15½	81	53	8970	.775

TESTS WITH MOVING AIR.

After the quiet air tests were completed the plenum box was put in place and the blower started. Velocity measurements showed the air to be moving at above 750 feet per minute. All other conditions and operations were the same as before. The results were as follows:

DATE	HOURS	t_1	t_2	B.T.U.	K
Plate Glass.					
3-5-19	10¼	66.1	15.9	16420	1.19
3-6-19	10	68.6	28.5	10670	1.00
Rolled Glass.					
2-19-19	9	69.7	39.3	9065	1.24
2-20-19	12	69.3	38.9	11250	1.16
3-25-19	8	80.5	52.7	7300	1.23
3-27-19	7	79.5	41.1	10140	1.41

TESTS WITH DIRECT RADIATION.

After the above tests were completed the paper collars were removed from the lamps and bright tin reflectors were placed behind the lamps. These reflectors are shown in place in the photograph giving the box arrangement. In front of the lamps was then placed a black-board sixteen inches high which cut off all direct radiation to the glass. A test was run under these conditions and then the blackboard was removed, leaving the glass exposed to direct radiation from the lamps. With these conditions another test was made. With the unprotected lights thus exposed to the glass, a large part of the light rays naturally were lost before being absorbed in the box. In the previous tests it has been assumed that all light rays were absorbed, and no account was taken of them. Where these rays were permitted to pass thru unhindered, however, some part of them was necessarily lost and had to be considered. Professor Shepardson gives the lighting efficiency of Mazda lamps as seven or eight percent. Some of these rays are reflected by the glass and eventually absorbed in the box. Others are lost and in calculating for K this loss has been assumed as five percent of the total heat.

In the case of plate glass the test with the black shield in place gave values as follows:

DATE	HOURS	t_1	t_2	B.T.U.	K
3-7-19	30	70	38	19833	.751
3-9-19	21½	70.5	34.8	12208	.608

These results are quite similar to the previous tests as might be expected. With the direct radiation the values of K for plate glass are as given below:

DATE	HOURS	t_1	t_2	B.T.U.	K.
3-10-19	18½	73.1	31	18410	.885
3-11-19	21¼	73.1	41.7	16100	.905

When this test was applied to the ordinary glass the blackboard was not used and the results for direct radiation were as follows during four successive periods:

DATE	HOURS	t_1	t_2	B.T.U.	K
4-4-19	19	86.5	54	17870	1.08
4-5-19	24¼	86.3	52.2	22930	1.04
4-6-19	23¾	86.3	49.5	24340	1.04
4-7-19	23¼	86.5	45.2	25970	1.02

Just why the value for ordinary glass should be so much higher than for plate glass is not clear, but it is probably largely because of the higher polish of plate glass, which causes more reflection and consequently higher absorption of the rays in the box.

DISCUSSION OF RESULTS, COMPARISON AND CONCLUSIONS.

Perhaps the most notable feature of the results on plate glass with quiet air is the great variation in the constant for different days; and this variation was quite disconcerting for some time. Similar variations appear in the results given by Dean John R. Allen in the Heating and Ventilating Magazine for August 1916. A good part of the cause became apparent however, when the wind tests were completed. Dean

Allen says there are perhaps a hundred variables affecting the transmission of heat thru material. A few of the variable factors which might be mentioned are, intensity of heat at the source, difference in temperature between inside and outside, humidity, air velocity, and the condition of the surface seen by the transmitting body. As in these tests none of these variables were under control entirely, it is not to be wondered at that the results are not constant.

The coefficient for the glass with wind on one side appears to vary between 50 percent to 100 percent higher than that for quiet air. Bearing in mind the fact that the wind in this case had a velocity of only 750 feet per minute which is merely a light breeze, it is evident that the rapidity of circulation of the air in the room was accountable for the biggest variations in the constant. A study of the weather conditions during the tests shows that the highest constants appeared on windy days. We may then be justified, in the case of plate glass, in assuming that a coefficient of about .67 applies to a very still day, and .894 applies to a very windy day. Here it is to be remembered that these air conditions were only partially effective inside of the room.

The rolled glass tests are quite constant and an average of .76 would be a fair value, these results all applying to quiet conditions. We see then that there is a probably difference in K for the two kinds of glass of fifteen to twenty percent. A similar difference is apparent under windy conditions. This fact is of particular interest in view of the contentions of certain builders, and perhaps manufacturers, that when plate glass is used in windows, double windows are unnecessary. Whether or not this contention is justifiable is questionable, and final decision would probably rest on the basis of first cost of glass. Undoubtedly it is true that the greater expense of the plate glass would lead to better fitting of sashes, but the same results might be obtained with ordinary glass with proper care.

TESTS BY PROFESSOR MOYER.

Professor Moyer has conducted numerous tests for the effect of wind, at the laboratory of Pennsylvania State College. The results of some of these tests are reported in the Heating and Ventilating Magazine.* His investigations also included the effect of humidity upon the transmission. The values he obtained appear to be high, but this may be accounted for by the fact that he had a circulating fan inside of the box.

Moyer gives curves showing the effect of humidity and velocity, and these have been copied for presentation with this paper.

A study of these curves shows that humidity has some effect on the coefficient and that the higher the humidity the higher will be the value of K. That this might be so will be realized when we consider the nature of the resisting body as discussed previously. On page five was discussed the theory of the transmission of heat thru

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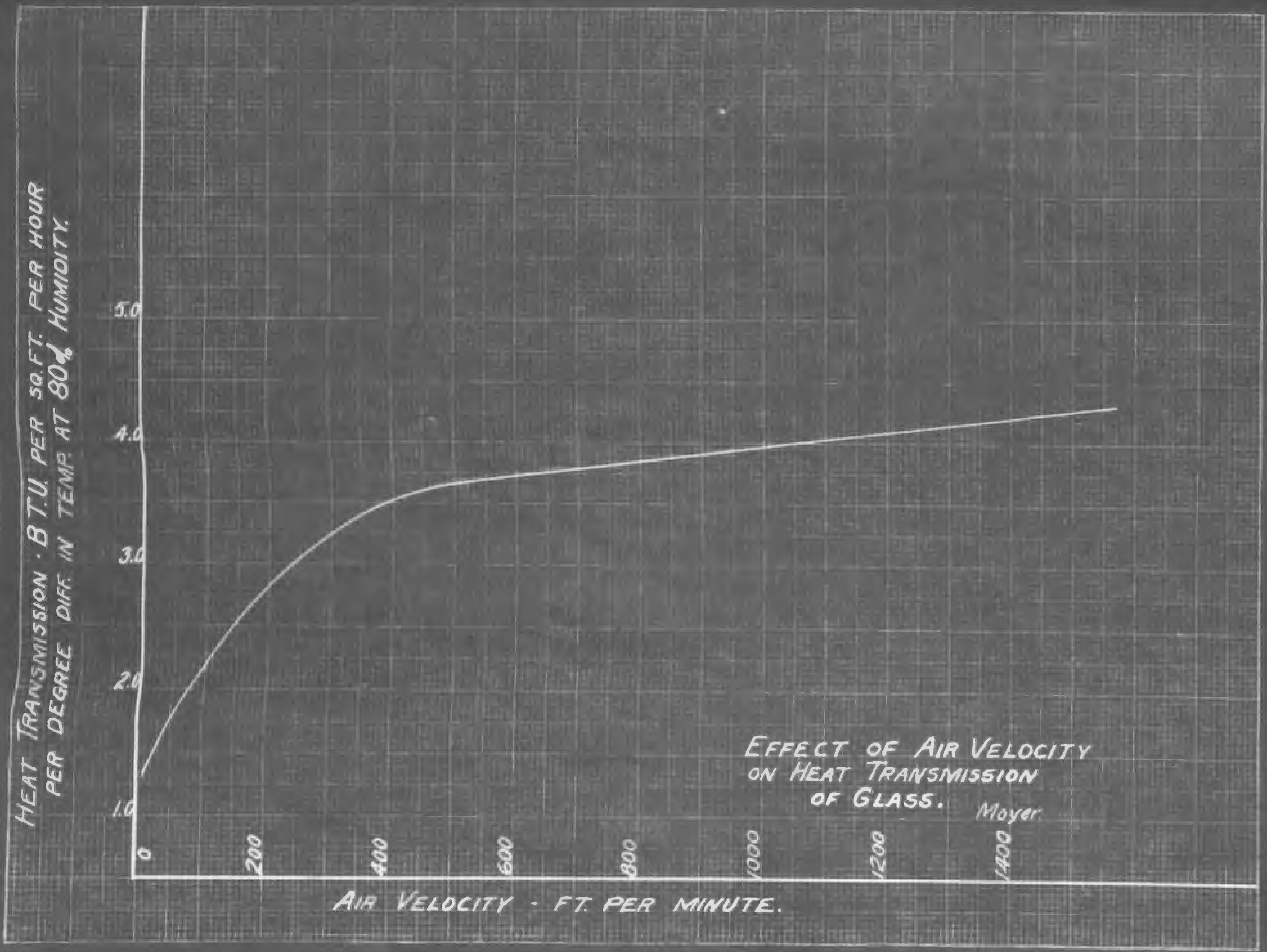
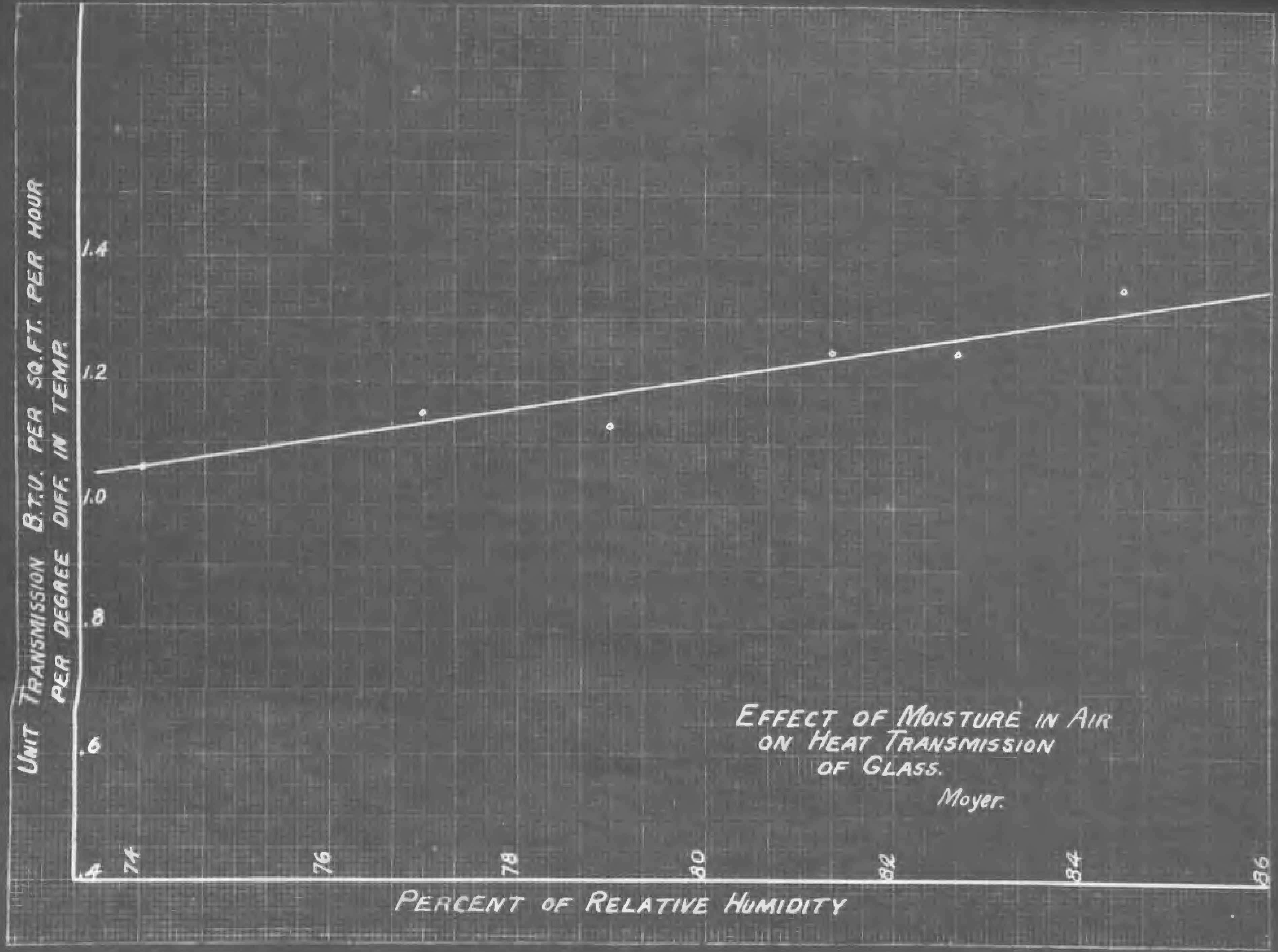
* Heating and Ventilating Magazine, February 1916. pp 18 & 19. Fig. 4 & 5 B.



EFFECT OF AIR VELOCITY
ON HEAT TRANSMISSION
OF GLASS.
Moyer.



EFFECT OF MOISTURE IN AIR ON HEAT TRANSMISSION OF GLASS.

Moyer.

a wall, and there we saw that the resisting body consisted of two dead air columns in addition to the wall. It probably is the resistance of these air columns which is affected by the humidity.

The second curve given by Moyer shows that the wind velocity rapidly increases the coefficient until it reaches five hundred feet per minute, after which the effect is not so marked. We also see that at a velocity of fourteen hundred feet the coefficient of conductivity is nearly four times as great as with still air. Experiments by Dean Allen gave similar results with an increase of over one hundred percent, and our experiments show that with a velocity of 750 feet the coefficient is more than double that for still air. This fact has led to some speculation as to the correctness of the formula for K as derived previously.

Here we showed that

$$K = \frac{1}{\frac{X_1}{K_1} + \frac{1}{a_1} + \frac{X_2}{K_2} + \frac{1}{a_2} + \frac{X_3}{K_3}}$$

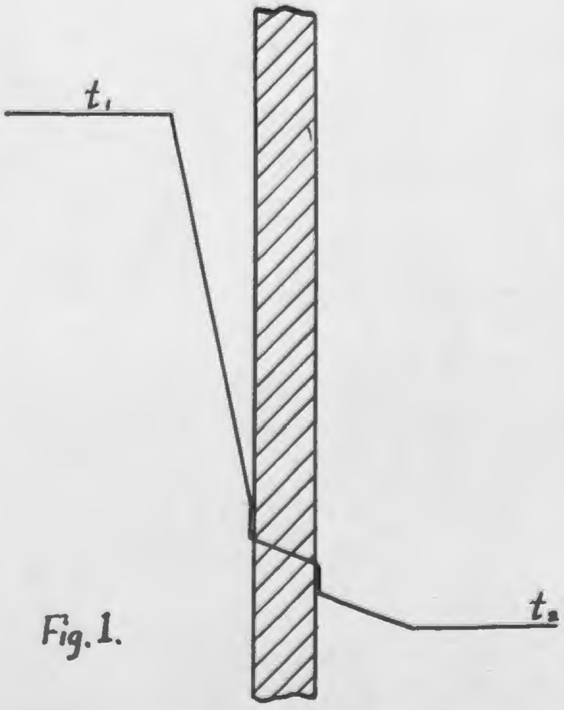


Fig. 1.

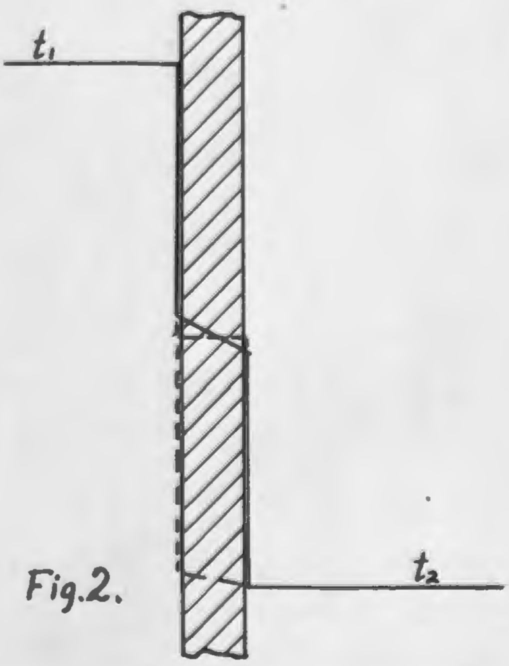


Fig. 2.

It has been customary to assume that the air columns surrounding the wall were very thin and that in computing K these might be neglected. Likewise the thickness of glass being very small it was neglected. This would leave:

$$K = \frac{1}{\frac{1}{a_1} + \frac{1}{a_2}}$$

In this case the diagram of temperature drop is much simplified as shown in Figure 2. Here it is assumed that the temperature does not drop until it reaches the face of the glass, and assuming similar air conditions inside and outside, the temperature drop at each surface will be

$$\frac{1}{2} (t_1 - t_2)$$

Now if a_2 were greatly increased by application of wind and rain to the outer surface, it is conceivable that all the drop might take place at the inner surface as shown by t" in which case the temperature drop thru the inner surface would be doubled and consequently the heat quantity flowing would be doubled. But Q, under these assumptions could not be more than doubled.

The experimental results would, at first glance, seem to indicate that the theory is at fault, but a consideration of the conditions under which the experiments were conducted, will show how this may be so. In the above tests the thermometers with which t_1 and t_2 were measured were about two inches from the face of the glass. The value of K was then the coefficient for a column of air four inches thick and the sheet of glass. Under these conditions, what was the temperature at the face of the glass? As we suspected that herein lay the solution of the apparent fallacy of the formula, we decided to determine this temperature as accurately as we were able. The theory by which this would be effective to more than double K with changes of air conditions is that the temperature drop between the actual surfaces of the glass more than doubles, and as stated before, the quantity of heat flowing thru any plane is proportional to the drop in temperature thru the plane.

Temperature Gradients.

In order to measure the temperatures a thermo-couple of No. 30 I. I. A. and copper wires was constructed and this was used in connection with a D'Arsonval galvanometer. Temperatures were taken at measured distances from the surface and also at the surface, as nearly as this could be reached, inside and outside of the glass. In order to find the temperature difference between the inside and outside surfaces of the glass, the ends of the couple were placed opposite each other at the two surfaces, the difference in temperature between the surfaces causing a measureable current to flow. When measuring the temperature at the surface the real surface temperature could necessarily not be obtained, as the junction of the couple had a thickness of .015", and no matter how thin it might have been, it would always have air on one side which would cause a higher temperature to be recorded.

The following curves have been drawn to show the temperature the temperature at different distances on either side of the glass under various conditions.

Curve number one gives the temperature gradient under quiet air conditions when $t_1 = 90^0$ and $t_2 = 46.4^0$, the glass being protected from direct radiation.

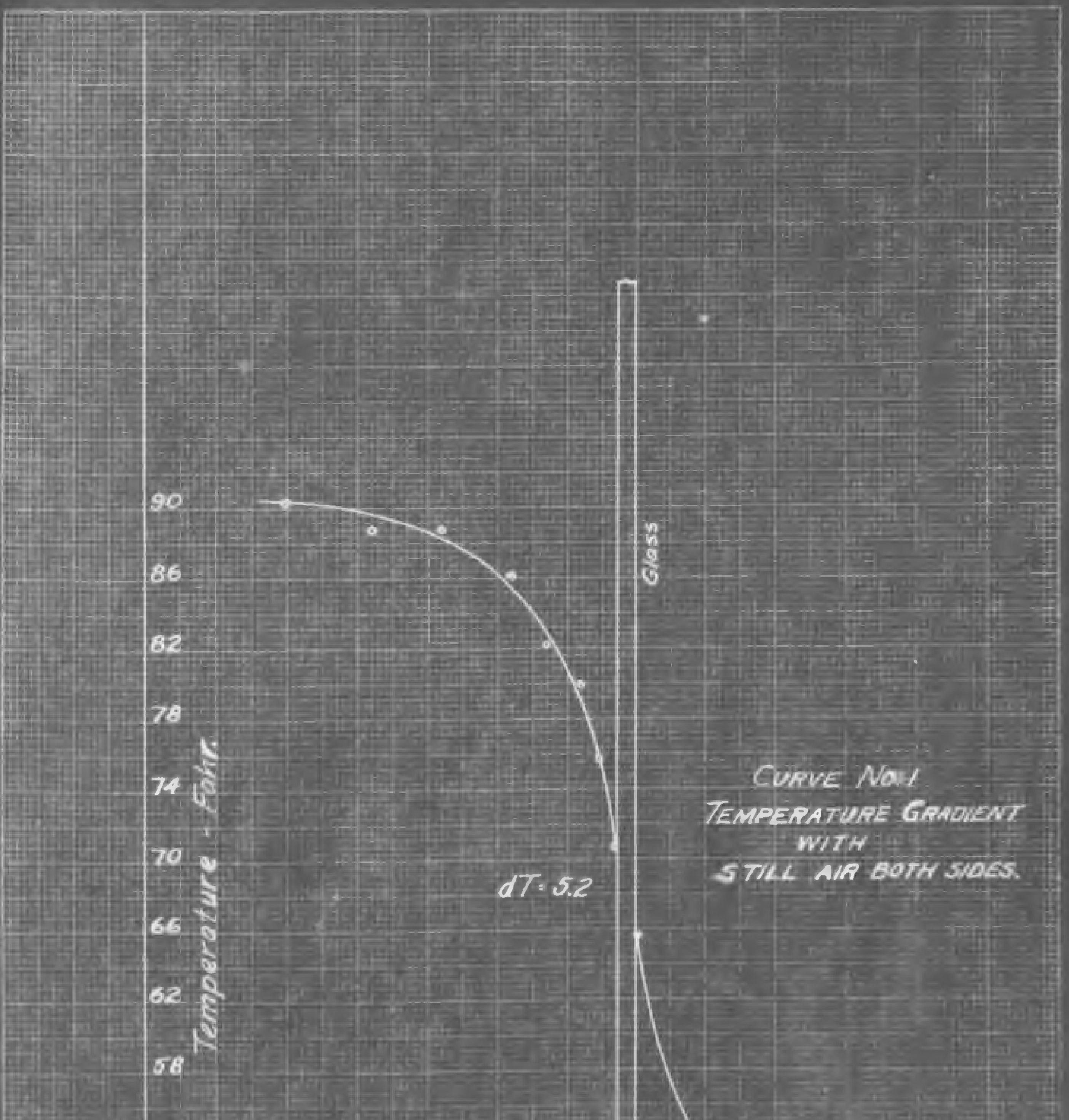
Curve number two is the gradient for the same air conditions with the glass exposed to the direct rays of the lamps.

Curve number three shows the effect of a heavy wind on the gradient. In this case air with a velocity of twelve hundred feet per minute was directed against the glass by letting the pipe from the blower exhaust full on the spot where temperatures were being taken. The value d T given on the curves is the temperature difference between the inside and outside surfaces of the glass.

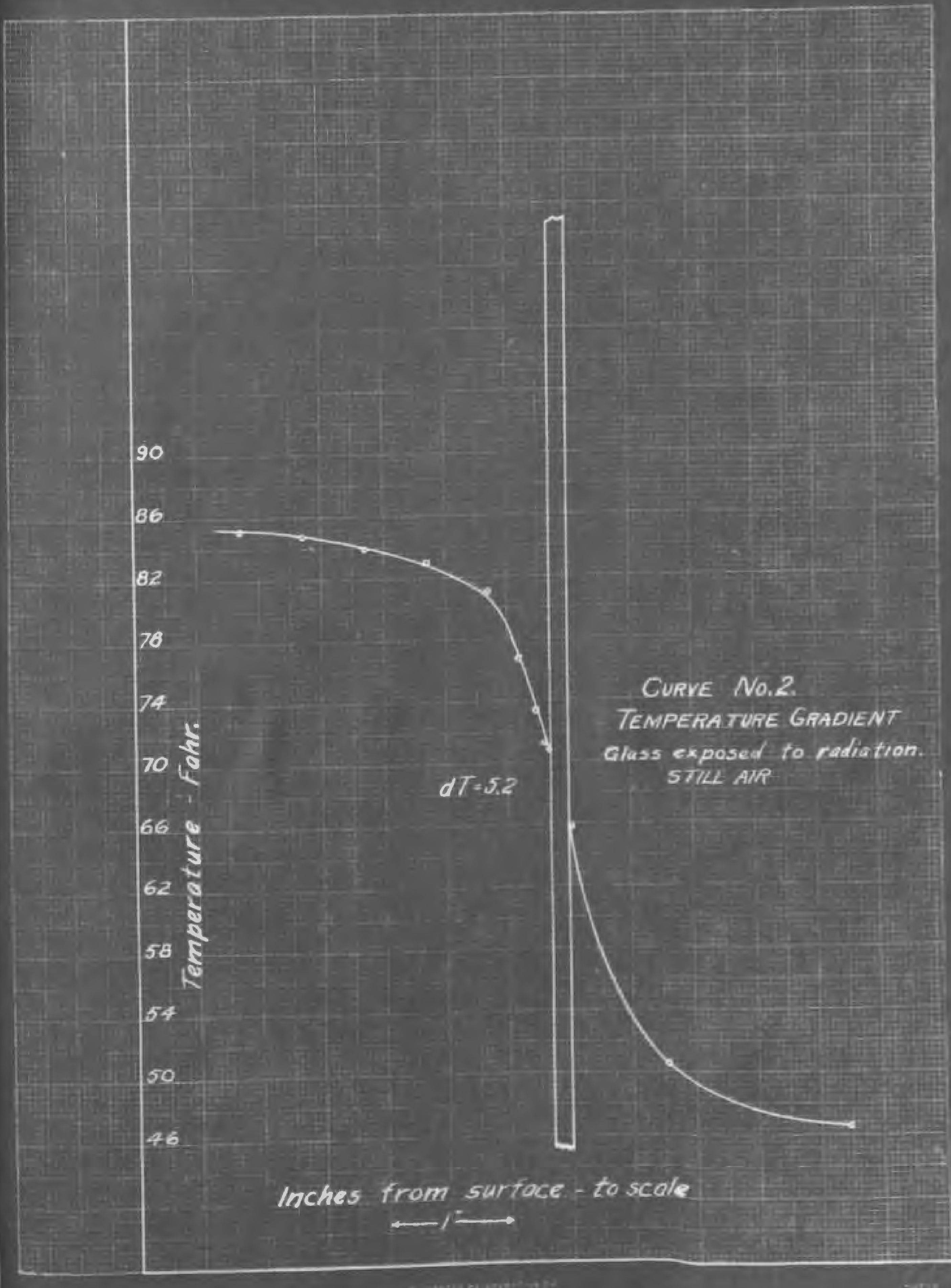
Curve number four shows the conditions which were found on a window in the engineering building on a rather windy day.

These curves show that for air under quiet conditions the major part of the temperature drop takes place as the gradient approaches and leaves the glass and the drop between the surfaces of the glass is very small. This value of dT would appear to be about ten percent of the total drop altho an exact ratio for this would be difficult to determine under the conditions available and indeed dT varied considerably under supposedly constant conditions, probably because of air currents, and because the couples had air on the outside. The true value of dT is probably much less than ten perdent.

With wind on the outside of the glass we see that the upper



CURVE No. 1
TEMPERATURE GRADIENT
WITH
STILL AIR BOTH SIDES.

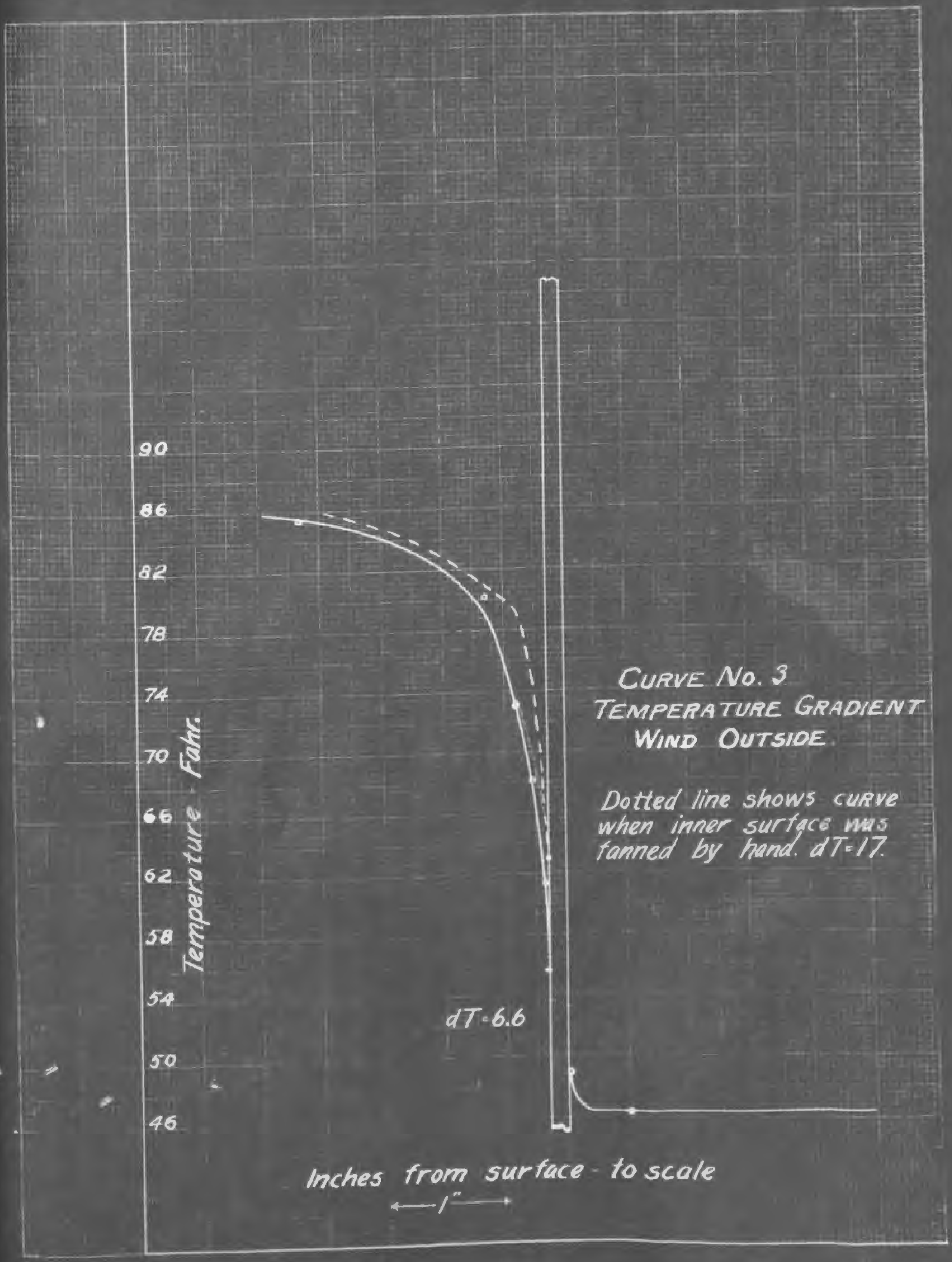


CURVE No. 2.

TEMPERATURE GRADIENT

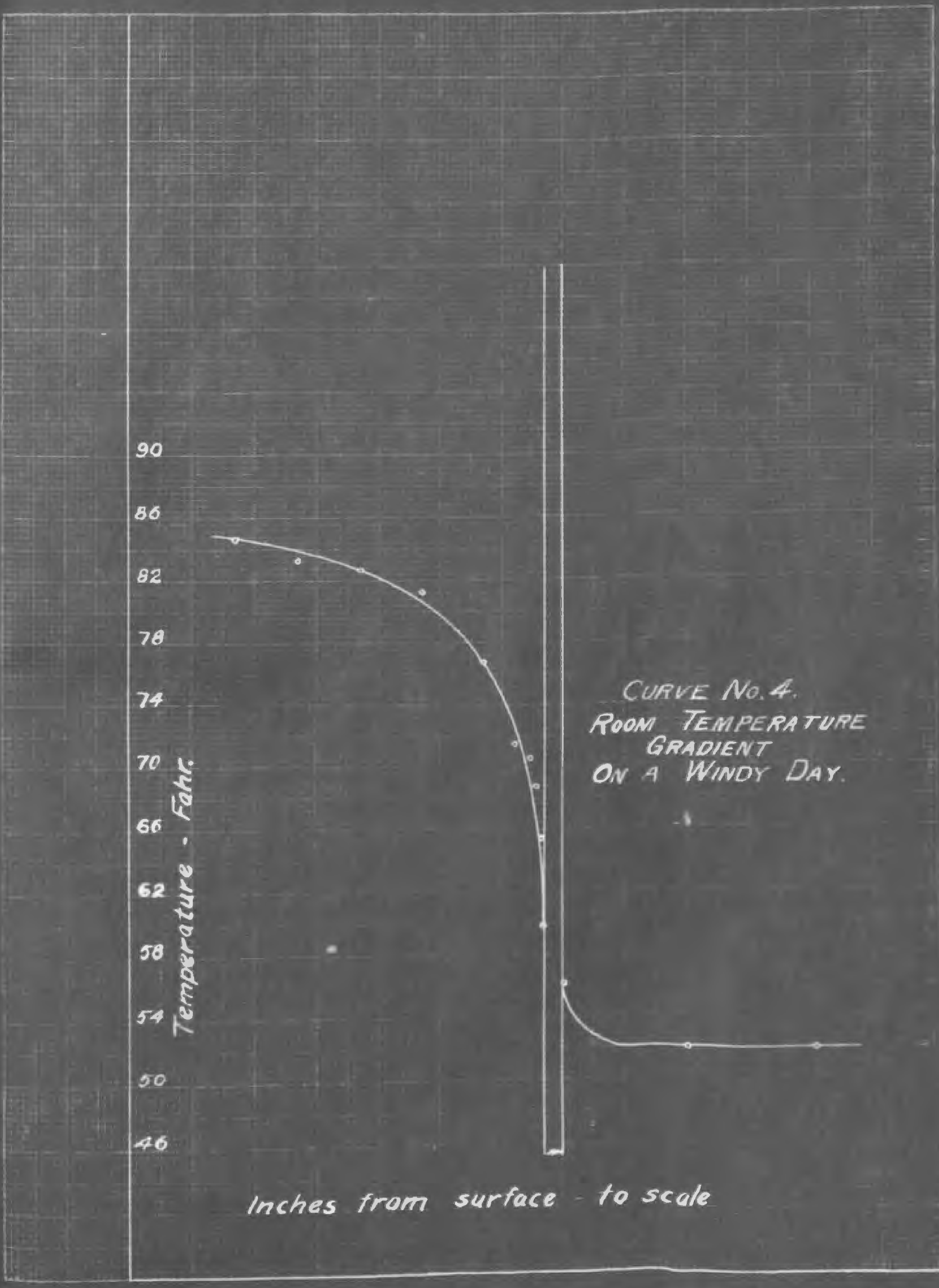
Glass exposed to radiation.

STILL AIR



CURVE No. 3
TEMPERATURE GRADIENT
WIND OUTSIDE.

Dotted line shows curve
when inner surface was
fanned by hand. dT=17.



CURVE No. 4.
ROOM TEMPERATURE GRADIENT
ON A WINDY DAY.

temperature gradient drops with the lower gradient, dT is greater, and the major drop takes place in the inside air column. A little air circulation on the warm side caused by a paper fan, very rapidly increases dT, and if there were a high rate of circulation it is probably that the upper gradient would be similar to the lower gradient inverted. It is apparent on studying this curve that at the same room temperatures the surface temperature difference might conceivably become several times as great and K would correspondingly increase. Harding and Willard give K = 24.3

A study of the curve of the gradient when the glass is exposed to direct radiation, shows it to be flatter and much more abrupt in its flexure than the other curves. Just why this should be it not clear, but very probably it is due to the reflection of the radiated heat after striking the glass, the effect here being proportional to the square of the distance from the glass. This might be taken as evidence of the cause proposed for the difference in K for plate glass and rolled glass with direct radiation as explained previously.

In the curves shown this effect does not show as it was expected to, as dT is nearly the same under the two conditions. This is probably due to the fact that the thermo-couple ends were not in the face of the glass and did not represent the actual conditions of the surface. It is reasonable to suppose that under proper conditions for measuring dT it would be found to increase greatly as wind was applied to the glass because the gradient has its maximum steepness at the face of the glass. What probably takes place is that dT increases more and more as the velocity of wind increases on the outside, even when the inner air remains still. As dT increases K must increase in direct proportion.

While this is not a conclusive proof of the theory expounded, it is indicative of the probable causes for K showing such marked increases under varying conditions of wind and rain.

Radiation Effects.

The results of the third part of the experiment in which the glass was exposed to the direct radiation from the lamps shows quite distinctly that the intensity of the heat as exposed to the glass has a marked effect on the heat loss. In the case of plate glass the increase in K for direct radiation is approximately ten percent and for rolled glass it is 20%. This is of interest in view of previous contentions that heat passes directly thru windows without heating the room, and proves one of the contentions in favor of indirect heating. In this connection it is to be noted that the source of direct radiation was thirty inches from the glass and so hot that it could hardly be held in the hand for more than a second or two. Direct radiators are usually nearer to the glass and often are quite as hot or hotter and in that case are evidently inefficient, since radiation varies with the square of the distance and with the fourth power of the absolute temperature. Evidently the low temperature radiators would be less open to this objection.

SUMMARY OF RESULTS.

In summarizing the results of the experiments, we find that the combined coefficient of conductivity for plate glass is from fifteen to twenty percent less than for ordinary rolled glass. We find that wind on one surface of the glass may greatly increase the coefficient and in this connection have shown how the temperature gradient approaches and leaves the glass and how the coefficient might more than double itself. And we have found that the coefficient of conductivity increases greatly with the intensity of heat.

From these results we conclude that plate glass does have a lower coefficient than rolled glass. The curves of temperature gradient indicate that double windows are desirable as they protect the glass from wind and thus keep down the temperature drop to the face of the glass. And finally, we have definitely proved one of the main contentions in favor of indirect radiation by showing how heat may radiate directly thru glass.

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