THE EFFECT OF MOISTURE CONTENT UPON THE COEFFICIENT OF THERMAL CONDUCTIVITY OF INSULATING MATERIALS

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PREFACE

The effect that moisture has on the thermal conductivity coefficient of an insulation has been given very little consideration. In design work, calculations of heat transfer are based upon the conductivity values for oven dried insulation. In practice the insulation is installed at atmospheric conditions at which time it will undoubtedly contain some moisture and the moisture content will continue to vary with the surrounding conditions. In many cases the insulation will be subjected to conditions where condensation will take place and the moisture content of the insulation will increase greatly.

It is therefore, the purpose of this investigation to determine how great an effect a change in the moisture content will have upon the value of the coefficient of thermal conductivity.

The guarded hot box located in the Mechanical Engineering Laboratory at Oklahoma Agricultural and Mechanical College was used for testing several kinds of insulation under varied moisture conditions.

SYMBOLS

A = Area of test wall, sq ft

H = Heat flow, Btu per hr

HC = Cost of heat or refrigeration, dollars per Btu

IC = Cost of insulation installed, dollars

K = Coefficient of thermal conductivity, Btu per hr per degree per sq ft per inch

M = Mark on wattmeter, .711 Btu

PQW = Percentage gained in weight based upon dry insulation, percent

t = time, hour

T = Temperature, degrees fahrenheit

Wt = Weight, pounds

X = Thickness of insulation, inches

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INTRODUCTION

Insulations are used primarily to reduce the heat flow through a given wall section. The question of whether to use an insulation or not, and if so, the thickness and the type to use, is in many instances an economic problem. The saving in the cost of fuel or cost of refrigeration resulting from the reduction in heat flow throughout the useful life of the insulation must be greater than the cost of the insulation installed. This statement may be rewritten in the form of an equation as shown below.

$$\frac{A\ K\ (T_1 - T_2)\ t\ \ H.C.}{X} \quad I.C. \qquad (1)$$

Where A is the area, sq ft; K the coefficient of thermal conductivity, Btu per hr per degree fahrenheit per sq ft per in.; T_1 and T_2 the inside and outside temperatures respectively, degree fahrenheit; t the time, hr; X the thickness, in.; H.C. the cost of heat or refrigeration, dollars per Btu; I.C. the cost of insulation installed, dollars. In this discussion the cost of the insulation, as installed, will include the cost of the vapor barrier, if one is used, as well as the cost of the insulation itself and the cost of the installation. A vapor barrier is herein defined as any material which is moisture resistant such as; aluminum, asphaltic and varnish paints, duplex paper, roll roofing and aluminum foil. The cost of the various insulating materials as installed, I.C., may readily be obtained from the suppliers. The thickness, X, of the insulation required for a project will vary as each type of insulation is considered. For any particular installation under consideration the cost of energy, H.C. to supply heat or refrigeration; the inside and outside temperature, T_1 and T_2 respectively; and the area, A, of the heated or the cooled surface may be secured. The useful life, t, of an insulation is considered to be the length of time that the thermal conductivity coefficient remains reasonably close to its original value. The two principle items affecting the time element are the temperature and the moisture conditions to which the insulation is subjected. The temperature limits of an insulation depend upon the materials from which the insulation is made. Physical tests indicate the maximum and minimum temperature limits of any material. If the operating temperature is held within these limits, no appreciable deterioration will take place due to this factor. The presence of moisture in the insulation has long been considered detrimental because its presence causes the insulation to settle and degenerate. For this reason vapor barriers are used to limit moisture infiltration, so that the valuable life of the insulation will not decrease more than necessary. Based upon experience the useful life of an insulating material may be estimated with a reasonable degree of accuracy for any particular insulation and vapor barrier when the specific temperature and moisture conditions are known.

In equation (1) (see page 1) the only variable remaining undefined is the thermal conductivity coefficient, K, which is the ability of a material to transmit heat. The thermal conductivity coefficient is also known as the coefficient of heat transfer and the greater its value the poorer are the insulating qualities. The thermal conductivity coefficient of all insulation materials, at oven dried conditions may be obtained from any good text on this subject or from the manufacturer. Insulations at oven dried conditions have been thoroughly dried and all possible moisture has been removed.

The author noted that very little attention has been given to the problem of the change in the value of the thermal conductivity coefficient which results from a change in moisture content. If the thermal conductivity of an insulation does not change appreciably with a change in moisture content, the above mentioned values of conductivity at oven dried conditions may be used in equation (1); and it becomes a simple matter to solve for the most economical insulation and its thickness. However, if the thermal conductivity does change with an increase or a decrease in moisture content, the correct value of thermal conductivity corresponding to the particular moisture conditions encountered should be used. In this case a vapor barrier is of value because it increases the life of the insulation as previously stated, and also it may have a desirable effect on the value of the thermal conductivity coefficient because it limits the extent of moisture infiltration. If the thermal conductivity coefficient increases in value with an increase of the moisture content in the insulation, it may be wise, from an economical standpoint, to install a better vapor barrier, even if it becomes necessary to decrease the thickness of the insulation.

Based upon our knowledge of the thermal conductivity coefficient values of various solids and liquids it is possible to make some assumptions concerning the effect of moisture in the insulation. If the moisture wets the fibers of the insulation but is not suspended in the form of droplets in the insulation, one might expect the coefficient of heat transfer to be greater than that for dry insulation; because, in general, the thermal conductivity coefficient of solids varies directly with the bulk density. On the other hand, if droplets of moisture form in the voids in the insulation, the coefficient of heat transfer can be expected to approach that of water ($K = 3.6$). Although the above assumptions may be correct, one must realize that they are merely an indication of the trend, and they are not absolute values which can be used in required calculations. For design purposes it is necessary to have accurate values of the heat transfer coefficient for each insulation at definite moisture contents, therefore the above assumptions are inadequate and another approach must be used.

The problem of determining the effect of moisture upon the coefficient of thermal conductivity of an insulation lends itself well to an experimental solution. The heat transfer coefficient may be determined experimentally, first with the insulations at oven dried conditions. Then a definite quantity of water may be added to the insulation and allowed to become thoroughly and representatively mixed with the insulation and another test made to determine the value of the conductivity at this new moisture condition. This process of adding water and then determining, the heat transfer coefficient may be repeated until the sample of insulation can retain no more moisture. After these results are obtained the value of the coefficient of heat transfer versus moisture content may be plotted on a graph. Then with known moisture conditions one may read from the graph the value of conductivity for this particular insulation. The moisture conditions for any insulating material may be determined by weighing a representative sample as it exists in service and then reweighing the material after it is thoroughly dried.

Three insulations used for low, medium and high temperature application were tested, and the results of these tests are recorded and explained in the following pages. Rock Cork was selected as an insulating material for low temperature application. Rock Wool for medium temperature application, and Kaylo for high temperature application. Since the conditions which cause condensation of moisture to take place are most prevelant at low temperatures, insulations being used commercially for low temperature work should be highly moisture resistant. Insulations being used commercially for high temperature conditions need little moisture resisting qualities.

APPARATUS

The guarded hot box, in the Mechanical Engineering Laboratory at the Oklahoma Agricultural and Mechanical College was chosen for use in making this investigation. The guarded hot box and its accessories consists of the following components: (See figures 1, 2 and 3 for the locations of these items)

1. Inner Box

The inner box is a three foot, inside dimension, cubical box with five of the surfaces being insulated frame constructed walls, three and three quarters inches thick. The sixth side of this box is open.

2. Outer Box

The outer box is a five foot, inside dimension, cubical box. Five of the sides of the outer box are five inches thick insulated frame construction and the sixth face is open.

3. Test Wall

The test wall is a frame constructed wall 6' x 6' by eight inches thick. A section three feet square, where the insulation is placed, is centrally located in this wall as shown in figure 3. This section in which the insulation is placed, is lined with building paper so that moisture in the insulation can not escape. The outside surface is removable to allow installing and removing the insulation.

4. Three Motor Driven Fans

One motor driven fan is used to circulate the air in the inner box. The remaining motor driven fans are used to circulate the air located between the inner and outer boxes.

5. Two Electrical Heating Elements

One of the electrical heating elements is located in the inner box. The other is located in the space between the inner and outer boxes.

6. Wattmeter

The wattmeter is connected so as to meter the electrical energy being supplied to the heating element located in the inner box. This wattmeter has been regeared so that one mark on the dial is equivalent to 0.711 Btu. The British Thermal Unit, Btu, being a unit of heat.

7. Two Thermostats

One thermostat is wired to control the temperature in the inner box and the other to control the temperature in the space between the two boxes.

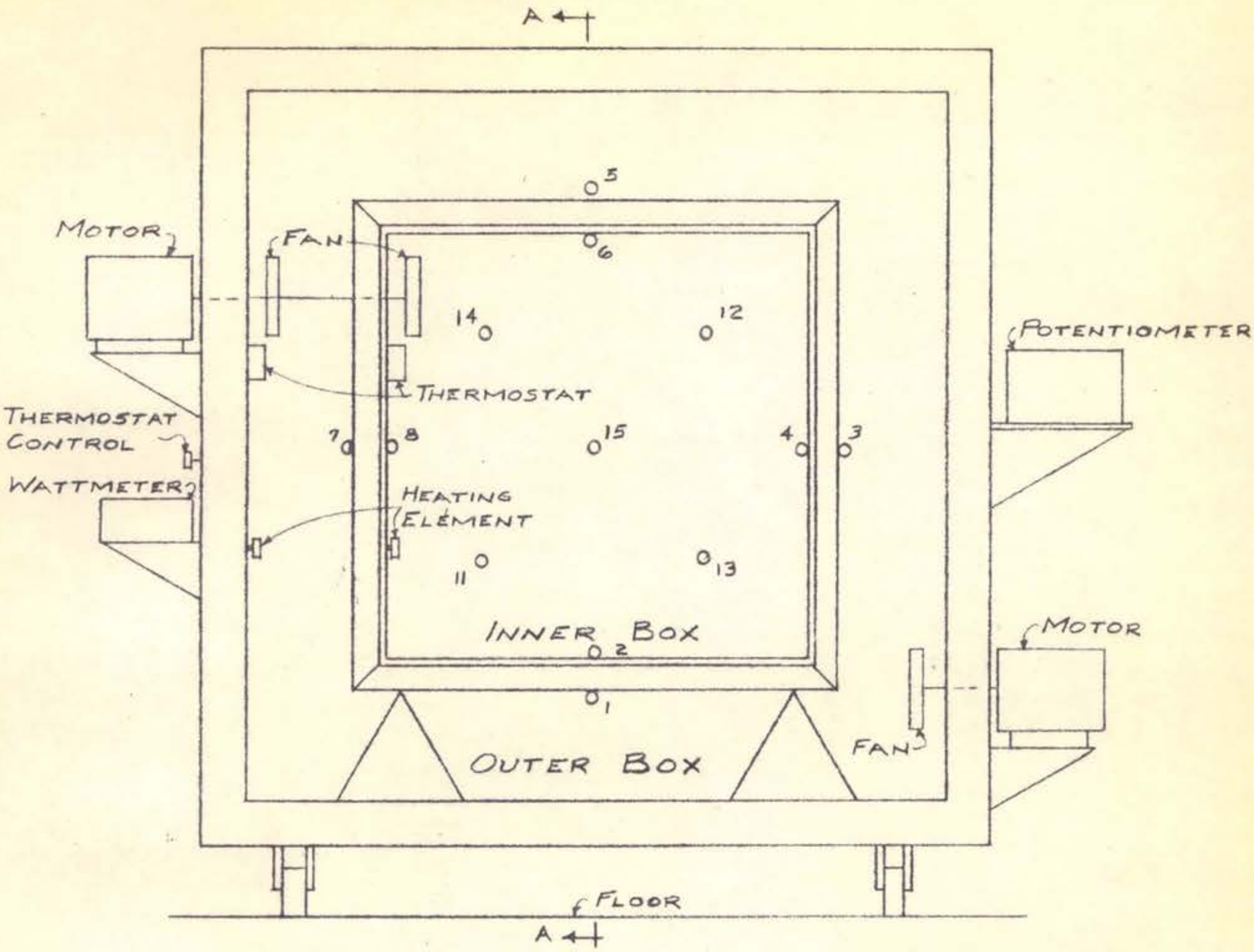
8. Twenty-two Thermocouples

Five of these thermocouples are located on the outside surface of the inner box, eleven inside the inner box and the other six are located in the test wall. Three of the six thermocouples located in the test wall are placed on the inside surface of the sample of insulation and the other three on the outside surface.

9. Potentiometer

The potentiometer is used to measure the difference in voltage between the cold junction (located in ice water) and any one of the twenty-two above mentioned thermocouples.

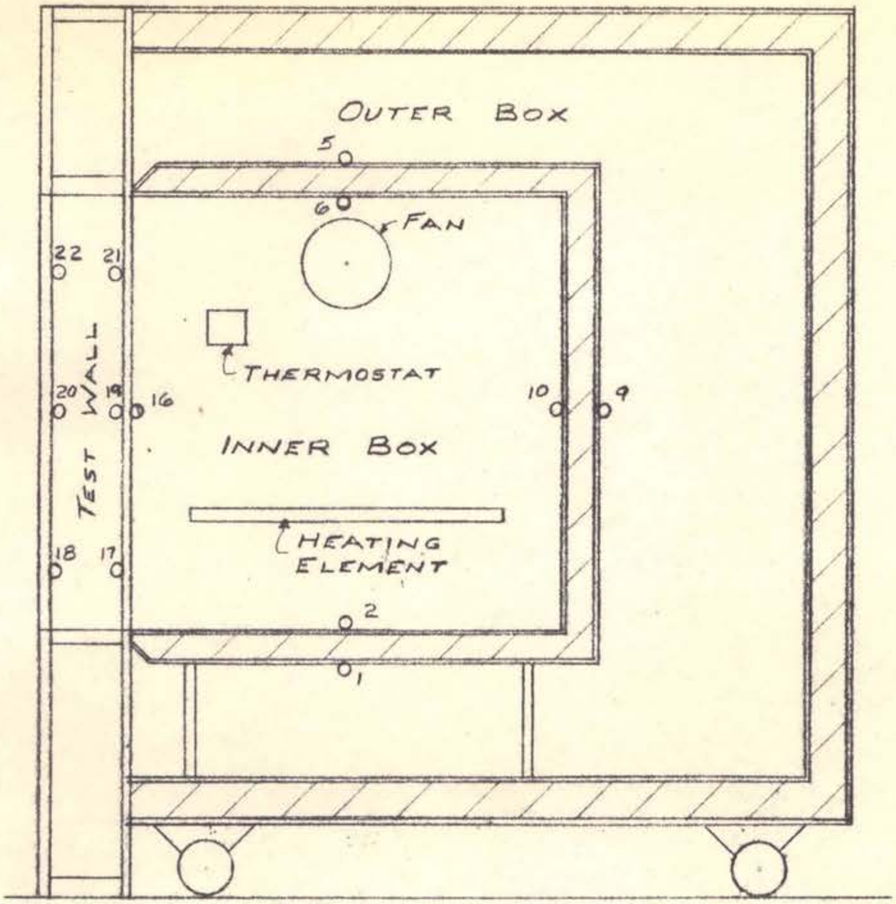
The name "guarded-hot-box" originated from the fact that the inner box, called the hot box because the air inside is kept at an elevated temperature during a test, is guarded from heat loss through the five surfaces surrounded by the outer box. The principle of the guarded hot box is based on the well known law which states that heat will not flow between two points of equal temperature. In the following discussion the term, temperature of the inner,



NOTE: O INDICATES LOCATION OF THERMOCOUPLES

FRONT VIEW
SCALE: 3/4" = 1'-0"

GUARDED HOT BOX
FIGURE 1.



NOTE: O INDICATES LOCATION OF THERMOCOUPLES

SECTION - A A
SCALE: 3/4" = 1'-0"

GUARDED HOT BOX AND WALL
FIGURE 2

or guarded, box will refer to the temperature inside the inner box and the term, temperature of the outer box, will refer to the temperature of the space between the two boxes. When the thermostats are adjusted so that the temperature of the inner box and the temperature of the outer box are equal, the temperature of the inside and the outside surfaces of the wall of the inner box will be the same. As stated above, no heat will flow between two isolated points having the same temperature. When the thermostats in the guarded hot box are adjusted properly heat will not flow through five of the six surfaces of the inner box, all of the heat then supplied to the inner box by its heating element must flow through the open face. As shown in figure 2, the test wall seals the open side of the inner box, therefore the heat supplied to the inner box must also pass through the sample of insulation being tested. We therefore are able to read directly from the wattmeter the quantity of heat passing through the insulation.

The temperature of the inner box and the outer box may be determined by connecting each thermocouple one at a time, by a switch arrangement, to the potentiometer. A reading in millivolts is obtained, resulting from the difference in temperature between the cold junction and the thermocouple being checked. One may then refer to a graph or a chart and secure the temperature equivalent of the known millivolt reading.

In a similar manner the temperature on either side of the insulation being tested may be determined.

The heat flow per hour through any insulation may be calculated from equation (2)

$$H = \frac{A\,K\,(T_1 - T_2)}{X} \qquad (2)$$

Where H is the heat flow, Btu per hr; A the area, sq ft; K the coefficient of thermal conductivity, Btu per hr per degree per sq ft per inch; T_1 the inside temperature, degrees; T_2 the outside temperature degrees; X the thickness, inches. Rearranging and solving for the conductivity, equation (3) is obtained

$$K = \frac{H\ X}{A\ (T_1 - T_2)} \tag{3}$$

One mark, M, on the wattmeter equals .711 Btu therefore the above equation may be rewritten as equation (4).

$$K = \frac{M\ X\ .711}{A\ (T_1 - T_2)} \tag{4}$$

The temperatures, T_1 and T_2, which represent the inside and the outside temperatures respectively may be determined as previously explained. Also the wattmeter reading, M, may be obtained. The area, A, remains constant and the thickness of the insulation, X, may be measured for the particular insulation being tested. All of the items on the right hand side of the equal sign in equation (4), are obtainable and therefore the value of the conductivity, K, may be calculated.

ADJUSTMENT OF THERMOSTATS FOR EQUAL TEMPERATURE

As previously explained the temperatures of the inner and the outer boxes must be equal while testing insulations with the guarded hot box. For this reason the two thermostats must be adjusted so that they will maintain the same predetermined temperature. The outer face of the test wall will be subjected to a room temperature of approximately 75 F. It is desirable to have an overall temperature difference through the wall of about 75 F; therefore the thermostats are adjusted to maintain a temperature of approximately 150 F. All temperatures referred to in this discussion are in degrees fahrenheit. Although this is not the usual operating temperature for Kaylo and Rock Cork, the results will not be affected greatly because the value of conductivity varies only slightly for a reasonable change in the average operating temperature. Also the highest temperature in the insulation, which will be approximately 146 F, is not sufficiently high as to cause any deterioration of the Rock Cork.

The adjustment of the thermostats was started by supplying electrical energy to the two heating elements and to the three electric motors. Six hours later the temperatures at the sixteen locations in the inner and the outer boxes were checked and recorded as shown in Table 1 reading number 1. The average temperature of the inner box was observed to be 241 F and the average temperature of the outer box was 180 F. The control on the thermostat regulating the inner temperature was rotated clockwise three revolutions, and the control regulating the temperature in the outer box was rotated clockwise one revolution. Thereafter at four intervals the temperatures of the inner box and the outer box were recorded as shown in Table 1, then the thermostats were adjusted accordingly. After forty hours of observation and adjustment the temperatures of the inner box and the outer box were both 152 F and the temperatures remained constant for another eight hours. With these temperatures remaining constant and equal within the accuracy of the potentiometer, which has an accuracy within one half of a degree, tests of the samples of insulation were carried out.

TEMPERATURE READINGS
IN GUARDED HOT BOX

Table 1 Sheet 1

Temperatures In Degrees F At Locations Shown
Inner Box

Reading	2	4	6	8	10	11	12	13	14
1	241	242	241	240	241	241	241	241	241
2	191	193	191	191	192	191	191	191	191
3	172	172	172	171	172	172	172	172	171
4	168	168	168	168	169	168	169	168	168
5	164	165	165	165	165	166	165	165	165
6	161	161	162	162	161	161	161	161	161
7	154	155	154	154	154	154	154	155	154
8	145	146	145	145	145	145	145	146	145
9	149	150	149	149	149	149	149	149	149
10	151	151	151	150	151	151	151	151	151
11	152	153	152	152	152	152	152	152	152
12	152	153	152	152	152	152	152	152	152
13	152	153	152	152	152	152	152	152	152

TEMPERATURE READINGS
IN GUARDED HOT BOX

Table 1 Sheet 2

Temperatures In Degrees F At Locations Shown

	Inner Box			Outer Box					
Reading	15	16	Ave.	1	3	5	7	9	Ave
1	242	241	241	180	182	180	180	180	1[illegible]0
2	192	190	191	162	164	162	161	162	162
3	173	171	172	159	160	159	159	159	159
4	169	167	168	156	158	156	157	156	156
5	166	164	165	154	157	154	154	154	154
6	162	160	161	152	155	153	153	153	153
7	155	153	154	153	154	153	153	152	153
8	145	144	145	152	153	152	153	152	152
9	150	148	149	152	153	152	152	152	152
10	152	150	151	152	154	152	152	152	152
11	153	151	152	152	153	152	152	152	152
12	153	151	152	152	154	152	152	152	152
13	153	151	152	152	153	152	152	152	152

CHANGE IN THE VALUE OF THE COEFFICIENT OF

THERMAL CONDUCTIVITY OF ROCK CORK

The test sample of Rock Cork consisted of four blocks, thirty-six inches by eighteen inches by three inches thick. The blocks were dried at 150 F for a period of two weeks before being placed in the test wall. The drying process was accomplished by placing the samples of insulation on top of the number 2 boiler at the Oklahoma Agricultural and Mechanical College power plant. The insulation was not as free of moisture as oven dried insulation although this condition was approached. After the insulation was in place the switches controlling the two heaters and the three fan motors were turned on and allowed to operate for twenty-four hours. Readings for test number 1 continued for three hours during which time six wattmeter readings and four temperature readings were made and recorded. The temperatures in both boxes and on the inside and outside surfaces of the insulation remained constant. Also the heat applied per hour to the inner box varied little during the test. It was assumed that the guarded hot box was in equilibrium and the results reliable. The insulation was then removed from the test wall and weighed.

The next step consisted of sprinkling water on the surface of the blocks. One hour was allowed for the moisture to soak into the insulation at the end of that time the insulation was reinstalled in the test wall. The temperature in the test wall was allowed to equalize for twenty-two hours before starting test number 2.

Tests 2, 3, 4 and 5 were conducted in the same manner, each test allowing the system to equalize for approximately twenty-two hours after the insulation was installed; recording readings of temperatures, wattmeter and time for a period of approximately three hours; weighing the insulation as it was removed from the wall; then adding a definite amount of water to the insulation. In one hundred and twenty hours it was not possible to fully saturate the Rock Cork and it is believed that a considerable amount of moisture would be absorbed over a longer period of time.

With the data accumulated in Tables 2 and 3 it is now possible to calculate the value of the conductivity for each of the five test conditions as follows:

Test Number 1

$M = 60.5 \qquad T_1 - T_2 = 55^{\circ}$

$A = 9\ ft^2 \qquad X = 6\ in.$

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{60.5 \times 6 \times .711}{9 \times 55} = .52\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

Test Number 2

$M = 67.5 \qquad T_1 - T_2 = 51^{\circ}$

$A = 9\ ft^2 \qquad X = 6\ in.$

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{67.5 \times 6 \times .711}{9 \times 51} = .628\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

Test Number 3

$M = 63.3 \qquad T_1 - T_2 = 49^{\circ}$

$A = 9\ ft^2 \qquad X = 6\ in.$

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{63.3 \times 6 \times .711}{9 \times 49} = .611\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

Test Number 4

$M = 61.3 \qquad T \qquad T_1 - T_2 = 49^{\circ}$

$A = 9\ ft^2 \qquad X = 6\ in.$

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{61.3 \times 6 \times .711}{9 \times 49} = .591\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

Test Number 5

$M = 66.0$ $\qquad T_1 - T_2 = 48^o$

$A = 9\ ft^2$ $\qquad X = 6$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{66.0 \times 6 \times .711}{9 \times 48} = .65\ Btu/hr/^oF/ft^2/in.$$

A graph plotted using the above calculated values of the thermal conductivity coefficient as the ordinate and the weight of the insulation as the abscissa is shown in figure 4. A graph plotted with the percentage gained in weight due to moisture versus the conductivity may be more useful, therefore the following values of percentages gained in weight (P.G.W.) are calculated. The weight of the insulation material after drying for two weeks at 150 F was used as the dry weight.

Test Number 1

Weight of dry insulation = 65.98 lb.

Weight of water = 0

$$P.G.W. = \frac{0}{65.98} = 0\%$$

Test Number 2

Weight of insulation = 66.40 lb.

Weight of water = 66.40 - 65.98 = .42 lb.

$$P.G.W. = \frac{.42}{65.98} = .638\%$$

Test Number 3

Weight of insulation = 66.70 lb.

Weight of water = 66.70 - 65.98 = .72 lb.

$$P.G.W. = \frac{.72}{65.98} = 1.09\%$$

ROCK CORK
HEAT SUPPLIED TO
INNER BOX

Table 2 Sheet 1

Time (Hr)	Meter Reading (Mark)	Time Elapsed (Min)	Heat Supplied (Mark)	Heat Supplied Per Hr (Mark)	Ave. Heat Supplied Per Hr (Mark)	Weight (Lb)
TEST NUMBER 1						
5:40	6444.5					
6:16	6481.2	36	36.7	61.2		
6:54	6520.2	38	39.0	61.5		
7:27	6552.7	33	32.5	59.1		
8:02	6588.3	35	35.6	61.1		
8:34	6620.1	32	31.8	59.6	60.5	65.98
TEST NUMBER 2						
4:55	405.5					
5:29	443.9	34	38.4	67.9		
6:00	478.0	31	34.1	66.0		
6:36	519.0	36	41.0	68.5		
7:11	559.0	35	40.0	68.6		
7:43	594.5	32	35.5	66.5	67.5	66.40
TEST NUMBER 3						
5:10	2333.2					
5:45	2370.5	35	37.3	63.9		
6:19	2405.5	34	35.0	61.7		
6:56	2443.8	37	38.3	62.1		
7:29	2479.4	33	35.6	64.7		
8:05	2517.8	36	38.4	64.1	63.3	66.70

ROCK CORK
HEAT SUPPLIED TO
INNER BOX

Table 2 Sheet 2

Time (Hr)	Meter Reading (Mark)	Time Elapsed (Min)	Heat Supplied (Mark)	Heat Supplied Per Hr (Mark)	Ave. Heat Supplied Per Hr (Mark)	Weight (Lb)
TEST NUMBER 4						
4:50	5510.5					
5:26	5546.6	36	36.1	60.2		
6:09	5580.9	33	34.3	62.4		
6:41	5613.8	32	32.9	61.7		
7:19	5651.6	38	37.8	59.6		
7:52	5686.0	33	34.4	62.6	61.3	66.97
TEST NUMBER 5						
9:10	8169.2					
9:45	8208.0	35	38.8	66.6		
10:16	8242.8	31	34.8	67.3		
10:49	8278.6	33	35.8	65.1		
11:18	8310.9	29	32.3	66.8		
11:49	8344.2	31	33.3	64.5	66.0	67.19

ROCK CORK
TEMPERATURE
READINGS

Table 3 Sheet 1

Time (Min)	Inner Box E.M.F. (Millivolt)	Inner Box Temp (°F)	Outer Box E.M.F. (Millivolt)	Outer Box Temp (°F)	Inside Wall E.M.F. (Millivolt)	Inside Wall Temp (°F)	Outside Wall E.M.F. (Millivolt)	Outside Wall Temp (°F)	Temp Drop Thru Wall (°F)
Test Number 1									
5:30	3.51	152.0	3.51	152.0	3.32	146.0	1.72	91.0	55.0
6:40	3.51	152.0	3.51	152.0	3.32	146.0	1.73	91.5	54.5
7:40	3.51	152.0	3.51	152.0	3.32	146.0	1.72	91.0	55.0
8:30	3.51	152.0	3.52	152.0	3.32	146.0	1.72	91.0	55.0
Test Number 2									
4:50	3.51	152.0	3.51	152.0	3.25	144.0	1.76	93.0	51.0
5:45	3.51	152.0	3.51	152.0	3.25	144.0	1.76	93.0	51.0
6:30	3.52	152.0	3.51	152.0	3.25	144.0	1.76	93.0	51.0
7:30	3.52	152.0	3.52	152.0	3.25	144.0	1.76	93.0	51.0
Test Number 3									
5:00	3.51	152.0	3.51	152.0	3.24	143.5	1.78	94.0	49.5
6:05	3.51	152.0	3.51	152.0	3.22	143.0	1.78	94.0	49.0
7:00	3.52	152.0	3.52	152.0	3.22	143.0	1.77	94.0	49.0
8:10	3.52	152.0	3.52	152.0	3.22	143.0	1.77	94.0	49.0

ROCK CORK
TEMPERATURE
READINGS

Table 3 Sheet 1

Time (Min)	Inner Box E.M.F. (Millivolt)	Inner Box Temp (°F)	Outer Box E.M.F. (Millivolt)	Outer Box Temp (°F)	Inside Wall E.M.F. (Millivolt)	Inside Wall Temp (°F)	Outside Wall E.M.F. (Millivolt)	Outside Wall Temp (°F)	Temp Drop Thru Wall (°F)
Test Number 4									
4:50	3.51	152.0	3.51	152.0	3.23	143.0	1.77	94.0	49.0
6:00	3.52	152.0	3.51	152.0	3.23	143.0	1.77	94.0	49.0
7:10	3.52	152.0	3.51	152.0	3.22	143.0	1.77	94.0	49.0
8:00	3.52	152.0	3.52	152.0	3.22	143.0	1.77	94.0	49.0
Test Number 5									
9:00	3.51	152.0	3.51	152.0	3.20	142.0	1.78	94.0	48.0
9:55	3.51	152.0	3.52	152.0	3.20	142.0	1.78	94.0	48.0
10:45	3.52	152.0	3.51	152.0	3.20	142.0	1.79	94.5	47.5
11:40	3.52	152.0	3.52	152.0	3.20	142.0	1.78	94.0	48.0

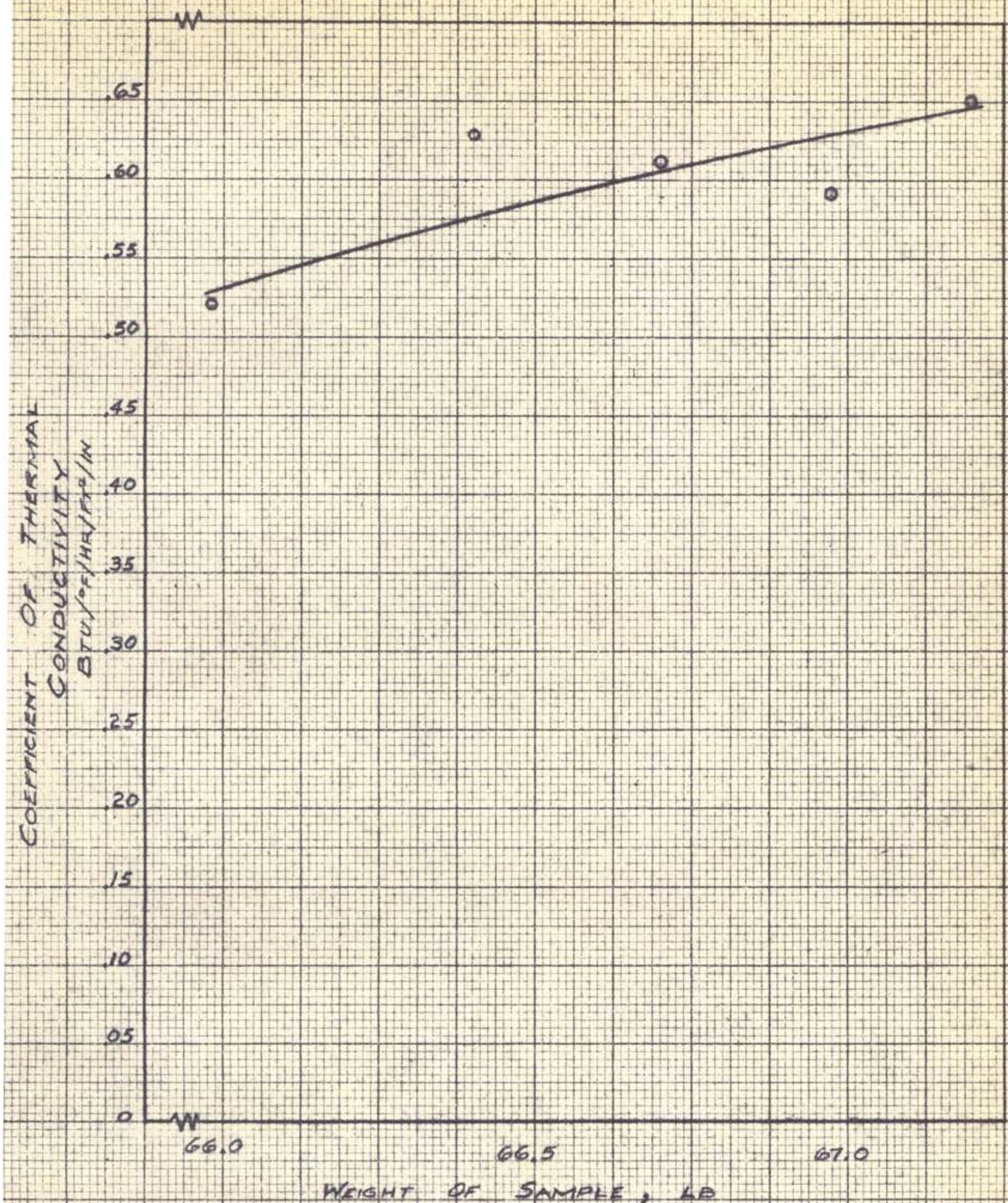


FIGURE 4 - CONDUCTIVITY VS WEIGHT RELATIONSHIP FOR ROCK CORK

CHANGE IN THE VALUE OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF ROCK WOOL

The sample of loose fill Rock Wool was dried for two weeks at 200° by placing it on the Number 2 boiler at the Oklahoma Agricultural and Mechanical College power plant. The Rock Wool was placed in the test wall and packed to a density of 10 pounds per cubic foot. This experiment was conducted in the same manner as the one with Rock Cork which has previously been described in full detail. The data accumulated during the five tests made with Rock Wool was recorded, see Tables 4 and 5. The Rock Wool absorbed moisture quite readily and therefore the insulation was thoroughly saturated and would hold no more moisture at the time test Number 5 was conducted.

Using the data listed in Tables 4 and 5 it is possible to calculate the value of the thermal conductivity coefficient for the insulation under the conditions of test 1 through 5 as follows:

Test Number 1

$M = 57.6 \qquad T_1 - T_2 = 60°$

$A = 9\ ft^2 \qquad X = 5\ in.$

$$K = \frac{M \times X \times .711}{A\,(T_1 - T_2)} = \frac{57.6 \times 5 \times .711}{9 \times 60} = \underline{.378}\ Btu/hr/°F/ft^2/in.$$

Test Number 2

$M = 119.0 \qquad T_1 - T_2 = 51°$

$A = 9\ ft^2 \qquad X = 5\ in.$

$$K = \frac{M \times X \times .711}{A\,(T_1 - T_2)} = \frac{119.0 \times 5 \times .711}{9 \times 51} = \underline{.92}\ Btu/hr/°F/ft^2/in.$$

Test Number 3

$M = 172.6$ $\qquad T_1 - T_2 = 44^{\circ}$

$A = 9\ ft^2$ $\qquad X = 5$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{172.6 \times 5 \times .711}{9 \times 44} = \underline{1.48}\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

Test Number 4

$M = 214.0$ $\qquad T_1 - T_2 = 38^{\circ}$

$A = 9\ ft^2$ $\qquad X = 5$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{214.0 \times 5 \times .711}{9 \times 38} = \underline{2.22}\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

Test Number 5

$M = 296.1$ $\qquad T_1 - T_2 = 34^{\circ}$

$A = 9\ ft^2$ $\qquad X = 5$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{296.1 \times 5 \times .711}{9 \times 38} = \underline{3.42}\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in}$$

A graph, using as ordinate, the coefficient of thermal conductivity and the weight of the sample of insulation as abscissa has been plotted, See Figure 6 for Rock Wool. The values of percentages gained in weight (P.G.W.) due to added moisture is also calculated and this value is plotted against the coefficient of thermal conductivity and is of more practical value than Figure 6.

Test Number 1

Weight of dry insulation = 37.4 lb

Weight of water = 0

$$\text{P.G.W.} = \frac{0}{37.4} = 0\%$$

Test Number 2

Weight of insulation = 39.0 lb

Weight of water 39.0 - 37.4 = 1.6 lb

$$\text{P.G.W.} = \frac{1.6}{37.4} = 4.28\%$$

ROCK WOOL
HEAT SUPPLIED TO
INNER BOX

Table 4 Sheet 1

Time (Hr)	Meter Reading (Mark)	Time Elapsed (Min)	Heat Supplied (Mark)	Heat Supplied Per Hr (Mark)	Ave Heat Supplied Per Hr (Mark)	Weight (Lb)
TEST NUMBER 1						
3:12	1534.2					
4:04	1583.8	52	49.6	57.3		
5:08	1645.6	64	61.8	57.9		
5:58	1693.6	50	48.0	57.7		
6:55	1748.7	57	55.1	57.9		
7:47	1798.2	52	49.5	57.2		
					57.6	37.40
TEST NUMBER 2						
3:53	2665.6					
4:22	2723.0	29	57.4	118.7		
4:50	2778.6	28	55.6	119.2		
5:20	2838.1	30	59.5	118.8		
5:48	2893.9	28	55.8	119.5		
6:19	2955.4	31	61.5	118.8		
					119.0	39.00
TEST NUMBER 3						
2:48	3771.2					
1:16	3852.2	28	81.0	173.4		
1:38	3915.7	22	63.5	172.7		
1:58	3973.1	20	57.4	172.0		
2:23	4044.9	25	71.8	172.3		
2:44	4105.4	21	60.5	172.6		
					172.6	41.00

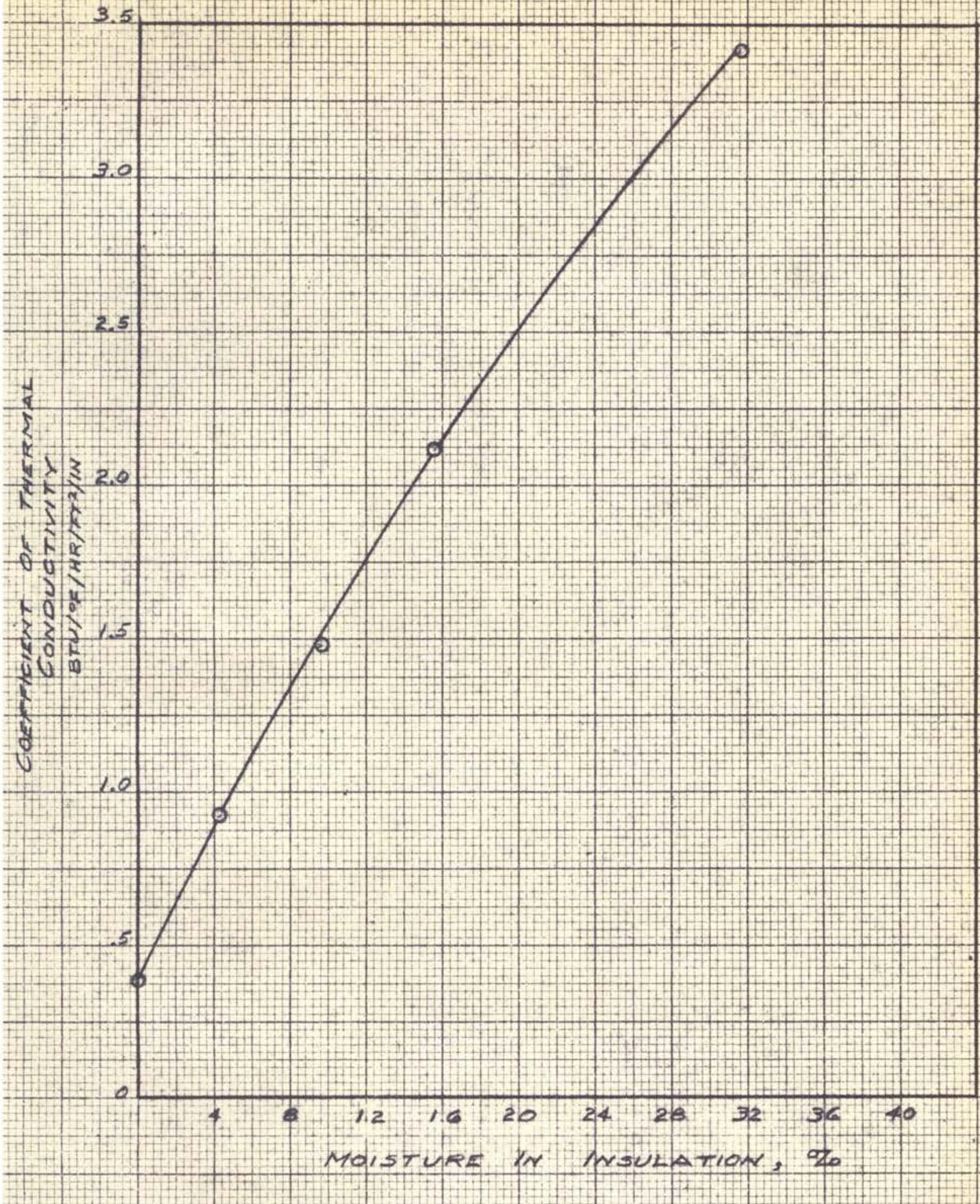


FIGURE 7 - CONDUCTIVITY VS PER CENT MOISTURE RELATIONSHIP FOR ROCK WOOL

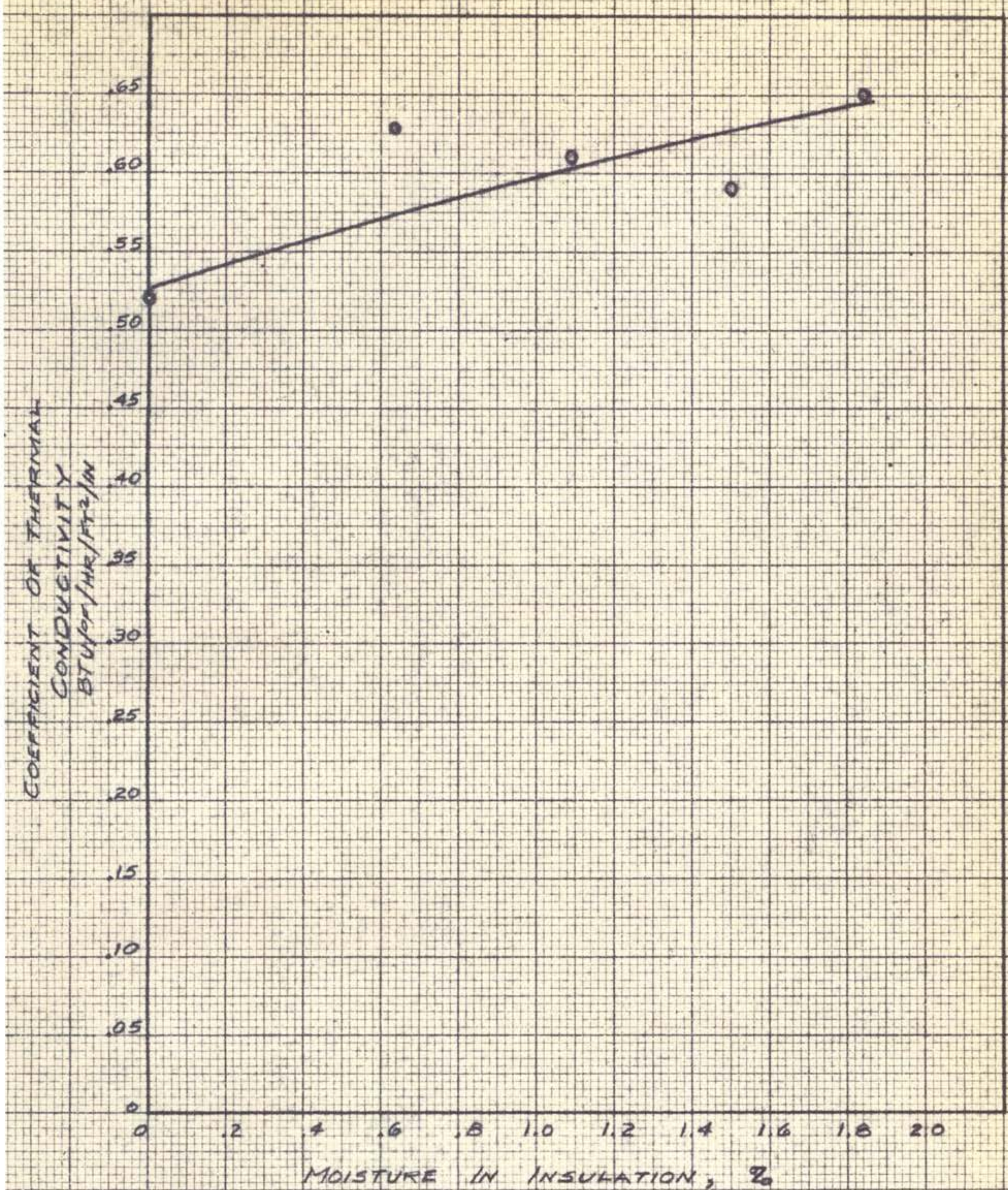


FIGURE 5 – CONDUCTIVITY VS PER CENT MOISTURE RELATIONSHIP FOR ROCK CORK

Test Number 4

Weight of insulation = 66.97 lb.

Weight of water = 66.97 - 65.98 = .99 lb.

$$P.G.W. = \frac{.99}{65.98} = \underline{1.50\%}$$

Test Number 5

Weight of insulation = 67.19 lb.

Weight of water = 67.19 - 65.98 = 1.21 lb.

$$P.G.W. = \frac{1.21}{65.98} = \underline{1.83\%}$$

The value of the thermal conductivity coefficient versus percentage gained in weight as plotted is shown in Figure 5.

ROCK WOOL
HEAT SUPPLIED TO
INNER BOX

Table 4 Sheet 2

Time (Hr)	Meter Reading (Mark)	Time Elapsed (Min)	Heat Supplied (Mark)	Heat Supplied Per Hr (Mark)	Ave Heat Supplied Per Hr (Mark)	Weight (Lb)
TEST NUMBER 4						
8:18	3771.2					
8:38	3842.6	20	71.4	214.1		
8:58	3914.1	20	71.5	214.9		
9:19	3989.1	21	75.0	213.9		
9:39	4060.2	20	71.1	213.5		
9:58	4127.8	19	67.6	213.6		
					214.0	43.29
TEST NUMBER 5						
3:44	5602.5					
4:03	5686.2	17	83.7	295.5		
4:17	5755.6	14	69.4	297.2		
4:34	5839.7	17	84.1	296.9		
4:51	5923.7	17	84.0	295.6		
5:09	6012.4	18	88.7	295.3		
					296.1	49.20

ROCK WOOL TEMPERATURE READINGS

Table 5 Sheet 1

Time	Inner Box		Outer Box		Inside Wall		Outside Wall		Temp Drop Thru Wall
	E.M.F.	Temp	E.M.F.	Temp	E.M.F.	Temp	E.M.F.	Temp	
(Min)	(Millivolt)	(°F)	(Millivolt)	(°F)	(Millivolt)	(°F)	(Millivolt)	(°F)	(°F)
				Test Number 1					
3:10	3.52	152.0	3.52	152.0	3.34	147.0	1.60	87.0	60.0
4:00	3.51	152.0	3.52	152.0	3.34	147.0	1.60	87.0	60.0
5:50	3.51	152.0	3.51	152.0	3.35	147.0	1.59	87.0	60.0
7:20	3.51	152.0	3.51	152.0	3.34	147.0	1.60	87.0	60.0
				Test Number 2					
3:55	3.51	152.0	3.51	152.0	3.20	142.0	1.72	91.0	51.0
4:30	3.51	152.0	3.52	152.0	3.22	142.5	1.72	91.0	51.5
3:20	3.52	152.0	3.52	152.0	3.20	142.0	1.72	91.0	51.0
6:15	3.52	152.0	3.52	152.0	3.20	142.0	1.72	91.0	51.0
				Test Number 3					
12:30	3.51	152.0	3.52	152.0	3.10	138.0	1.78	94.0	44.0
1:30	3.51	152.0	3.51	152.0	3.10	138.0	1.77	94.0	44.0
2:10	3.51	152.0	3.51	152.0	3.10	138.0	1.78	94.0	44.0
2:50	3.51	152.0	3.51	152.0	3.10	138.0	1.78	94.0	44.0

ROCK WOOL TEMPERATURE READINGS

Table 5 Sheet 2

Time (Min)	Inner Box E.M.F. (Millivolt)	Inner Box Temp (°F)	Outer Box E.M.F. (Millivolt)	Outer Box Temp (°F)	Inside Wall E.M.F. (Millivolt)	Inside Wall Temp (°F)	Outside Wall E.M.F. (Millivolt)	Outside Wall Temp (°F)	Temp Drop Thru Wall (°F)
Test Number 4									
8:10	3.51	152.0	3.51	152.0	2.95	134.0	1.88	97.0	38.0
8:50	3.52	152.0	3.51	152.0	2.96	135.0	1.88	97.0	39.0
9:30	3.51	152.0	3.51	152.0	2.96	135.0	1.88	97.0	38.0
10:00	3.51	152.0	3.51	152.0	2.96	135.0	1.88	97.0	38.0
Test Number 5									
3:50	3.51	152.0	3.51	152.0	2.92	133.0	1.93	99.0	34.0
4:20	3.51	152.0	3.52	152.0	2.92	133.0	1.93	99.0	34.0
4:50	3.52	152.0	3.51	152.0	2.92	133.0	1.94	99.5	33.5
5:20	3.52	152.0	3.51	152.0	2.92	133.0	1.93	99.0	34.0

Test Number 3

Weight of insulation = 41.0 lb.

Weight of water = 41.0 - 37.4 = 3.6 lb.

$$P.G.W. = \frac{3.6}{37.4} = \underline{9.64\%}$$

Test Number 4

Weight of insulation = 43.29 lb.

Weight of water = 43.29 - 37.4 = 5.89 lb.

$$P.G.W. = \frac{5.89}{37.4} = \underline{15.7\%}$$

Test Number 5

Weight of insulation = 49.2 lb.

Weight of water = 49.2 - 37.4 = 11.80 lb.

$$P.G.W. = \frac{11.80}{37.4} = \underline{31.6\%}$$

The percentage gained in weight, as calculated above, and the coefficient of thermal conductivity are now used as abscissas and ordinates respectively and the curve, see Figure 7 is plotted.

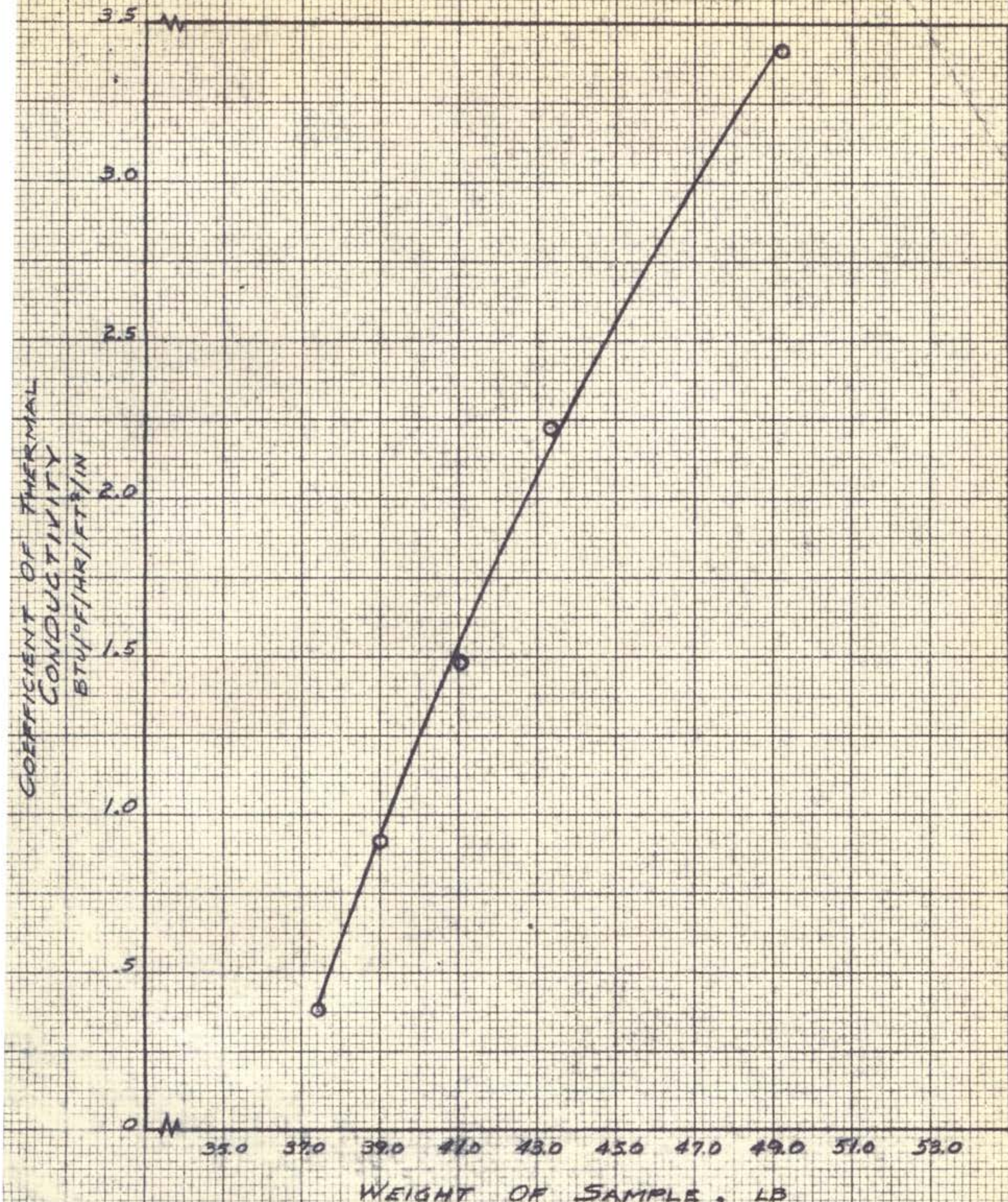


FIGURE 6 - CONDUCTIVITY VS WEIGHT RELATIONSHIP FOR ROCK WOOL

CHANGE IN THE VALUE OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF KAYLO

The test sample of Kaylo used for this experiment consisted of four blocks thirty-six inches by eighteen inches by three inches in thickness. The blocks were dried at 200° for a period of three weeks by placing on the number 2 boiler at the Oklahoma Agricultural and Mechanical College power plant. The insulation was then placed in the test wall and a series of five tests were made in the same manner as those with Rock Cork and Rock Wool. The observed data during these tests is recorded in Table 6 and 7. Kaylo, like Rock Wool, absorbed water very readily and was therefore completely saturated with moisture by the time test Number 5 was made.

The value of the coefficient of thermal conductivity of Kaylo is calculated as follows at each of the five test conditions and by use of the data accumulated in Tables 6 and 7.

<u>Test Number 1</u>

$M = 88.7$ $\qquad T_1 - T_2 = 52.5^{\circ}$

$A = 9\ ft^2$ $\qquad X = 6$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{88.7 \times 6 \times .711}{9 \times 52.5} = \underline{.801}\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

<u>Test Number 2</u>

$M = 186.1$ $\qquad T_1 - T_2 = 42.0^{\circ}$

$A = 9\ ft^2$ $\qquad X = 6$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{186.1 \times 6 \times .711}{9 \times 42} = \underline{2.10}\ \text{Btu/hr/}^{\circ}\text{F/ft}^2\text{/in.}$$

KAYLO
HEAT SUPPLIED TO
INNER BOX

Table 6 Sheet 1

Time (Hr)	Meter Reading (Mark)	Time Elapsed (Min)	Heat Supplied (Mark)	Heat Supplied Per Hr (Mark)	Ave Heat Supplied Per Hr (Mark)	Weight (Lb)
TEST NUMBER 1						
1:39	5278.4					
2:13	5330.2	34	51.8	89.7		
3:11	5415.2	58	85.0	88.1		
3:40	5457.6	29	42.4	87.6		
4:12	5505.2	32	47.6	89.3		
4:48	5558.5	36	53.3	88.8		
					88.7	52.15
TEST NUMBER 2						
8:13	7305.0					
8:31	7363.7	19	58.7	185.0		
8:52	7429.0	21	65.3	186.8		
9:15	7500.5	23	71.5	186.5		
9:37	7568.8	22	68.3	186.1		
					186.1	71.43
TEST NUMBER 3						
4:06	8690.7					
4:21	8760.8	15	70.1	280.6		
4:36	8831.2	15	70.4	281.3		
4:54	8915.6	18	84.4	281.4		
5:11	8995.3	17	79.7	281.2		
5:27	9070.1	16	74.8	280.5		
					281.0	105.49

KAYLO
HEAT SUPPLIED TO
INNER BOX

Table 6 Sheet 2

Time (Hr)	Meter Reading (Mark)	Time Elapsed (Min)	Heat Supplied (Mark)	Heat Supplied Per Hr (Mark)	Ave Heat Supplied Per Hr (Mark)	Weight (Lb)
TEST NUMBER 4						
7:03	3013.0					
7:17	3083.2	14	70.2	300.1		
7:34	3168.7	17	83.5	301.5		
7:51	3253.8	17	85.1	300.3		
8:07	3234.0	16	80.2	300.9		
					301.2	130.59
TEST NUMBER 5						
7:01	4683.1					
7:15	4756.3	14	73.2	313.6		
7:30	4834.6	15	78.3	312.8		
7:43	4900.3	13	65.7	313.9		
7:59	4982.8	16	82.5	313.4		
8:14	5061.5	15	78.7	314.3		
					313.6	155.80

KAYLO TEMPERATURE READINGS

Table 7 Sheet 1

Time (Min)	Inner Box E.M.F. (Millivolt)	Inner Box Temp (°F)	Outer Box E.M.F. (Millivolt)	Outer Box Temp (°F)	Inside Wall E.M.F. (Millivolt)	Inside Wall Temp (°F)	Outside Wall E.M.F. (Millivolt)	Outside Wall Temp (°F)	Temp Drop Thru Wall (°F)
Test Number 1									
2:00	3.56	154.0	3.56	154.0	3.4	148.5	1.85	96.0	52.5
2:40	3.57	154.5	3.56	154.0	3.4	148.5	1.85	96.0	52.5
3:30	3.57	154.5	3.57	154.5	3.4	148.5	1.86	96.5	52.0
4:00	3.56	154.0	3.57	154.5	3.4	148.5	1.85	96.0	52.5
Test Number 2									
8:00	3.56	154.0	3.57	154.5	3.12	139.0	1.89	97.5	41.5
8:30	3.56	154.0	3.56	154.0	3.12	139.0	1.88	97.0	42.0
8:50	3.56	154.0	3.56	154.0	3.12	139.0	1.88	97.0	42.0
9:10	3.56	154.0	3.56	154.0	3.12	139.0	1.88	97.0	42.0
Test Number 3									
4:00	3.56	154.0	3.56	154.0	2.82	130.0	1.90	98.0	32.0
4:30	3.56	154.0	3.54	153.0	2.82	130.0	1.90	98.0	32.0
4:50	3.54	153.0	3.56	154.0	2.83	130.0	1.90	98.0	32.0
5:20	3.56	154.0	3.56	154.0	2.82	130.0	1.90	98.0	32.0

KAYLO
TEMPERATURE
READINGS

Table 7 Sheet 2

Time (Min)	Inner Box E.M.F. (Millivolt)	Inner Box Temp (°F)	Outer Box E.M.F. (Millivolt)	Outer Box Temp (°F)	Inside Wall E.M.F. (Millivolt)	Inside Wall Temp (°F)	Outside Wall E.M.F. (Millivolt)	Outside Wall Temp (°F)	Temp Drop Thru Wall (°F)
				Test Number 4					
6:50	3.57	154.5	3.56	154.0	2.78	128.0	1.94	99.5	28.5
7:10	3.56	154.0	3.57	154.5	2.78	128.0	1.93	99.0	29.0
7:40	3.56	154.0	3.56	154.0	2.78	128.0	1.93	99.0	29.0
8:10	3.56	154.0	3.56	154.0	2.78	128.0	1.93	99.0	29.0
				Test Number 5					
6:55	3.57	154.5	3.57	154.5	2.72	126.0	1.96	100.0	26.0
7:20	3.56	154.0	3.57	154.5	2.72	126.0	1.96	100.0	26.0
7:45	3.57	154.5	3.56	154.0	2.72	126.0	1.96	100.0	26.0
8:15	3.56	154.0	3.56	154.0	2.72	126.0	1.96	100.0	26.0

Test Number 3

$M = 281.0 \qquad T_1 - T_2 = 32^o$

$A = 9\ ft^2 \qquad X = 6$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{281.0 \times 6 \times .711}{9 \times 32} = \underline{4.17}\ Btu/hr/^oF/ft^2/in$$

Test Number 4

$M = 301.2 \qquad T_1 - T_2 = 29^o$

$A = 9\ ft^2 \qquad X = 6$ in.

$$K = \frac{M \times X \times .711}{A\ (T_1 - T_2)} = \frac{301.2 \times 6 \times .711}{9 \times 29} = \underline{4.91}\ Btu/hr/^oF/ft^2/in$$

Test Number 5

$M = 313.6 \qquad T_1 - T_2 = 26^o$

$A = 9\ ft^2 \qquad X = 6$ in.

$$K = \frac{M \times X \times .711}{A(T_1 - T_2)} = \frac{313.6 \times 6 \times .711}{9 \times 26} = Btu/hr/^oF/ft^2/in\ \underline{5.70}$$

The graph shown in figure 8 is now plotted using the above calculated values of the coefficient of thermal conductivity as the ordinate and the weight of the sample as the abscissa. A 10 pound sample of Kaylo was removed from one of the blocks and placed in an oven to dry thoroughly at 400 degrees. After ninety-six hours the sample weighed 3.07 pounds and failed to lose any more weight in the next forty-eight hours. The weight of the four blocks of Kaylo insulation at oven-dried-conditions then may be calculated as follows:

$$\text{Weight} = \frac{3.07 \times 155.8}{10} = \underline{47.8}\ \text{lb}$$

Referring to Figure 9 one will note that the value of the coefficient of thermal conductivity, corresponding to a weight of 47.8 pounds is equal to .45. This value compares very closely with manufacturers information.

Using the above calculated weight as the dry condition, the percentage gained in weight may be calculated as follows:

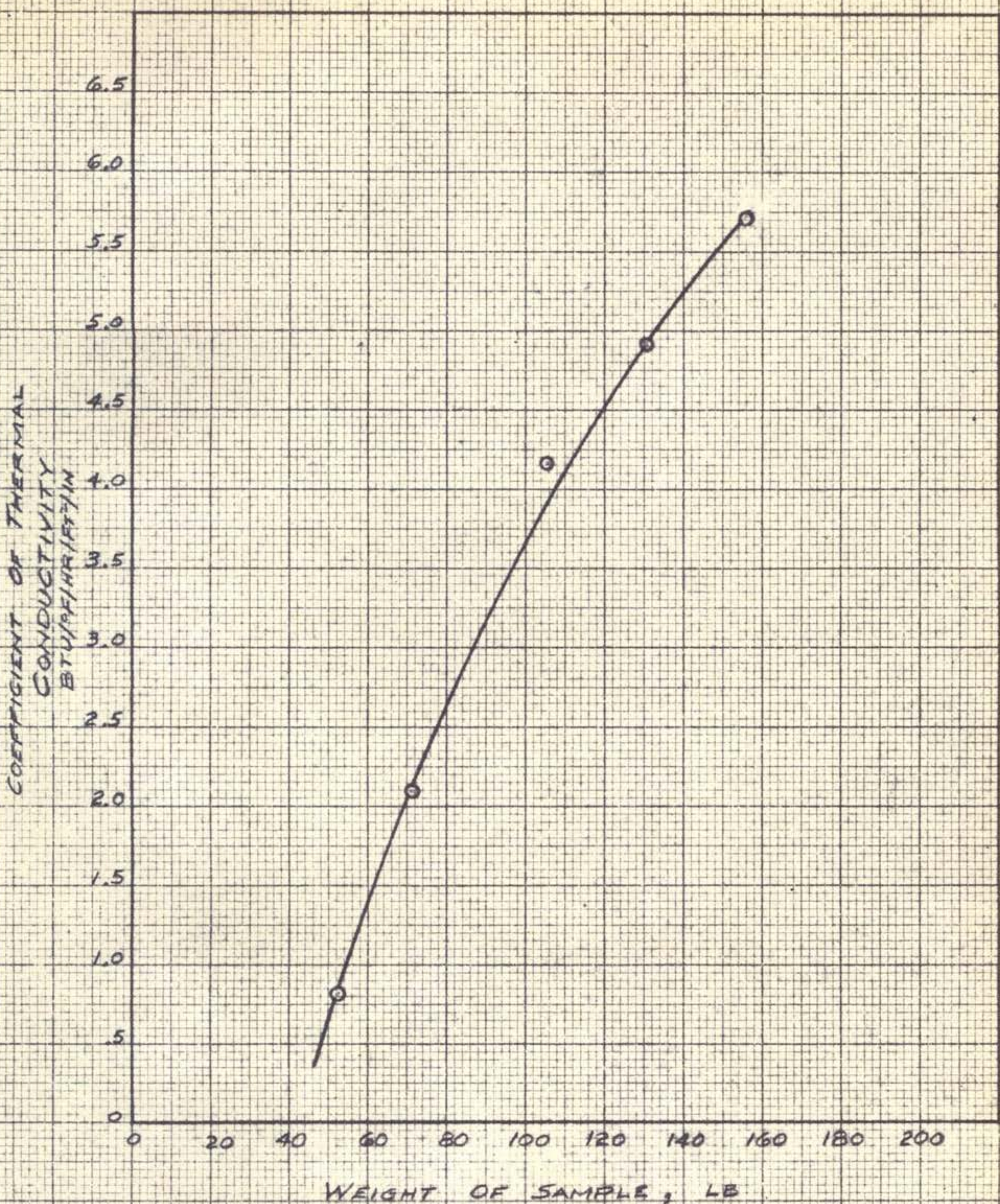


FIGURE 8 - CONDUCTIVITY VS WEIGHT RELATIONSHIP FOR KAYLO

Test Number 1

Weight of dry insulation = 47.8 lb.

Weight of insulation = 52.19 lb.

Weight of water = 52.19 - 47.8 = 4.35 lb.

$$P.G.W. = \frac{4.35}{47.8} = \underline{9.1\%}$$

Test Number 2

Weight of insulation = 71.43 lb.

Weight of Water = 71.43 - 47.8 = 22.63 lb.

$$P.G.W. = \frac{22.63}{47.8} = \underline{47.4\%}$$

Test Number 3

Weight of insulation = 105.49 lb.

Weight of water = 105.49-47.8 = 56.69 lb.

$$P.G.W. = \frac{56.69}{47.8} = \underline{119.0\%}$$

Test Number 4

Weight of insulation = 130.59 lb.

Weight of water = 130.59 - 47.8 = 81.79 lb.

$$P.G.W. = \frac{81.79}{47.8} = \underline{171.0\%}$$

Test Number 5

Weight of insulation = 155.8 lb.

Weight of water = 155.8 - 47.8 = 105.0 lb.

$$P.G.W. = \frac{105.0}{47.8} = \underline{219.0\%}$$

The values of the above calculated percentages gain in weight, versus the coefficient of thermal conductivity are plotted, see Figure 9.

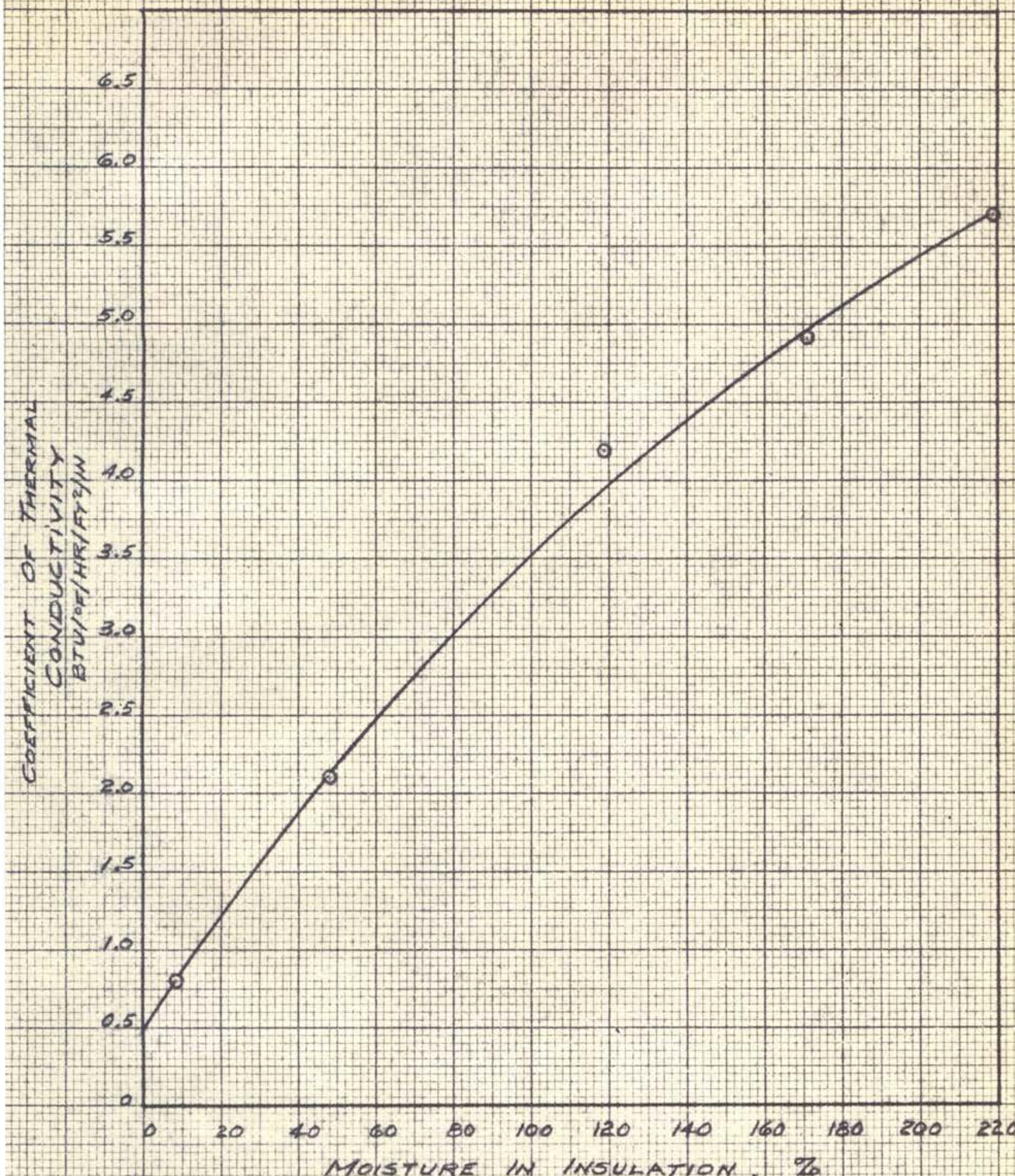


FIGURE 9 - CONDUCTIVITY VS PER CENT MOISTURE RELATIONSHIP FOR KAYLO

DISCUSSION OF RESULTS AND CONCLUSION

The Rock Cork absorbed very little moisture and the value of the conductivity changed by only a small amount, although one may observe from figure 10 that the value of the coefficient of the thermal conductivity did have a tendency to increase slightly with an increase in moisture content. As previously pointed out, this insulation would undoubtedly absorb more moisture and the coefficient of thermal conductivity would increase in proportion if it were subjected to moisture for a longer period of time.

A great deal of moisture was absorbed by the Rock Wool and the value of the coefficient of thermal conductivity when it was completely saturated was nine times greater than the value when oven dried. The value of the coefficient of thermal conductivity (K = 3.42)[1] when wet, approaches the value of the coefficient of thermal conductivity for water.

The 47.8 pound sample of Kaylo absorbed 105.0 pounds of water and the coefficient of thermal conductivity increased from .468 to 5.7. This value of 5.7[2] is comparable to the value of the conductivity for common brick. The differing effects of moisture upon the three above tested insulations becomes more apparent when the values are plotted on one graph as shown in Figure 10. The curve for Rock Cork as plotted in Figure 10 is too small to observe because the Rock Cork absorbs so little moisture. The reader should realize that these insulations were designed for different purposes and therefore they should not be compared at any one moisture condition.

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[1]Ingersoll and Zobel. Heat Conduction, p. 245
[2]Allen, Walker and James, Heating and Air Conditioning, p. 633

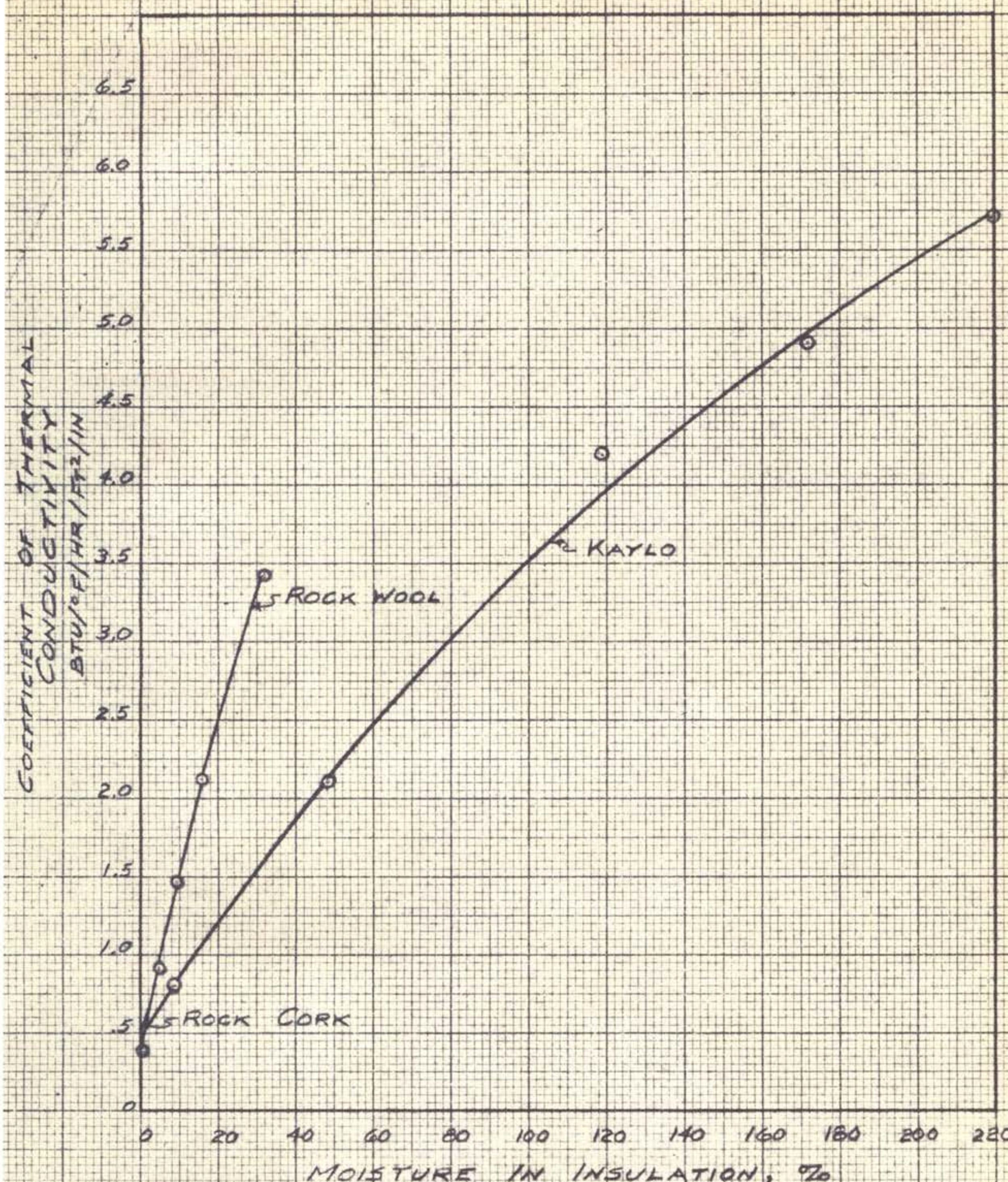

FIGURE 10 - CONDUCTIVITY VS PER CENT MOISTURE RELATIONSHIP

A study of Figure 10 indicates the unquestionable value of using a vapor barrier in conjunction with an insulation or of using a moisture resistant insulation provided of course the insulation is to be used where moisture conditions exist. In the case of Kaylo, where the operating temperature ranges from 250 to 1200°, very little moisture is absorbed from the atmosphere. While the operating temperatures for Rock Wool and Rock Cork are such that an appreciable amount of moisture will be absorbed from the atmosphere and under many conditions, condensation will actually take place in the insulation unless a vapor barrier is provided.

The presence of moisture in an insulating material has a very definite effect upon the value of the coefficient of thermal conductivity of that material. If moisture is allowed to come in contact with an insulation which is not moisture resistant, the water will be absorbed, and the insulation value will decrease accordingly.

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