THE EFFECT OF HOT SURFACE MOISTURE ON THE HEAT TRANSFER AND THE DRYING RATE OF SAND

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Leslie Erwin Lahti

1958

THE EFFECT OF HOT SURFACE MOISTURE ON THE HEAT TRANSFER AND THE DRYING RATE OF SAND

By

LESLIE ERWIN LAHTI

A THESIS

Submitted to the College of Engineering of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1958

TABLE OF CONTENTS

ABSTRACT

Recent work on the drying of sand on a hot surface, has suggested that thinner beds dry faster and have higher heat transfer coefficients, because of greater wetted areas at the hot surface. The problem of this study has been to evaluate that suggestion.

Drying was done on a steam heated plate held at a constant temperature of 220°F. Three bed thicknesses of sand were used; namely, one-half inch, one inch and one and one-half inch. Layer moisture content, composite moisture content, amount of steam condensed, and sand bed temperatures over intervals of time were taken as primary data. Hot surface moisture contents, heat transfer coefficients and drying rates were obtained from this data.

The drying rates and heat transfer coefficients were the highest with the one-half inch bed. The area of wetted hot surface was also the greatest for the one-half inch bed. Therefore, higher drying rates for the one-half inch bed are the result of higher heat transfer coefficients at the surface. These in turn are due to the greater area of hot wetted surface.

Approved: Randall M Ludt

ACKNOWLEDGEMENTS

The author gratefully wishes to thank Dr. Randall W. Ludt for his willing assistance, excellent guidance and cooperation in the preparation of this work.

Further thanks are expressed to Mr. D. T. Retford for his work on the original equipment design and to Mr. W. B. Clippinger for his work on making equipment alterations.

INTRODUCTION

INTRODUCTION

Since the process of drying has been used by industry for many years, it would seem that the mechanism of drying would be very well understood and described. A survey of the literature revealed that air drying, such as occurs in nature, has been very well described. However, very little has been written about hot surface drying. It has been only in recent years that the mechanism of hot surface drying has been advanced, publicized and accepted.

This study has been a continuation of the efforts in this field to more fully explain the hot surface drying phenomenon. Sand was selected as the material to be dried, in an effort to lessen the number of variables in the process. The effects of bound water on the process were eliminated by use of a nonhygroscopic material like sand and it was possible to obtain a uniform particle size and shape by classification. Water was selected as the liquid to be removed, since it represents one of the major drying problems in industry.

Purpose and Scope of This Investigation

The purpose of this study has been to provide information which could be used with other work to further explain the hot surface drying mechanism. It was hoped that relationships between hot surface moisture content, heat transfer coefficients and drying rates would aid in this explanation.

Three sand bed thicknesses were dried; namely, one-half inch, one inch and one and one-half inch. The hot surface temperature was held constant at 220°F during all runs. Moisture content, layer moisture content, amount of steam condensed and sand bed temperatures measured at periodic intervals were taken as primary data.

HISTORY

HISTORY

Drying is not a new operation. For centuries, air drying has taken place in nature and the mechanism of air drying has been very thoroughly expounded in the literature. However, very little work has been done on hot surface drying. A brief description of air drying might help to explain some phase of the mechanism of hot surface drying and is for that reason repeated here.

Air Drying

Essentially, it has been generally agreed that drying involves two steps; namely, the transfer of moisture as either liquid or vapor through the solid to the surface and transfer of water vapor from the surface of the solid into the main drying medium. Further, it has been generally accepted that during constant rate drying the latter case is an evaporation process from a wetted surface. Vaporization later takes place from within the bed.

However, the transfer of moisture through the solid to the surface created some controversy. Sherwood (18) from early work on drying, suggested that moisture transfer took place by means of diffusion. Ceaglske and Hougan (2) showed that flow of water in sand during air drying was due primarily to capillary forces. Hougan, McCauley and Marshall (10) showed wide discrepancies between diffusion equations and constant rate drying.

Haines (8) previously had explained how moisture was held between particles by starting with a dry bed of soil and adding water to it. His first stage of wetness was called the pendular stage, wherein a small amount of water was held at the points of contact of the particles or suspended between the particles. More water added to the bed led to his second stage of wetness, the funicular stage, wherein the particles were covered by a continuous water film but the pore spaces were still empty. After enough water was added to fill these pore spaces, he reached his last stage, the capillary stage, wherein all the cells between the particles were filled.

Ceaglske and Hougan (2) used the above terminology and also the method of Haines to determine the effect of suction in the sand, expressed as percentage of saturation.

Pearse, Oliver and Newitt (16) concurred with Ceaglske and Hougan and expanded the theory of air drying of granular materials. They explained that movement of moisture in the bed depended primarily on gravitational, capillary and frictional forces.

From this study, a brief summary of air drying would be as follows: The bed was made up of small particles between which were interconnecting void spaces. As water started evaporating from the surface of the saturated bed, concave surfaces developed in the large pores, setting up suction within the bed. As more water evaporated, this suctional force increased until it was great enough to break the continuous water film. At this time the water was pulled down the large capillaries and supplied to the surface through the small capillaries, keeping the surface particles wet. The constant rate drying continued as long as there was sufficient moisture in the bed to cover the surface particles.

When the small capillaries could not supply the surface with enough water to wet the particles, the critical moisture content was reached and the first falling rate period began. Vaporization continued at the surface at a reduced rate during this period.

The second falling rate period commenced when the bed was sufficiently dry, such that particles throughout the bed were no longer covered with a continuous film of moisture. Water was said to exist in the pendular state and vaporization occurred within the bed.

Newitt and Coleman (14) drying china clay, found increased drying rates and prolonged constant rate periods in thinner beds. They felt the reason was due to a reduction in friction opposing the liguid flow.

Hot Surface Drying

In spite of the difference in the mechanism of heat and mass transfer between air and hot surface drying, drying rate curves of similar shape have been reported. Ernst, Ardern, Schmied and Tiller (5) reported a constant rate period followed by a variable rate period for the vacuum drying of Prussian blue on heated shelves. Ernst, Ridgway and Tiller (6) dried Sil-O-Cel in the same manner. They also reported a similar drying rate curve and showed that in vacuum shelf drying, heat was supplied at both the top and bottom of the bed.

Likewise, McCready (13), drying paper pulp on a hot surface, showed a constant rate period, followed by a first and second falling rate periods. Hougan, McCauley and Marshall (10) showed a few curves for moisture distribution within a granular bed, dried on a hot surface and introduced the phenomenon of vapor condensation within the bed. King and Newitt (11) found a pseudo-constant rate followed by a falling rate while drying glass beads.

Tambling (19), using salt solutions instead of water, showed that at 12 per cent moisture, 60 per cent of the salt concentrated near the hot surface and about 15 per cent at the open surface. This indicated that liquid was vaporized at the hot surface, rose through the bed and left the salt behind. Some of the vapor condensed in a region above the hot surface, picked up salt and moved toward the hot surface. Some liquid movement to the air surface also took place.

Hadley and Eisenstadt (7) studied the movement of moisture in a granular material due to temperature gradients by using radioactive tracers. They also reported a liquid migration toward the hot end and a vapor movement away from it. Further, they observed that below a certain moisture content, migration was due to vaporization and not capillarity.

Dreshfield (4) used dye migration to determine liquid migration in paper pulp. He measured the moisture content of the fibrous sheets using beta-ray transmission and advanced the following description of the mechanism of hot surface drying: At the start of drying, there was a short period of time during which the drying rate and the temperature distribution adjusted from the initial conditions to the conditions of constant rate drying.

Heat was added to the sheet at the hot surface and caused vaporization to take place. This vapor rose through the sheet and entered the air stream at the open surface. Partial condensation took place as this vapor rose and transferred heat to the sheet. This heat moved by conduction in the direction of decreasing temperature. At the open surface, a small fraction of the heat was transferred to the air by convection and the remainder caused vaporization.

This process continued until the zone at the hot surface became too dry to maintain a steady rate of vaporization. At this time, the temperature drop across the hot zone increased and the rate of heat transfer to the sheet decreased. The temperatures of the rest of the sheet decreased and the drying rate decreased accordingly. Below the critical moisture content, the zone in which vaporization occurred moved slowly away from the hot surface, and a continuous readjustment of temperature within the bed took place. Liquid migration continued in the falling rate period, probably until the front of the zone of vaporization had reached the zone of maximum moisture content. By this time, the moisture content of the sheet was very low and remaining water was removed by vaporization and diffusion of water vapor from the interior.

Ludt (12), working independently of and simultaneously with Dreshfield, dried sand and essentially concurred with him in describing the mechanism of hot surface drying. Ludt however, pointed out that heat transfer through the sand bed was due primarily to passage of hot vapors through the bed. Harbert, Cain and Huntington (9) reported transfer to be by some other means than conduction. Ludt further explained that the hot surface was supplied by small capillaries and that the hot surface moisture content was constant during constant rate drying. Plate temperature was found to be the most important factor in determining the constant drying rate. Both Ludt and Dreshfield concurred that the critical moisture content was primarily determined by the hot surface moisture content.

Ludt stated that bed thickness influenced the critical moisture content but had little effect on the constant drying rate. Retford (17) expected a maximum drying rate at some intermediate bed thickness. When drying sand on a hot surface, he found the one-half inch bed dryed at a faster rate than either a one or a one and one-half inch bed.

Ludt, Bohl and Retford commenced the work leading to this study and designed the equipment with which this study was made.

EQUIPMENT AND PROCEDURE

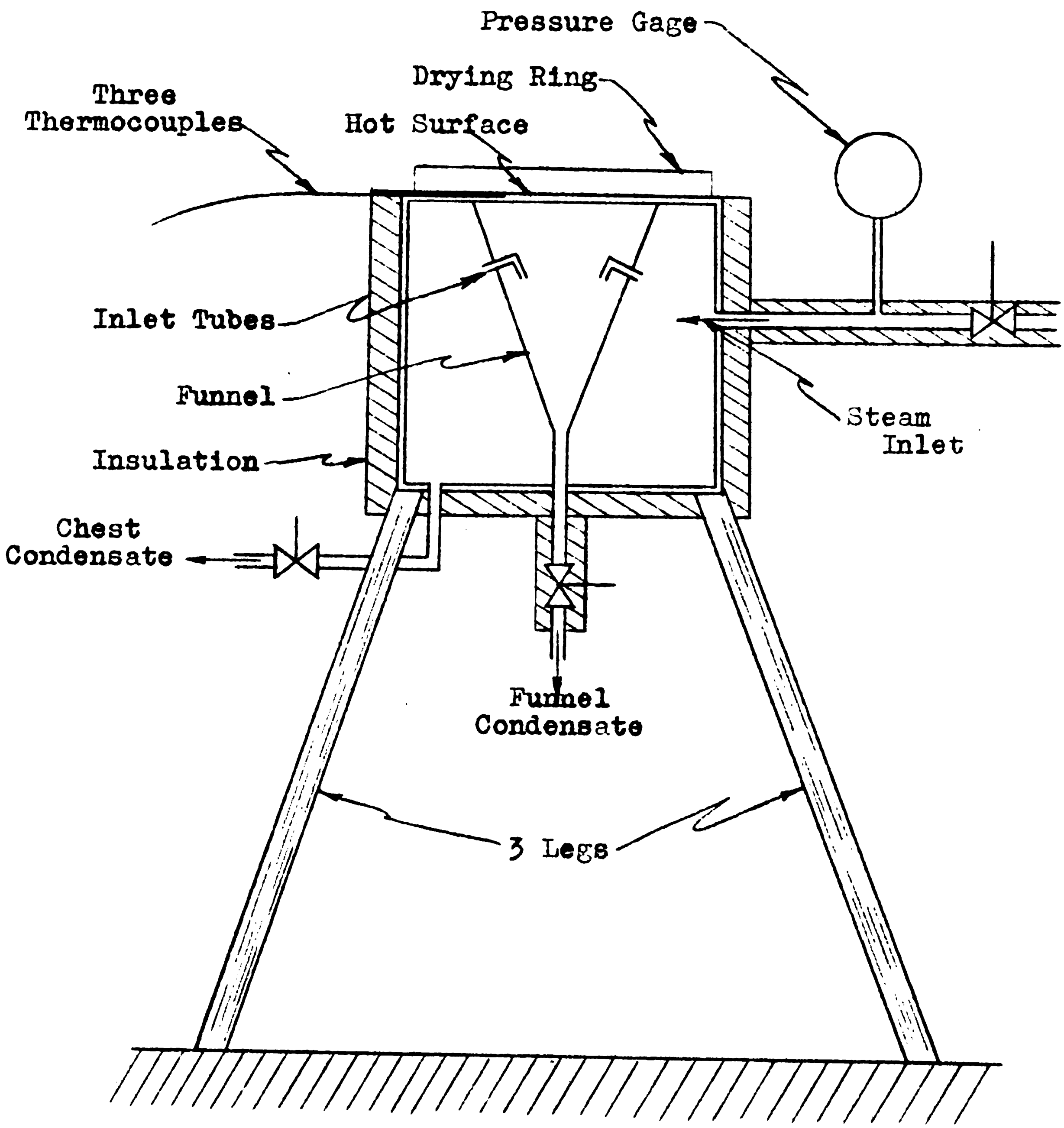
EQUIPMENT AND PROCEDURE

Equipment

The drying process was carried out on a steel plate, heated with steam. This plate, one-quarter inch thick by 12½ inches in diameter, was welded to a circular steam chest (Diagram No. 1). On the underside of this plate was welded a cone shaped funnel with an upper diameter of seven and one-half inches and a lower diameter equivalent to an one-half inch pipe. A pipe was welded to this end and extended through the bottom of the steam chest to an one-quarter inch needle valve.

Steam entered the chest through an one-half inch, 18 psig. supply line equipped with a globe valve. A pipe was connected to the bottom of the chest, enabling excess steam and condensate to be removed. This line led through a needle valve to two glass condensers connected in series with capacity to condense the full output of the supply line. Steam entered the funnel inside the chest, through eight one-quarter inch inlet tubes. These tubes were L-shaped and welded to the side of the funnel in such a way that the portions of the tube on either side of the funnel pointed down. This permitted steam to pass freely through the tube but prevented con-

Diagram No. 1
Steam Heated Hot Plate



densate from so doing. The chest, funnel, condensate pipe and valve were all well insulated with one inch magnesia block and rock wool insulation.

The temperature of the hot surface was measured by use of three No. 20 gage Iron-Constantan, fiberglass over asbestos thermocouples.(Diagram No. 2). These thermocouples were soldered in grooves which ran radially at 120 degrees toward the center of the plate. One thermocouple measured temperature at the center of the plate, the second measured it at a point one and three-quarters inches from the center and the third at a point three and one-half inches from the center. The centers of the hot junctions were approximately 0.05 inches below the surface of the plate. The thermocouple wire in the groove was covered with a strip of copper sheet, which was soldered to the plate. The iron lead wires were connected to a common ice bath cold junction, while the constantan lead wires were connected to individual throw type swithes.

Sand bed temperatures were also measured by No. 20 gage Iron-Constantan thermocouples. These thermocouples were mounted in a bridge, built of two parallel strips of micarta held together by two brass rods.(Diagram No. 3). The six thermocouples were arranged on the bridge in such a way that it was possible to measure temperatures throughout the bed. The hot junctions extended

Diagram No. 2
Top View - Drying Plate

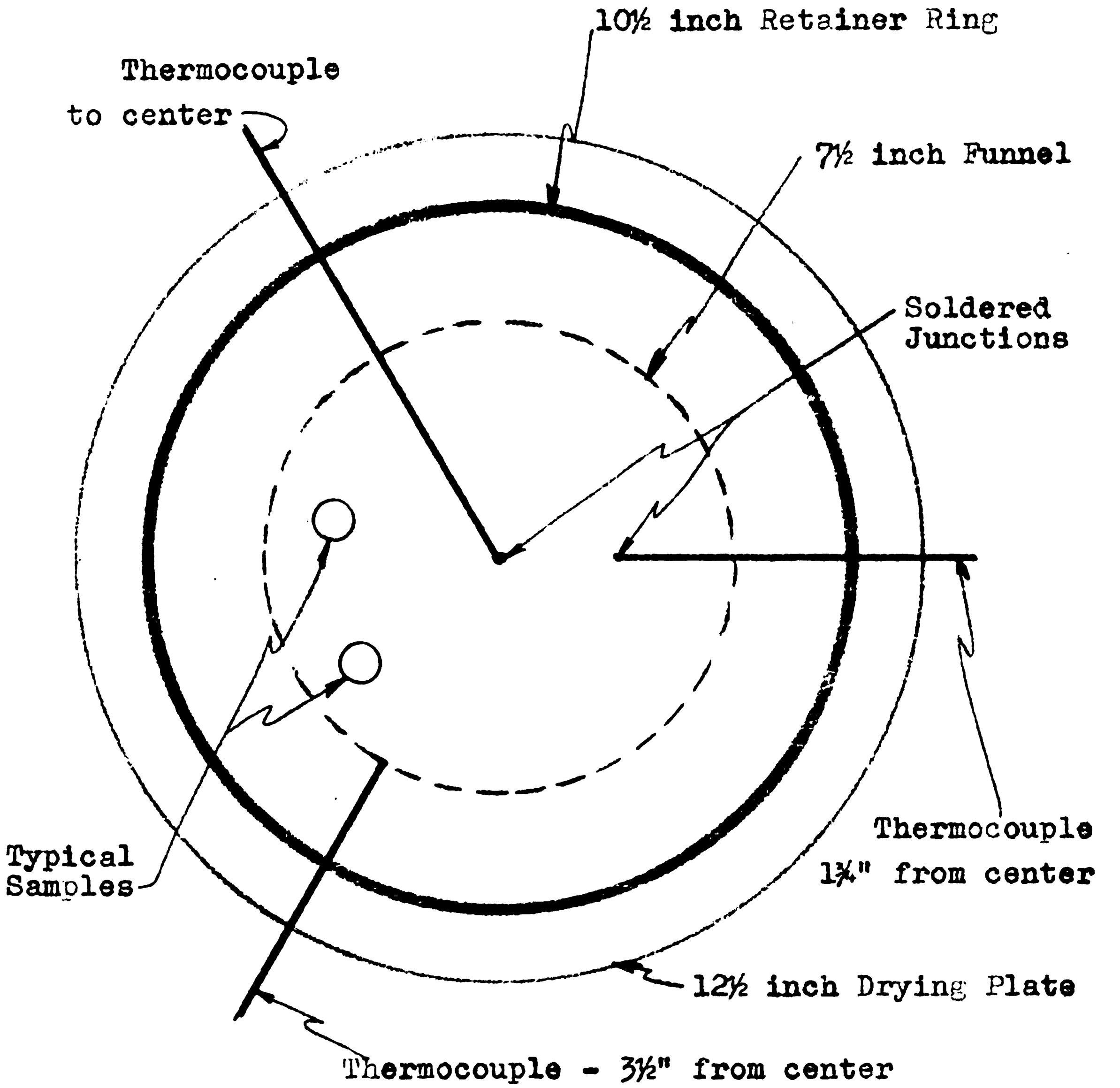
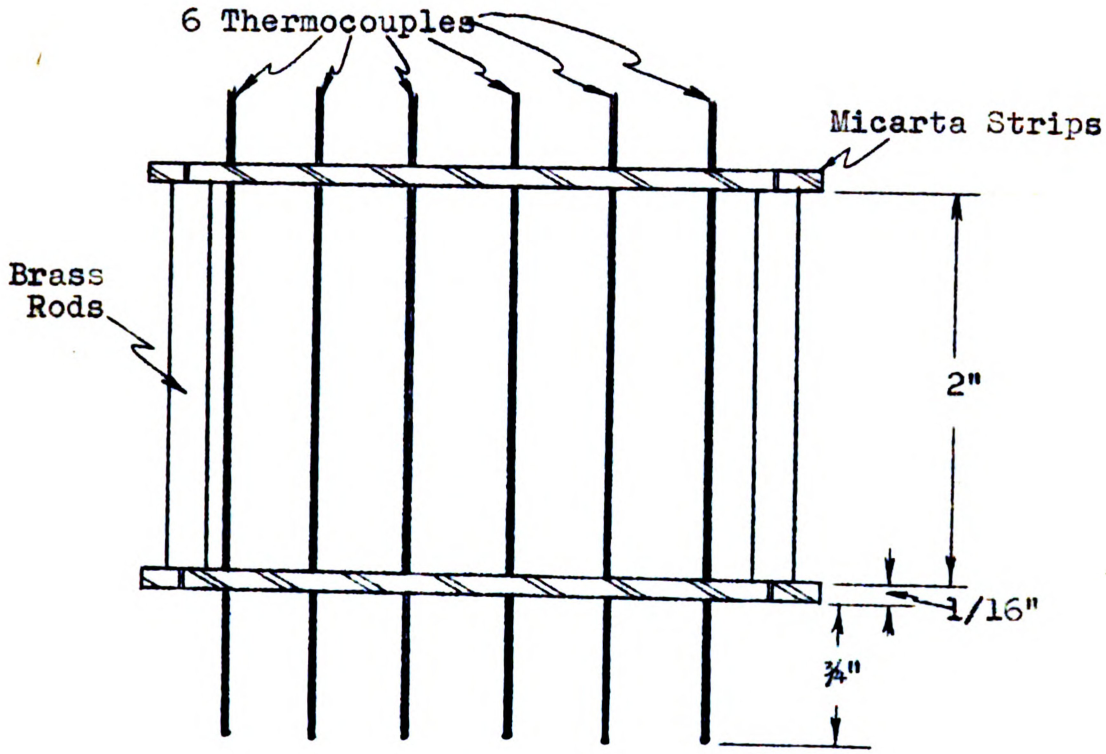
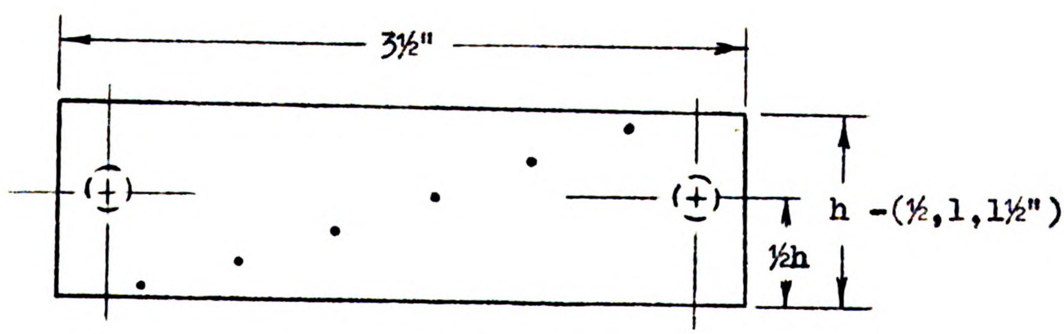


Diagram No. 3
Thermocouple Bridge



Top View



Front View

three-quarters of an inch beyond the micarta face into the sand and ran at the same level for approximately three inches. The e. m. f. generated was measured on a Leeds and Northrup Portable Precision Potentiometer.

Metal rings of 10½ inch diameter were used on the plate surface to hold the sand in place. Glass tubes of one and one-half centimeters in diameter were used as sample tubes during the drying rate runs. Layer samples were taken with iron tubes of 0.625 inches in diameter fitted with micarta liners or bushings 0.125 and 0.250 inches in height. The tubes and rings were of the height of the sand bed being investigated.

Procedure

Prior to each run the surface of the hot plate was cleaned with a course emery paper, followed by medium emery paper and finished with a fine emery paper; namely, 3-M emery paper of the wet-or-dry type, grit sizes 180, 280 and 400. The bottom of the retainer ring was also cleaned each time to assure a smooth fit on the plate.

The retainer ring was placed on the plate and the sampling tubes were placed inside the ring at least one and one-half inches from it and two inches between tubes. Dry Ottawa sand of 40-60 U.S. Standard mesh size with a density of 102.6 pounds per cubic foot was poured into the tubes and around them to the height of the ring.

The bed was leveled smooth with a straight edge to the height of the ring and tubes. Eight layers of cheese cloth was placed on the bed to prevent erosion when the bed was wetted.

All the air and the steam which had condensed in the chest and lines was removed by opening the inlet and blow down valves wide. After the pressure in the line had built up to 15 psig. again, the inlet valve was closed. The chest steam pressure was allowed to drop to three psig., at which time the blow down valve was closed. This allowed enough heat to remain in the bed and plate to heat the distilled water, from room temperature to approximately 190°F, after it was carefully poured on the cheese cloth. If this pressure were not allowed to drop, addition of the water would cause blow holes to form as a result of the sudden vaporization at the hot surface. The bed was fully saturated and after the excess water had drained off, the cheese cloth was removed.

The steam inlet and blow down valves were opened slightly. The steam inlet valve had to be opened very slowly and the temperature of the plate held at 212°F long enough to allow the water above approximately 20 per cent moisture content (#water/#dry Sand) to be vaporized. Otherwise the excessive vaporization would actually lift the sand bed in toto from the plate. It was necessary to puncture the thicker beds to allow this vapor to escape. After the excess water was removed in this manner, the inlet and blow down valves were manipulated until the desired surface temperature of 220°F was reached. A record of chest pressure and surface temperature was made. During the run, the inlet and blow down valves were regulated to hold the surface temperature constant.

After the surface temperature was constant, the accumulated condensate from the funnel was drained off and a timed run started. A sample tube was taken from the bed at the same time and immediately placed in a numbered glass weighing bottle and sealed. These samples were removed at periodic intervals by carefully extracting each sample with laboratory tongs.

The condensate from the funnel was also collected at the same time as the moisture samples were taken. This was done by inserting the tip of the pipe leading from the funnel into a graduated cylinder, quickly cracking the needle valve and collecting all the accumulated condensate. When steam started to come through, the valve was closed and the liquid level in the graduate read and recorded.

Layer moisture samples were taken during separate runs. The hot surface was prepared as before. The micarta bushings were fitted into the iron tubes and placed on the plate in the same manner as the glass tubes.

Sand was added, leveled with a straight edge and wetted as before. While the sand was drying, these units were removed at intervals with tongs. The micarta bushings were slipped from the iron tubes and separated into individual weighing bottles. Condensate samples were taken simultaneously.

Sand bed temperatures were also taken during separate runs. After the surface was cleaned, the micarta thermocouple bridge with the six thermocouples, was placed on the plate. All strain was removed from the thermocouple wires, so that the bridge would stay in place and level with the plate. The height between each thermocouple junction and the plate was measured and recorded. Several glass sampling tubes were placed on the plate also, keeping them at least two inches away from the thermocouple junctions. Sand was added as before, covering the tubes and thermocouples completely. The sand bed was leveled and water added as before.

After the plate temperature was brought up to 220°F again, a timed run was started. Sand bed temperatures and moisture samples were taken at timed intervals. No funnel condensate samples were taken because the temperatures for the runs were correlated by use of the moisture samples.

At the end of each run, the weighing bottles containing the moisture samples were weighed. They were placed in a constant temperature oven and dried for twenty four hours at 105°C. A check for dryness, revealed that the samples were completely dry after eight hours in the oven. After drying, the samples were weighed dry and tared.

Limitations of Equipment and Procedure

The biggest drawback in the use of micarta bushings to determine layer moistures, was the breaking down of the resin at the temperatures used in the study. This resin deposited a thin film on the hot surface and cut down heat transfer. The discrepancy caused by using these bushings, will be discussed in further detail under the section on Discussion of Results. In any future work, it might be advisable to use teflon or glass fiber reinforced epoxy tubing (if available in these small sizes). Also, it would be advisable to use brass tubes instead of iron, to reduce the corrosion of the tubes.

Some vaporization may have occurred between the time the samples were removed from the bed and before they were slipped into the individual weighing bottles. However, this delay was shortened by making the bushings fit very loosely into the tubes, enabling them to be slipped out very rapidly. Also, the top bushings were slipped out first, with the bushings closest to the hot surface being sealed in the weighing bottles first.

As the condensate from the funnel was collected, some vaporization of liquid may have occurred, due to the pressure drop through the valve. Also, some flash evaporation may have taken place because of the high temperatures of the condensate. Counterbalancing this may have been some condensation of steam at the end of the collection. All three errors were small. The collection was accomplished quickly and the liquid level read immediately.

From the behavior of the one inch bed on heat up; namely, rising from the plate, it is expected that the drying rates and heat transfer coefficients were lower than they probably would have been without the rising. This phenomenon might bear some future investigation.

No provision was made for removal of non-condensables from the steam. However, the continuous purging of the chest should have reduced this error. Condensate was removed from the steam in the line, preceding entry into the chest, with a trap. The design of the entry tubes into the funnel acted as a baffle in further removing any condensate before entry into the funnel.

Run #1 - ½ inch Bed

Time Min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Moisture: Height ins.	Layer Moisture: #Water / #Dry Sand
0	4.6	---	.1832	.0625	.1831
				.1875	.1895
				.375	.1902
2	4.4	17.2	.1342	.0625	.1318
				.1875	.1303
				.375	.1373
4	4.3	14.8	.1209	.0625	.1744
				.1875	.1156
				.375	.1127
6	4.3	8.4	.1155	.0625	.1245
				.1875	.1102
				.375	.1123
8	4.2	7.8	.0848	.0625	.0863
				.1875	.1192
				.375	.0754
10	4.2	5.6	.0714	.0625	.0918
				.1875	.0673
				.375	.0660
12	4.2	4.2	.0428	.0625	.0778
				.1875	.0436
				.375	.0271

Run #2 - ½ inch Bed

Time Min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Moisture: Height ins.	Layer Moisture: #Water / #Dry Sand
0	4.3	----	.1456	.0625	.1409
				.1875	.1443
				.375	.1433
3	4.2	26.2	.1044	.0625	.1033
				.1875	.1081
				.375	.1032
6	4.0	25.2	.0823	.0625	.0954
				.1875	.0818
				.375	.0763
9	3.8	13.8	.0576		

Run #3 - ½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
0	5.5	—	.1492	.0625	.1514
				.1875	.150
				.3125	.1568
				.4375	.1572
1	5.0	—	.1298	.0625	.1362
				.1875	.1366
				.3125	.1244
				.4375	.1225
2	5.0	—	.0774	.0625	.0834
				.1375	.0808
				.3125	.0738
				.4375	.0699
3	5.0	—	.0582	.0625	.0786
				.1875	.0654
				.375	.0472
4	4.5	34.0	.0527	.0625	.0598
				.1875	.0563
				.3125	.0463
				.4375	.0449
5	4.2		Sample lost		

Run #4 - ½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
0	6.0	—	.1093		
1	4.5	—	.0773		
2	4.2	18.5	.0331		
3	3.8	—	.0507	.0625	.0564
				.1375	.0611
				.375	.0443
4	3.7	8.3	.0188		
5	3.7	3.8	.0118		
6	3.7	3.6	.0393	.0625	.0404
				.1375	.0437
				.375	.0341

Run #5 - ½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.		Moisture #Water / #Dry Sand
0	4.4	----	.1302	.0625	----	.1430
				.1375	----	.1254
				.3125	----	.1222
				.4375	----	.1347
1	4.3	----	.1157	.0625	----	.1218
				.1375	----	.1145
				.3125	----	.1073
				.4375	----	.1185
2	4.2	21.2	.0918	.0625	----	.0444*
				.1875	----	.0977
				.375	----	.1055
3	4.0	----	.0978	.0625	----	.0825
				.1875	----	.1043
				.3125	----	.0947
				.4375	----	.1047
4	3.8	14.0	.0723	.0625	----	.0756
				.1875	----	.0674
				.375	----	.0733
5	3.8	----	.0442	.0625	----	.0526
				.1875	----	.0491
				.375	----	.0395
6	3.8	6.8	Sample lost - too dry.			

* Part of sample lost on plate.

Run #6 - ½ inch Bed

Time minutes	Pressure psig.	Condensate ml.	# Water Dry Sand
0	4.2	—	.1613
1	3.8	—	.1244
2	4.0	18.8	.1015
3	4.0	—	.0779
4	4.0	14.5	.0523
5	4.0	—	.0614
6	3.7	15.0	.0193
8	3.7	8.0	.0084

Run #7 - ½ inch Bed

Time minutes	Pressure psig.	Condensate ml.	# Water Dry Sand
0	4.7	—	.1372
1	4.5	—	.1123
2	4.0	18.8	.0731
3	3.7	—	.0626
4	3.5	16.5	.0313
5.	3.2	—	.0458
6	3.2	7.8	.0119
7	3.2	2.2	.0187

Run #8 - ½ inch Bed

Time minutes	Pressure psig.	Condensate ml.	#Water / #Dry Sand
0	4.0	----	.1502
1	3.8	9.8	.1247
2	3.8	7.4	.1068
3	3.8	4.5	.0705
4	3.8	3.8	.0641
5	3.8	3.4	.0434
6	3.8	3.0	.0327
7	3.8	3.4	.0353

Run #9 - ½ inch Bed

Time minutes	Pressure psig.	Condensate ml.	#Water / #Dry Sand
0	4.3	----	.1372
1	4.3	10.4	.1197
2	4.3	10.2	.0812
3	4.2	9.6	.0335
4	4.0	7.4	.0174
5	3.6	3.5	.0235
6	3.5	3.3	.0393
7	3.5	2.8	.0287

Run #10 - ½ inch Bed

Time min.	Pressure psig.	#Water / #Dry Sand	Temperature - °F: Height Above Plate - inches: 0.065"	0.16"	0.24"	0.31"	0.375"	0.44"
0	4.0	.1682	210	206	198	192	186	183
1	3.9	----	210	207	200	194	188	183
2	3.8	.1338						
3	3.7	.0878	210	207	195	182	171	166
5	3.6	----	208	189	175	169	163	160
6	3.6	.0606	194	180	170	165	162	157
8	3.5	.0549	180	169	162	161	159	153
10	3.5	.0395	172	164	159	158	155	149
11	3.5	.0211	169	162	158	157	155	149
14	3.5	.0190	166	160	157	156	153	148

Run #11 - ½ inch Bed

Time min.	Pressure psig.	#Water / #Dry Sand	Temperature - °F, Height Above Plate - inches: 0.065"	0.16"	0.24"	0.31"	0.375"	0.44"
0	4.5	.1021	210	210	210	205	200	188
2	4.5	.1048	210	210	210	204	199	192
4	4.4	.0687	210	210	205	193	184	173
6	4.2	----	204	183	173	166	159	156
8	4.0	----	183	170	166	160	158	152
9	4.0	.0315						
10	4.0	.0270	172	165	161	157	155	152
12	4.0	.0085	168	162	159	155	152	148
Run #12 - ½ inch Bed								
0	3.8	.1460	210	210	209	208	202	191
2	3.7	.0791	210	210	206	204	195	187
5	3.7	.0966 Layer	200	190	180	173	170	166
7	3.6	----	176	171	165	162	158	156

Run #13 - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
0	4.6	———	.1397		
2	4.5	18.5	.1215		
4	4.4	16.6	.1192	.0625 ———	.1252
				.1875 ———	.1082
				.375 ———	.11[illegible]7
				.625 ———	.1003
				.875 ———	.14[illegible]1
6	4.1	13.5	.0647		
8	3.9	11.0	.1258	.0625 ———	.1240
				.1875 ———	.1198
				.375 ———	.1313
				.625 ———	.1162
				.875 ———	.13[illegible]0
10	3.8	7.6	.0551		
12	3.7	5.8	.0352		
14	3.7	4.8	.0685	.0625 ———	.0643
				.1875 ———	.0673
				.375 ———	.0609
				.625 ———	.0683
				.875 ———	.0791
16	3.7	4.8	.0208 *		
18	3.7	4.4	.0231		
20	3.7	4.6	.0201		
22	3.7	4.2	.0687	.0625 ———	.0754
				.1875 ———	.0[illegible]16
				.375 ———	.0581
				.625 ———	.0570
				.875 ———	.1030

* Part of sample lost in transfer.

Run #14 - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	Water #Dry Sand	Layer Height in.	Layer moisture Water #Dry Sd
0	6.0	———	.1172		
3	5.2	22.8	.1004	.0625	.0732
				.3125	.1072
				.625	.0918
				.875	.1205
6	5.0	22.4	.1002		
9	4.7	20.2	.0792	.0625	.0387*
				.1875	.0823
				.375	.0802
				.625	.0879
				.875	.0897
12	3.8	13.8	.0391	.0625	.0774
				.1875	.0877
				.375	.0928
				.625	.0858
				.875	.0961
15	3.6	10.5	.0586	.0625	.0823
				.1875	.0464
				.375	.0693
				.625	.0544
				.875	.0555
18	3.5	7.4	.0551	.0625	.0491
				.1875	.0529
				.375	.0616
				.625	.0589
				.875	.0502
20	3.5	4.7	.0513	.0625	.0175*
				.1875	.0791
				.375	.0569
				.625	.0491
				.875	.0523
22	3.5	4.3	.0533	.0625	.1132
				.1875	.0566
				.375	.0491
				.625	.0453
				.875	. 0525

* Parts of sample lost.

Run #14 (cont.) - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	# Water / # Dry Sand	Layer Height in.	Layer Moisture # Water / # Dry Sand
24	3.5	----	.0594	.0625 --	.0344
				.1875 --	.0735
				.375 --	.0616
				.625 --	.0745
				.875 --	.0436
25	3.5	4.5	.0213		

Run #15 - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	# Water / # Dry Sand	Layer Height in.	Layer Moisture # Water / # Dry Sand
0	4.5	----	.2118	.0625 --	.18[illegible]0
				.1375 --	.211
				.375 --	.207
				.625 --	.219
				.875 --	.219
4	3.6	32.5	.203	.0625 --	.1615
				.1875 --	.1632
				.375 --	.197
				.625 --	.217
				.875 --	.203
8	3.4	28.6	.143		
12	3.3	27.4	.1152		
16	3.6	24.8	.1478	.0625 --	.1502
				.1875 --	.1437
				.375 --	.1521
				.625 --	.1618
				.875 --	.1418
20	3.6	17.0	.1257	.0625 --	.1220
				.1875 --	.1178
				.375 --	.1332
				.625 --	.1292
				.875 --	.1173

Run #15 (cont.) - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	% Water / Dry Sand	Layer Height in.		Moisture % Water / Dry Sand
24	3.6	10.8	.0965	.0625	—	.1004
				.1875	—	.0957
				.375	—	.1050
				.625	—	.1008
				.875	—	.0764
28	3.6	6.8	.0346			
32	3.5	6.8	.1024	.0625	—	.1242
				.1875	—	.1177
				.375	—	.0963
				.625	—	.0964
				.8125	—	.0976
				.9375	—	.0952
36	3.5	6.4	.0331	.0625	—	.0913
				.1875	—	.0953
				.375	—	.0837
				.625	—	.0788
				.875	—	.0597
40	3.5	4.8	.0263			

Run #16 - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	% Water / Dry Sand	Layer Height in.		Moisture % Water / Dry Sand
0	4.6	——	.1807			
3	4.3	17.0	.1648	.0625	—	.1462
				.1875	—	.1542
				.375	—	.1553
				.625	—	.1692
				.875	—	.1691
6	4.2	16.5	.1436			
9	4.1	18.5	.1532	.0625	—	.1374
				.1875	—	.1540
				.375	—	.1546
				.625	—	.1511
				.875.	—	.1535

Run #16 (cont.) - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.		Moisture #Water / #Dry Sand
12	3.9	14.5	.1042			
15	3.9	16.5	.1492	.0625	—	.1328
				.1875	—	.1586
				.375	—	.1712
				.625	—	.1444
				.8125	—	.1463
				.9375	—	.1322
18	3.9	14.2	.1032	.125	—	.1252
				.375	—	.1110
				.625	—	.0885
				.875	—	.0917
21	3.8	8.2	.0758	.0625	—	.0973
				.1875	—	.0827
				.375	—	.0820
				.625	—	.0599
				.875	—	.0761
24	3.6	8.5	.0588	.125	—	.0661
				.375	—	.0644
				.625	—	.0592
				.875	—	.0487
27	3.6	7.4	.0652	.125	—	.0721
				.375	—	.0682
				.625	—	.0592
				.875	—	.0612
30	3.5	6.8	.0643	.125	—	.0639
				.375	—	.0835
				.625	—	.0633
				.875	—	.0464
33	3.5	7.4	.0612	.125	—	.0625
				.375	—	.0670
				.625	—	.0667
				.875	—	.0498
36	3.5	6.4	.0141			

Run #17 - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	%Water Dry Sand	Layer Height in.	Moisture %Water Dry Sand
0	4.2	---	.2390		
4	4.0	28.0	.2210	.0625	.1728
				.1875	.2090
				.375	.1333
				.625	.2210
				.875	.2710
8	4.0	27.2	.1756		
12	4.0	29.4	.1552	.0625	.1314
				.1875	.1680
				.375	.1462
				.625	.1385
				.8125	.1395
				.9375	.1468
16	4.0	25.2	.0989		
20	3.8	15.4	.1458	.0625	.1143
				.1875	.1312
				.375	.1448
				.625	.1462
				.875	.1716
24	3.7	15.6	.0767		
28	3.7	10.0	.1326	.0625	.1298
				.1875	.1564
				.375	.1556
				.625	.1422
				.875	.1326
32	3.7	8.6	.0371		
36	3.7	7.0	.1005	.0625	.1051
				.1875	.1083
				.375	.1031
				.625	.0999
				.875	.0923
40	3.5	6.3	.0077*		

* Part of sample lost.

Run #18 - 1 inch Bed

Time minutes	Pressure psig.	Condensate ml.	#Water / #Dry Sand
0	4.2	---	.1470
2	4.2	17.0	.1292
4	4.2	19.3	.0998
6	4.0	14.5	.0744
8	3.9	13.2	.0830
10	3.9	10.8	.0594
12	3.8	6.5	.0317
14	3.8	5.4	.0479
16	3.8	5.0	.0331
18	3.7	4.8	.0234
20	3.7	5.0	.0109
22	3.7	3.8	.0082

Run #19 - 1 inch Bed

Time minutes	Pressure psig.	Condensate ml.	#Water / #Dry Sand
0	4.5	---	.1612
3	3.6	18.5	.1925*
6	3.4	17.5	.1533
9	3.4	15.4	.1065
12	3.4	14.8	.1277
15	3.5	15.5	---*

*Note: These samples developed blow holes during heat up and are discarded.

Run #19 (cont.) - 1 inch Bed

Time minutes	Pressure psig.	Condensate ml.	Water [illegible]
18	3.3	10.8	.0821
21	3.2	7.8	.0711
24	3.2	7.4	.0614
27	3.2	6.8	.0501
30	3.1	7.3	.0523

Run #20 - 1 inch Bed (Silicone treated tubes)

0	4.3	—	.1812
3	4.0	19.7	.1622*
6	3.9	13.0	.1276
9	3.8	16.4	.1152*
12	3.6	18.1	.0857
15	3.6	12.8	.0823*
18	3.5	7.9	.0887
21	3.5	8.0	.0730*
24	3.5	7.2	.0535
27	3.5	6.4	.0518*
30	3.5	5.0	.0537
33	3.5	7.6	.0437*
36	3.5	5.9	.0354
39	3.4	5.4	.0302*
42	3.4	4.8	.0156

*Sample tubes treated with silicone grease.

Run #21 - 1 inch Bed

Time min.	Pressure psig.	Condensate ml.	Water [illegible]
0	5.5	---	.2040
3	4.4	10.8	.1715
6	4.0	8.6	.1313
9	3.9	7.3	.1145
12	3.9	5.5	.1[illegible]1[illegible]
15	3.9	5.8	.0942
18	3.5	4.5	.1030
21	3.5	4.5	.1035
24	3.5	4.2	.0843
27	3.5	5.4	.0749
30	3.5	5.8	.0521
33	3.5	6.6	.0484
36	3.5	5.8	.06[illegible]
39	3.5	6.9	.0245
42	3.5	5.5	.0214

Note: On heat up of the bed, the entire bed raised from the hot surface about an one quarter inch. The samples seemed to be riding on a cushion of vapor as each tube would settle a fraction of an inch when the tongs were put on to remove the sample. This run is typical of the runs which were discarded for this reason.

Run #22 - 1 inch Bed

Temperature - ^{o}F

Time min.	Pressure psig.	#Water / #Dry Sand	Height Above Plate - inches 0.067"	0.16"	0.31"	0.50"	0.66"	0.91"
0	4.4	.2270	210	206	198	189	173	159
2	3.8	.----	210	209	205	196	180	165
4	3.8	.1578	210	210	205	198	184	168
6	3.8	.----	210	210	206	198	184	168
8	3.6	.0792	210	209	203	195	183	168
10	3.4	----	210	208	203	195	183	169
12	3.4	.1182	210	208	202	194	183	167
14	3.4	----	210	209	203	194	182	167
16	3.3	.0882	210	208	198	187	176	163
18	3.3	----	210	206	193	183	170	158
20	3.3	.0542	209	199	188	177	162	154
22	3.3	----	204	194	185	175	162	154
24	3.2	.0464	198	190	182	173	160	152
30	3.2	----	180	177	170	164	154	144

Run #23 - 1 inch Bed

Time min.	Pressure psig.	#Water / #Dry Sand	Temperature - °F Height Above Plate - inches 0.067"	0.16"	0.31"	0.50"	0.66"	0.91"
0	3.8	.1642	210	209	206	195	179	166
2	3.8	----	210	210	207	196	179	166
4	3.7	.1355	210	210	207	195	178	165
6	3.7	----	210	210	207	195	178	165
8	3.6	.0917	210	209	203	195	178	165
10	3.6	----	210	206	199	188	175	163
12	3.6	----	207	201	193	183	172	160
14	3.5	.0873	200	195	188	179	167	156
16	3.5	.0554	196	190	184	175	164	154
18	3.5	.0493	193	187	181	172	162	152
20	3.5	.0424	190	185	179	170	159	151
24	3.5	.0370	188	183	177	169	158	149

Run #24 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	# Water lb./lb. [illegible]	Layer Height in.		Moisture Water lb./lb. [illegible]
0	5.5	———	.2130	.0625	—	.1002
				.1875	—	.1965
				.375	—	.2150
				.625	—	.2330
				.875	—	.2250
				1.125	—	.2090
				1.375	—	.2050
3	4.0	17.2	.1685			
6	4.0	18.4	.1802			
9	4.0	18.8	.1238			
12	4.0	17.9	.1408	.0625	—	.1072
				.1875	—	.1157
				.375	—	.1273
				.625	—	.1637
				.875	—	.1457
				1.125	—	.1510
				1.375	—	.1503
15	3.9	18.0	.1123			
18	3.7	17.0	.1271	.125	—	.1317
				.375	—	.1268
				.625	—	.1265
				.875	—	.1303
				1.125	—	.1143
				1.375	—	.1348
21	3.7	16.2	.0870			
24	3.6	15.3	.0707			
27	3.6	15.0	.0494			
30	3.5	11.[illegible]	.0533			
33	3.3	7.4	.0342			

Run #25 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.		Moisture #Water / #Dry Sand
0	4.8	----	.1960	.0625	--	.1836
				.1375	--	.1935
				.375	--	.1952
				.625	--	.2170
				.875	--	.1965
				1.125	--	.1996
				1.3125	--	.1946
				1.4375	--	.1746
5	4.5	44.5	.1605	.0625	--	.1408
				.1375	--	.1504
				.375	--	.1703
				.625	--	.1575
				1.000	--	.1763
				1.3125	--	.1373
				1.4375	--	.1532
10	4.4	26.2	.1357	.0625	--	.1181
				.1375	--	.1212
				.375	--	.1292
				.625	--	.1465
				.875	--	.1353
				1.125	--	.1538
				1.375	--	.1237
15	4.3	29.7	.1360	.0625	--	.1258
				.1375	--	.1150
				.375	--	.1392
				.625	--	.1580
				.875	--	.1492
				1.125	--	.1490
				1.375	--	.1366
20	4.3	31.0	.1243	.0625	--	.1013
				.1375	--	.1360
				.500	--	.1336
				.875	--	.1195
				1.125	--	.1111
				1.375	--	.1092
25	4.3	34.8	.1175	.0625	--	.0965
				.1875	--	.1066
				.375	--	.1162
				.625	--	.1257
				.875	--	.1216
				1.125	--	.1187
				1.375	--	.1213

Run #25 (cont.) - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.		Moisture #Water / #Dry Sand
30	3.5	23.2	.0880	.0625	--	.1030
				.1875	--	.0870
				.500	--	.0869
				.750	--	.0834
				1.000	--	.0817
				1.250	--	.0772
				1.4375	--	.0863
35	3.2	12.2	.0840	.125	--	.0894
				.375	--	.0882
				.625	--	.0850
				.875	--	.0849
				1.125	--	.0757
				1.3125	--	.0743
				1.4375	--	.0877

Run #26 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.		Moisture #Water / #Dry Sand
0	7.5	-----	.2230	.0625	--	.2160
				.250	--	.2140
				.500	--	.2255
				.750	--	.235
				1.000-	--	.2110
				1.250	--	.2230
				1.4375	--	.2170
4	7.2	69.4	.1720	.0625	--	.1775
				.1875	--	.1732
				.375	--	.1721
				.625	--	.1570
				.875	--	.1671
				1.125	--	.1723
				1.3125	--	.1717
				1.4375	--	.1733
8	6.0	44.6	.1278	.0625	--	.1126
				.1875	--	.1162
				.375	--	.1441
				.625	--	.1401
				.875	--	.1443
				1.125	--	.1255
				1.375	--	.1262

Run #26 (cont.) - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
12	5.7	40.2	.1073	.0625	.1155
				.1875	.1000
				.375	.1092
				.625	.1063
				.875	.1101
				1.125	.1123
				1.375	.1402
16	5.0	29.2	.1046	.0625	.1061
				.1875	.1051
				.375	.1158
				.625	.1141
				.875	.1052
				1.125	.0916
				1.3125	.1028
				1.4375	.0923
20	5.0	14.8	.0733	.1875	.0787
				.500	.0793
				.750	.0696
				1.000	.0586
				1.250	.0764
				1.4375	.0638
24	4.5	10.0	.0706	.125	.0897
				.750	.0624
				1.375	.0818
28	4.0	6.8	.0645	.125	.0720
				.375	.0598
				.625	.0731
				.875	.0543
				1.125	.0672
				1.3125	.0610
				1.4375	.0548

Run #27 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
0	9.0	----	.290	.125	.310
				.375	.253
				.625	.245
				.875	.229
				1.125	.170
				1.375	.221
				1.4375	.221

Run 27 (cont.) - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	Water lb./pound	Layer Height in.		Moisture lb. per pound
5	8.0	77.3	.1400	.0625	--	.1528
				.250	--	.1547
				.500	--	.1459
				.750	--	.1519
				1.000	--	.1516
				1.250	--	.1194
				1.4375	--	.1085
10	6.0	34.2	.160	.250	--	.1674
				.625	--	.1492
				.875	--	.1[illegible]18
				1.125	--	.1494
				1.375	--	.1662
15	5.0	29.5	.092	.0625	--	.0908
				.1875	--	.0774
				.375	--	.10[illegible]3
				.625	--	.0966
				.875	--	.0993
				1.125	--	.0762
				1.375	--	.0978
20	4.5	14.5	.1005	.0625	--	.1232
				.1875	--	.0[illegible]68
				.375	--	.0973
				.625	--	.0972
				.875	--	.1048
				1.125	--	.0959
				1.3125	--	.1043
				1.4375	--	.0960
25	3.8	7.3	.0668	.1875	--	.0[illegible]44
				.500	--	.092
				.750	--	.0594
				1.000	--	.0476
				1.3125	--	.0[illegible]48
30	3.6	5.2	.0622	.125	--	.0555
				.750	--	.0517
				1.375	--	.0908
35	3.5	6.8	.0565	Layers stuck Together		

Run #28 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	Water / Dry Sand	Layer Height in.		Moisture Water / Dry Sand
0	4.4	----	.2150	.125	--	.2090
				.375	--	.2100
				.625	--	.2140
				.875	--	.2240
				1.125	--	.2190
				1.375	--	.2030
4	4.3	41.2	.1920			
8	4.0	34.8	.2130	.0625	--	.1945
				.1375	--	.207
				.375	--	.219
				.625	--	.210
				.875	--	.223
				1.125	--	.222
				1.375	--	.218
12	3.5	28.0	.1140	.		
16	3.2	27.4	.1638	.0625	--	.1710
				.1375	--	.1724
				.375	--	.1800
				.625	--	.1692
				.875	--	.1516
				1.125	--	.1450
				1.375	--	.1425
20	3.2	21.8	.0887			
24	3.1	24.5	.0626			
28	2.8	13.2	.0544			
32	2.7	12.0	.0634			
36	2.7	9.2	.0923	.0625	--	[illegible]
				.1375	--	.0913
				.375	--	.1193
				.625	--	.0964
				.875	--	[illegible]
				1.125	--	.0910
				1.375	--	.0748
40	2.6	6.7	.0381			

Run #28 (cont.) - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
44	2.6	6.4	.0358		
48	2.6	5.8	.0281		

Run #29 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	#Water / #Dry Sand	Layer Height in.	Moisture #Water / #Dry Sand
0	6.5	----	.1902	.125	-- .209
				.375	-- .1028
				.625	-- .1044
				.875	-- .1343
				1.125	-- .1335
				1.375	-- .1952
3	5.5	25.4	.1550		
6	5.4	20.8	.1493		
9	5.4	19.7	.1455		
12	5.4	17.4	.1275		
15	4.7	16.5	.1440	.125	-- .1368
				.375	-- .1485
				.625	-- .1408
				.875	-- .1393
				1.125	-- .1472
				1.375	-- .1527
18	4.7	15.2	.0658		
21	4.2	10.5	.0955	.0625	-- .1102
				.1875	-- .0751
				.375	-- .0771
				.625	-- .1033
				.875	-- .0853
				1.125	-- .0755
				1.375	-- .0837
24	3.8	8.6	.0350		
27	3.8	7.8	.0266		
30	3.8	6.5	.0383		

Run #30 - 1½ inch Bed

Time min.	Pressure psig.	Condensate ml.	Water [illegible]
0	7.0	----	.2150
4	4.6	26.8	------
8	4.1	20.5	.1518
12	4.0	23.0	------
16	4.0	22.7	.1118
20	3.8	24.8	.0826
24	3.8	23.4	.1008
28	3.6	20.5	------
32	3.6	15.5	.0466
36	3.5	12.0	.0446
40	3.5	10.4	.0303
44	3.4	8.3	.0301
48	3.4	8.3	.032[illegible]
52	3.4	8.5	.0229

Run #31 - 1½ inch Bed

Time min.	Pressure psig.	#Water / #Dry Sand	Temperature - °F Height Above Plate - inches 0.09"	0.34"	0.59"	0.84"	1.11"	1.40"
0	5.0	.2040	210	208	205	182	165	148
3	4.4	----	210	210	206	185	169	152
7	4.2	.2020	210	210	209	190	174	153
9	4.0	----	210	210	208	191	174	154
12	4.0	.1492	210	210	205	189	173	153
15	4.0	----	210	210	206	189	172	153
18	4.0	.1182	210	210	205	190	174	153
21	3.9	----	210	210	204	190	174	155
24	3.9	.1131	210	210	205	191	175	157
27	3.7	----	210	210	203	191	176	158
30	3.7	.0952	210	210	204	193	178	159
33	3.7	----	210	210	204	193	178	160
36	3.7	.0631	210	210	204	191	178	158
39	3.7	----	210	208	200	190	176	158
42	3.7	----	210	207	199	190	176	157
45	3.7	----	209	205	197	187	174	155
48	3.7	.0520	200	194	187	178	167	152

Run #32 - 1½inch Bed

Time min.	Pressure psig.	#Water / #Dry Sand	Temperature - °F, Height Above Plate - inches: 0.09"	0.34"	0.59"	0.84"	1.11"	1.40"
0	4.4	.2190	210	200	178	161	147	137
3	4.3	----	210	203	186	169	155	143
6	4.2	----	210	205	191	178	166	151
9	4.1	.1714	210	207	198	185	173	156
12	4.0	----	210	209	200	188	175	157
15	4.0	----	210	209	200	188	176	157
18	3.9	.1266	210	208	199	188	176	157
21	3.8	----	210	208	200	189	177	157
24	3.7	----	210	207	200	190	178	159
27	3.6	.0854	210	208	200	190	178	160
30	3.6	----	210	208	200	190	178	161
33	3.5	----	210	208	200	191	178	161
36	3.5	----	210	205	196	187	174	157
38	3.5	----	206	196	186	178	168	154
42	3.5	----	193	184	178	169	159	148
45	3.5	----	185	177	170	161	150	141
48	3.5	----	178	169	165	156	146	136

PRESENTATION OF DATA

PRESENTATION OF DATA

Four to six runs with glass tubes for moisture samples, were used to determine drying rates for each bed thickness. Each run was plotted on a moisture-time graph. The slope of the constant rate period was determined by the method of least squares. Plots for each bed thickness were correlated to obtain similar moisture content at zero time. The correlated data was plotted on a composite moisture-time graph for each thickness (Graphs No. 1, 2 and 3). The method of least squares was again used to determine the slope of the constant rate period. The curved portion of each plot was drawn in such a way as to represent the average of the points. Drying rates for each bed were calculated from these graphs, using the slope or $dw/d\theta$ to represent the rate, at any instant. The rates were plotted against moisture content on graph No. 4.

Heat transfer coefficients were calculated from the amount of steam condensed and were plotted against average moisture content for each bed (Graphs No. 5A, 5B and 6A). A smooth curve was drawn through the points with a straight line to represent the average of the points during the period of constant hot surface moisture content.

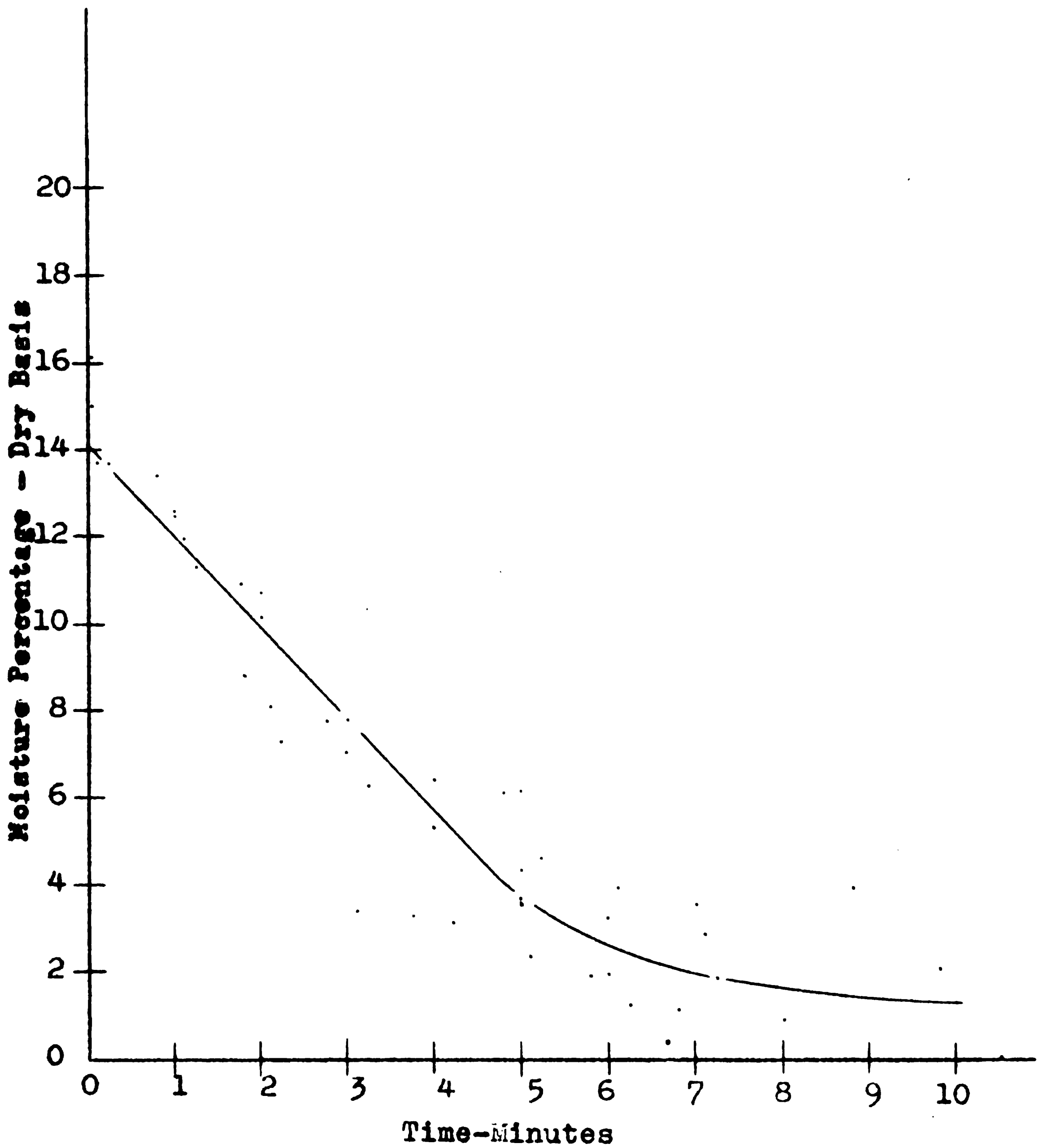
Four to six other runs with iron-micarta sample units were used for each bed thickness to determine layer moistures. This data was grouped for each bed, in such a way that samples of similar composite moisture content were averaged in two per cent moisture intervals. (For example: all samples between 14 and 16 per cent were grouped in one interval). These groups were all plotted on individual layer moisture content-height above plate graphs. A smooth curve was drawn through the points. This was repeated for each group and the smoothed curves plotted on a composite layer moisture-height above plate graph (Graphs No. 7, 8 and 9). The moisture content of the layer closest to the surface and the moisture content of the layer of maximum moisture were plotted against composite moisture for each bed (Graphs No. 10, 11 and 12).

Heat transfer coefficients were plotted against hot surface moisture contents (Graph No. 6B). These values were taken at the same average moisture contents.

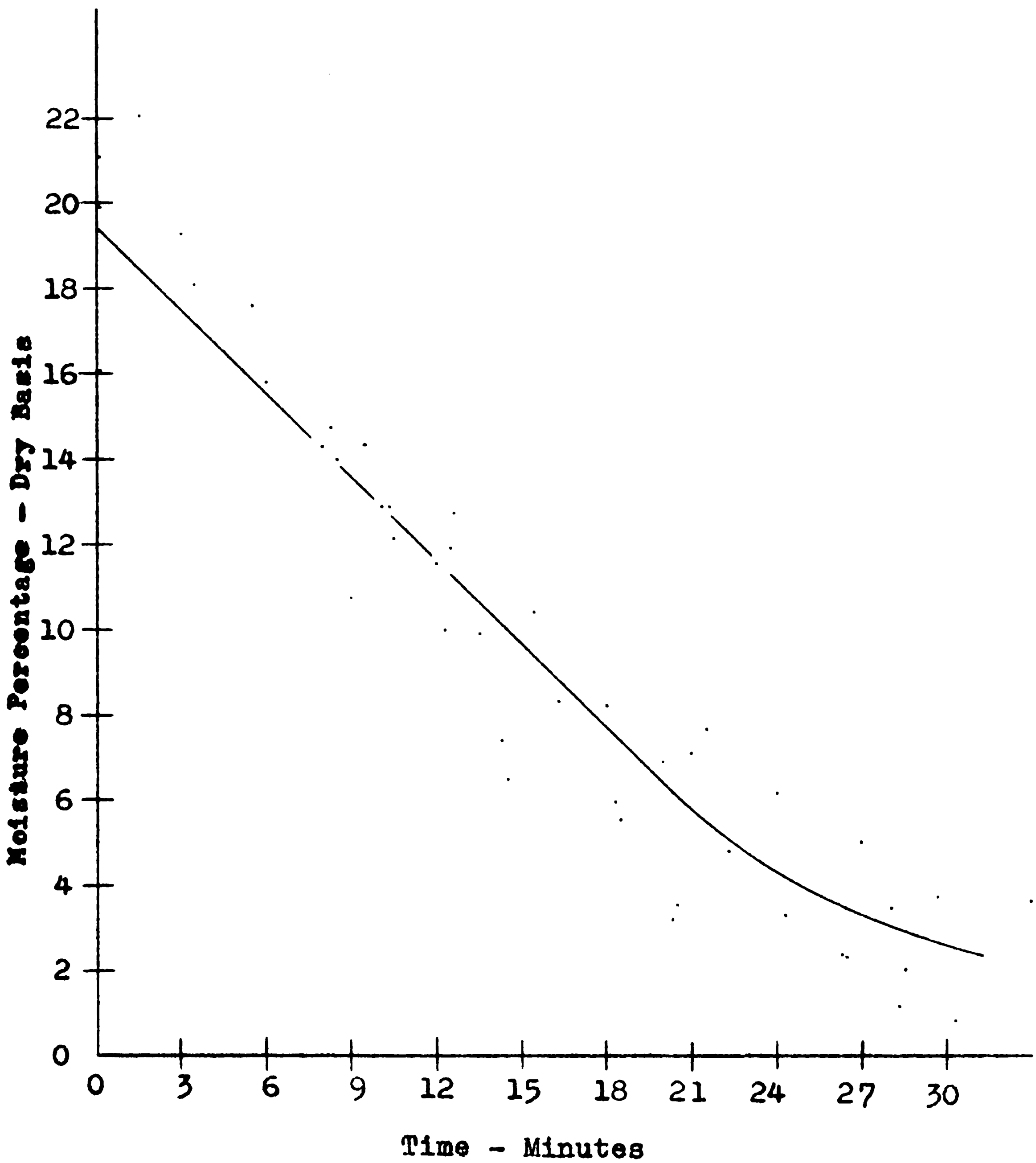
Two to four tests were made to determine temperature distribution within the beds. Temperatures were plotted against height above the plate at various moisture contents (Graphs No. 13, 14 and 15).

A special plot showing the difference in drying times between the iron-micarta units and the glass units was shown by graph No. 16.

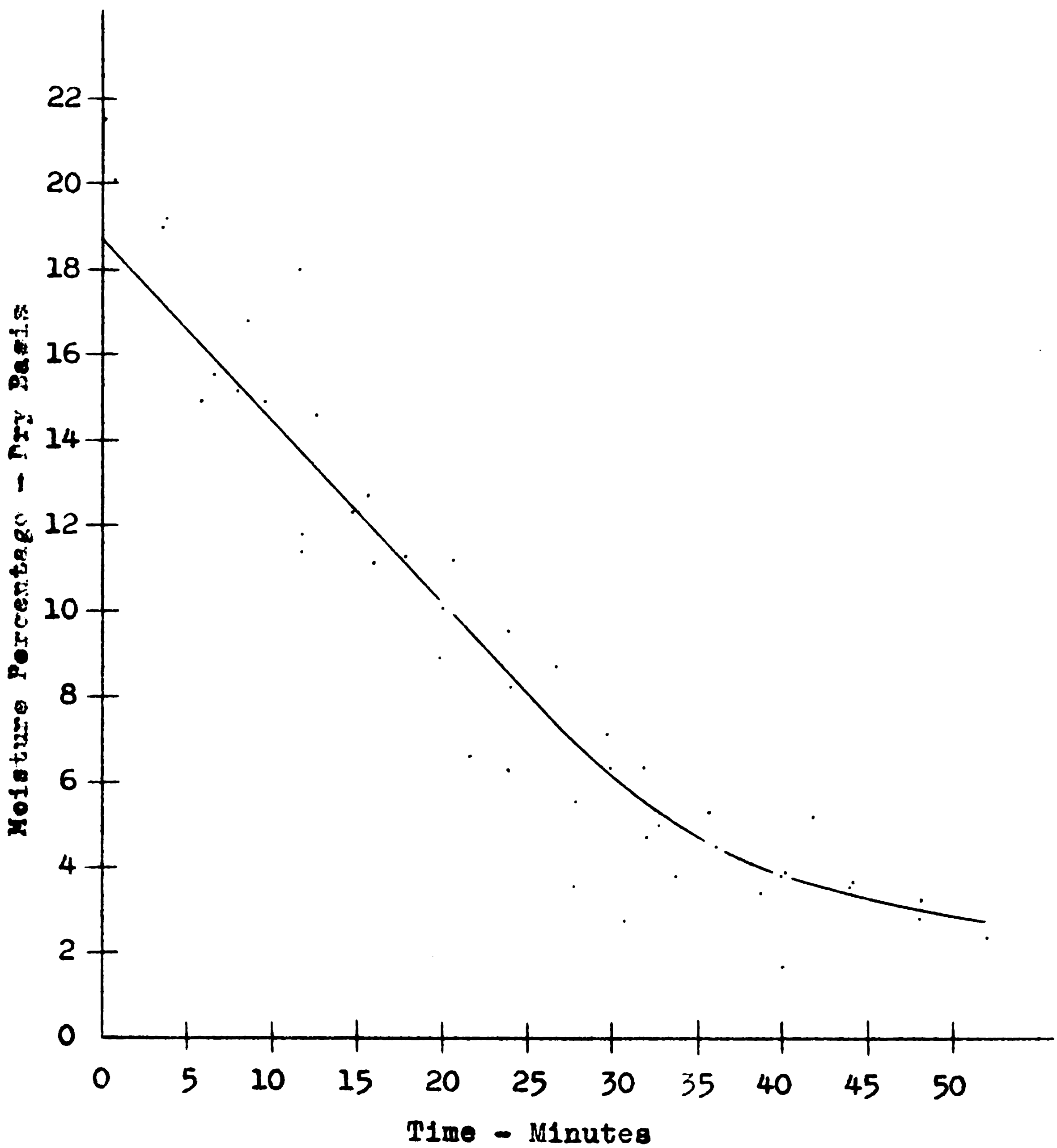
Graph No. 1
Moisture Content vs. Time
½ inch Sand Bed



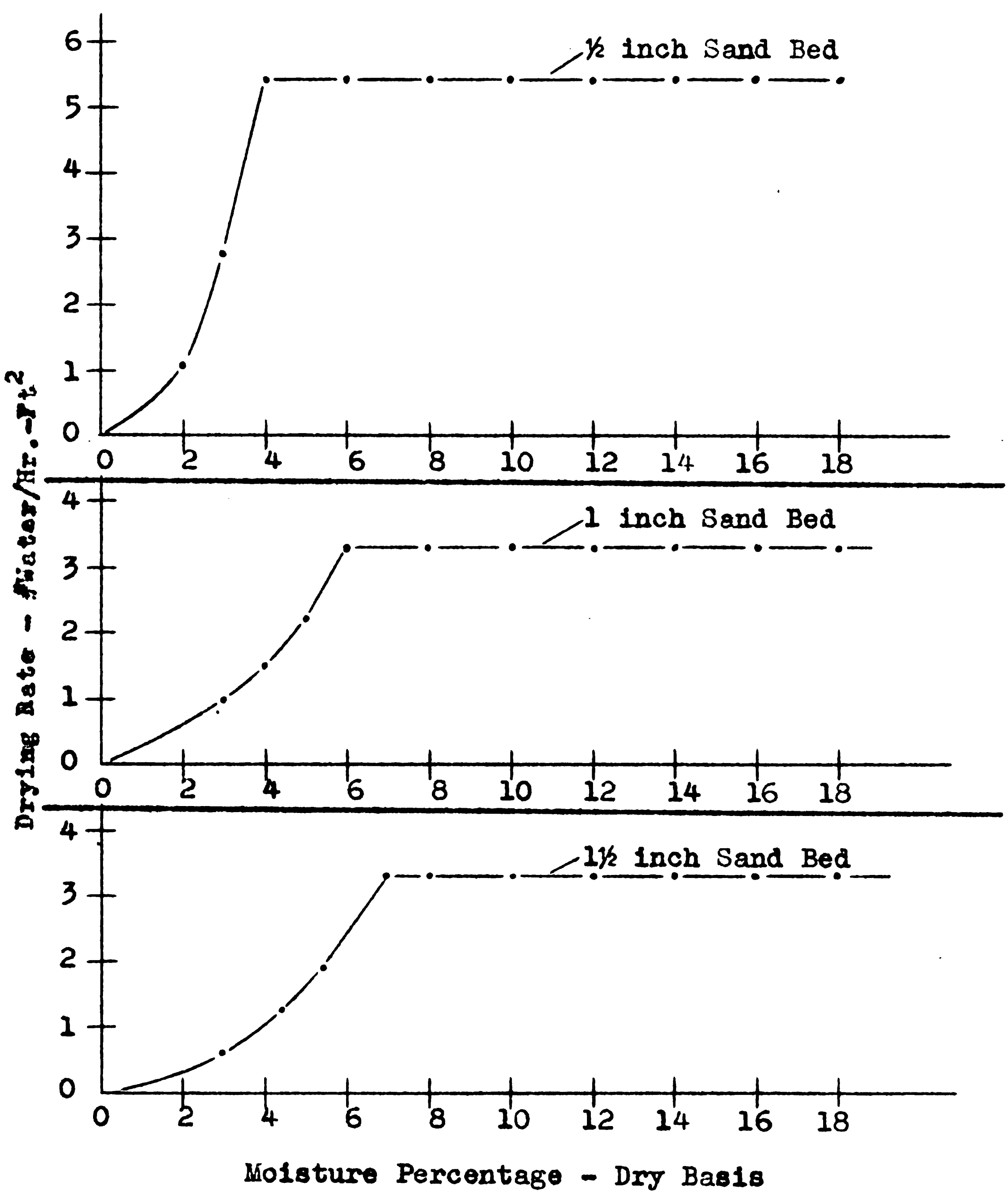
Graph No. 2
Moisture Content vs. Time
1 inch Sand Bed



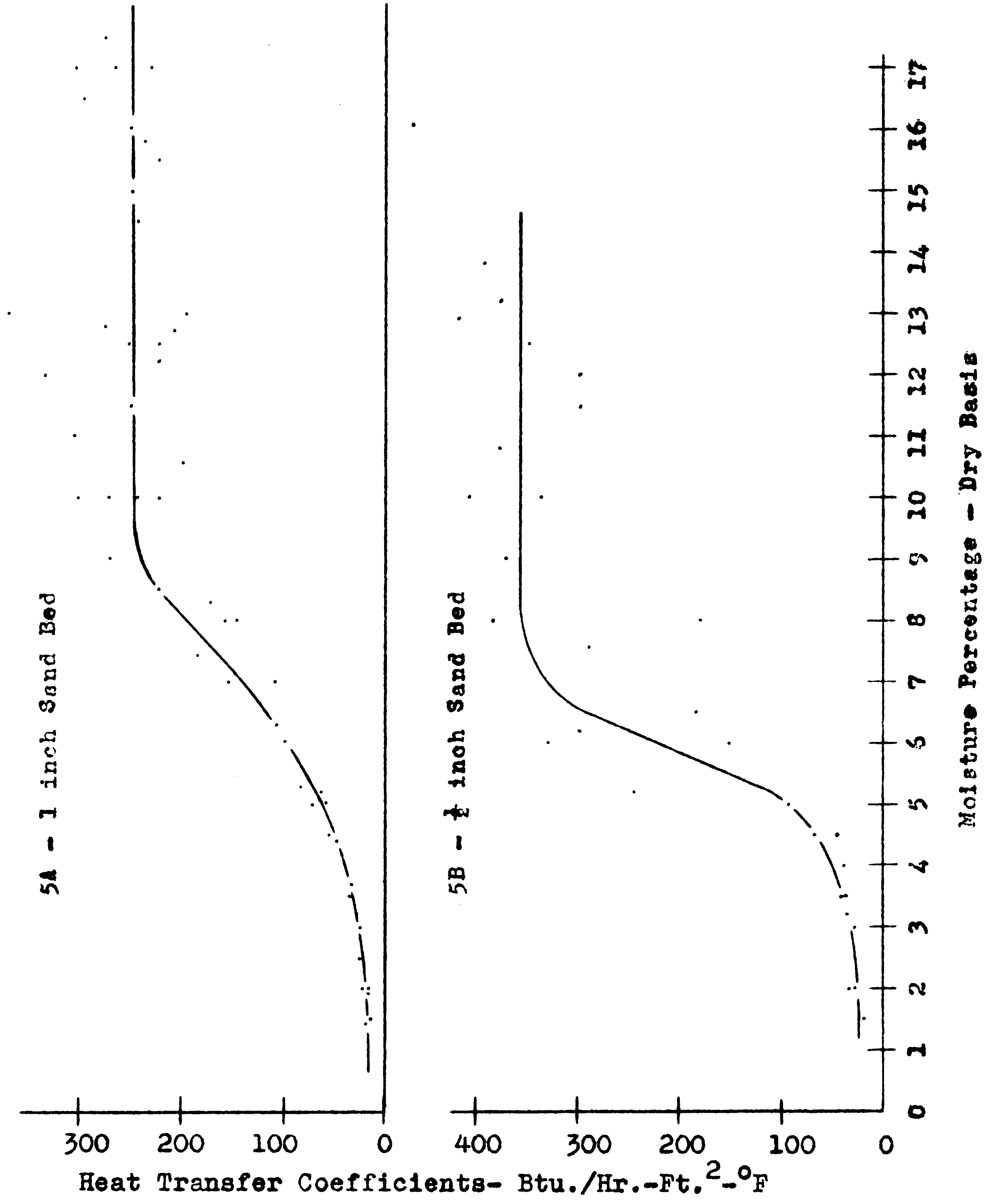
Graph No. 3
Moisture Content vs. Time
1½ inch Sand Bed



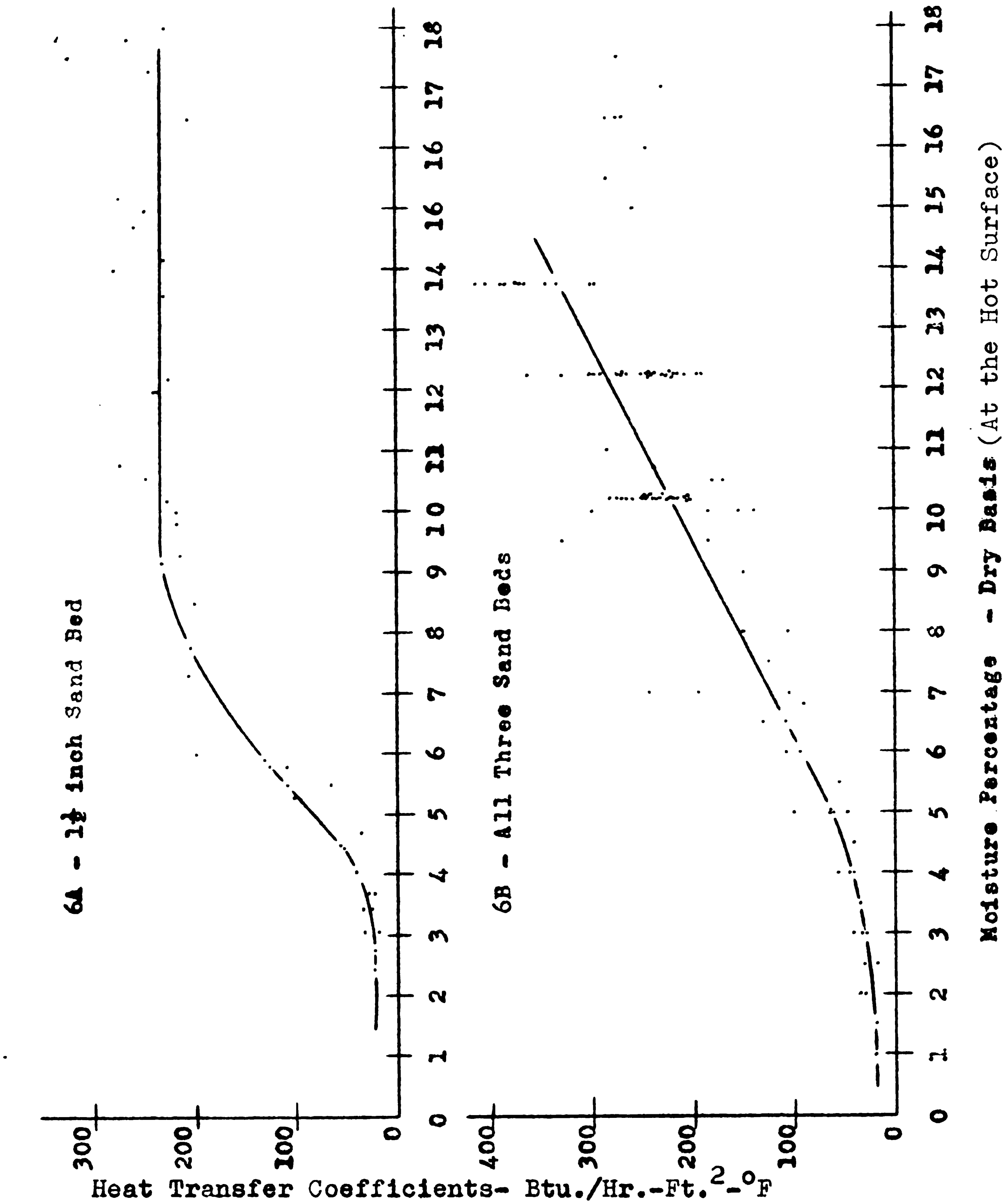
Graph No. 4
Drying Rates vs.
Moisture Contents



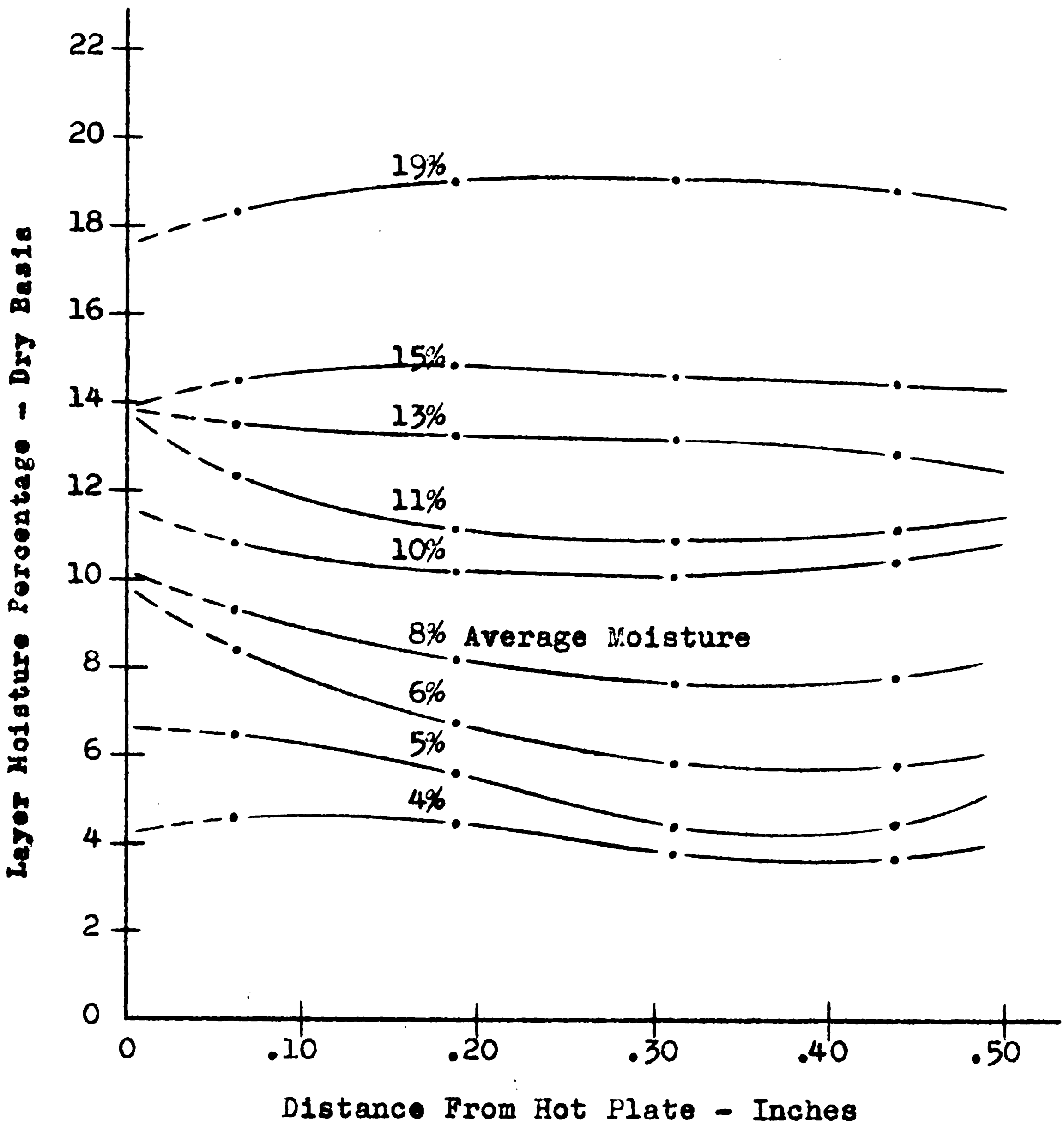
Graph No. 5
Heat Transfer Coefficients
vs. Moisture Content



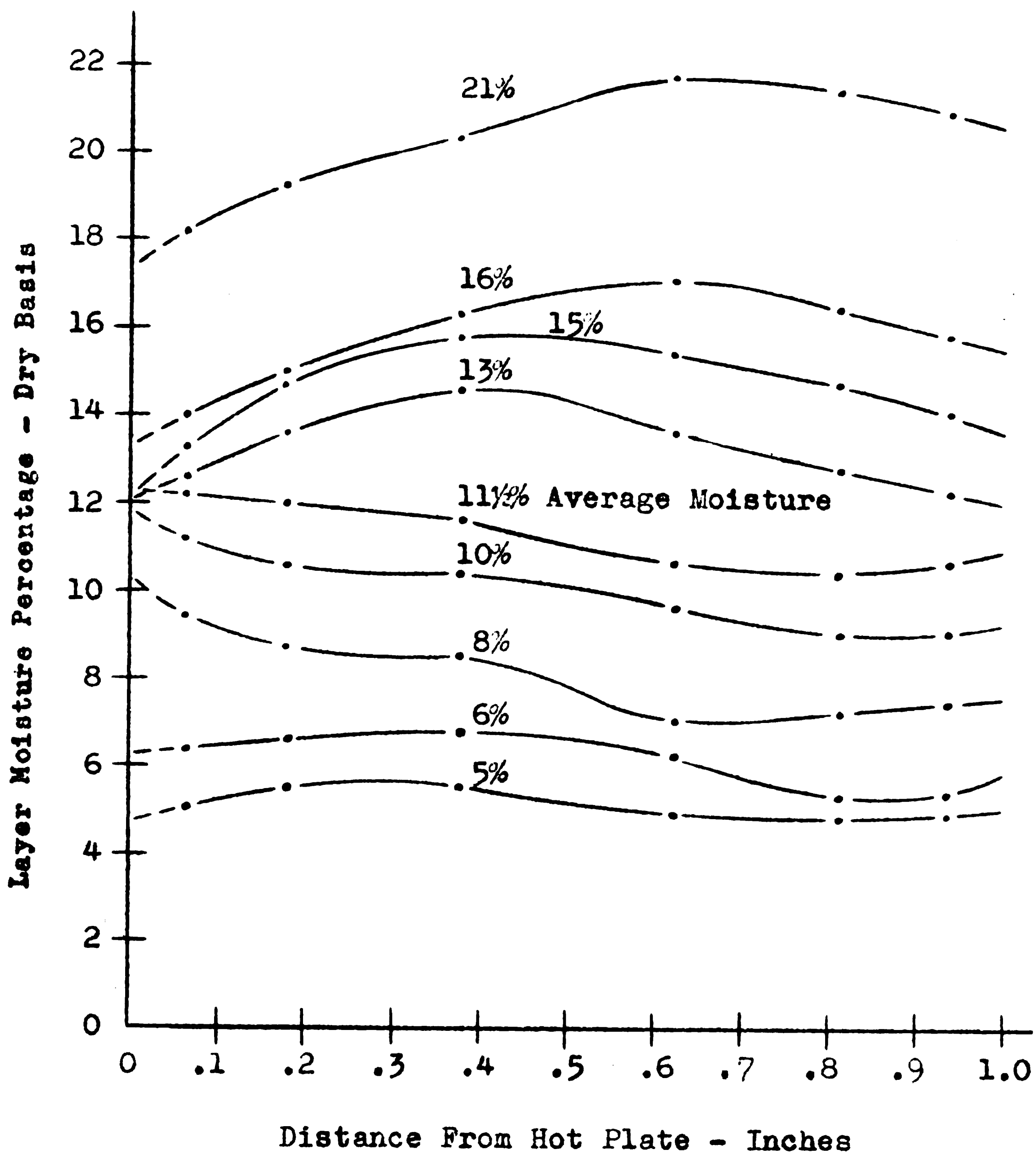
Graph No. 6
Heat Transfer Coefficients
vs. Moisture Content



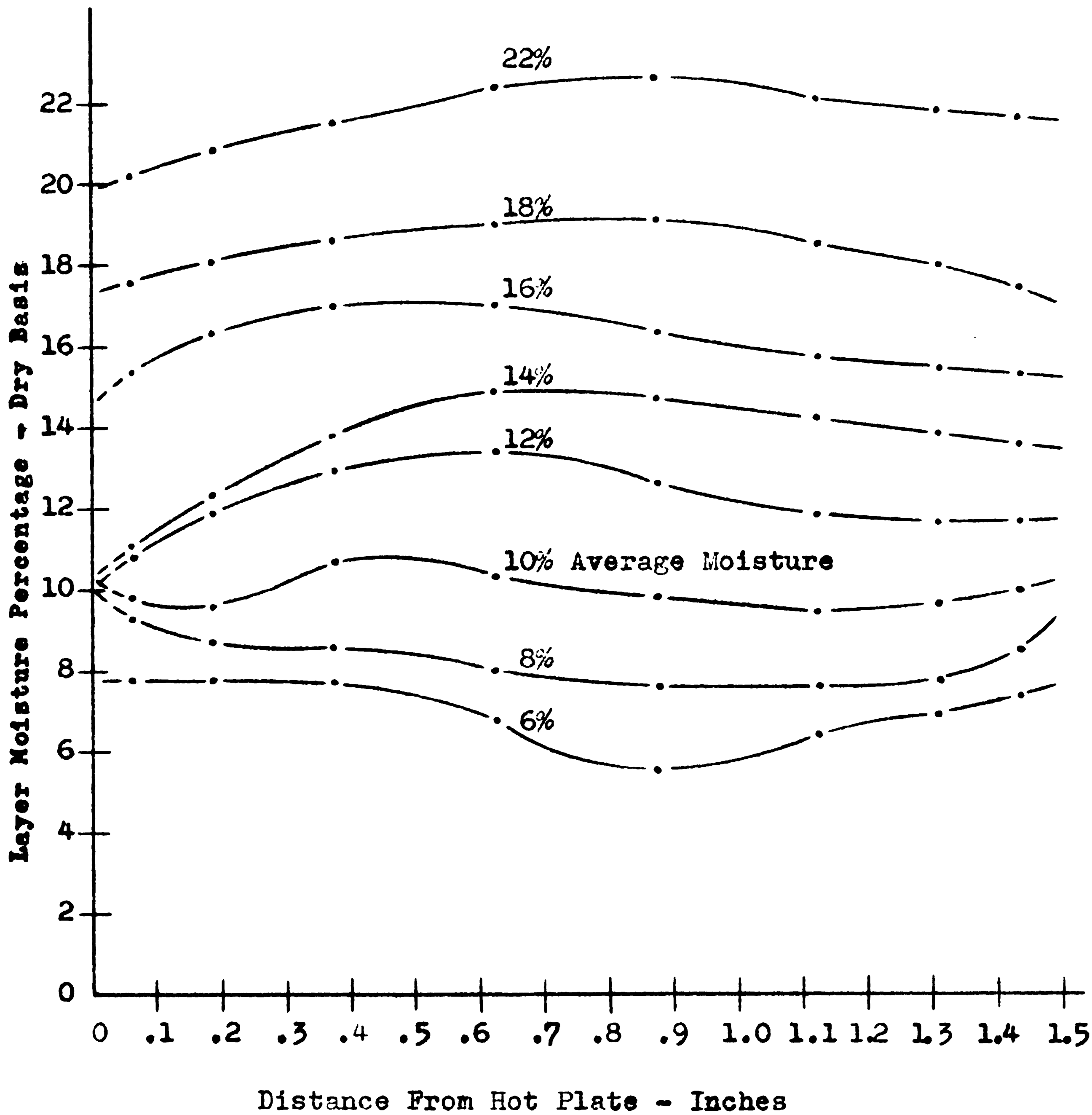
Graph No. 7
Layer Moisture vs.
Height Above Plate
½ inch Sand Bed



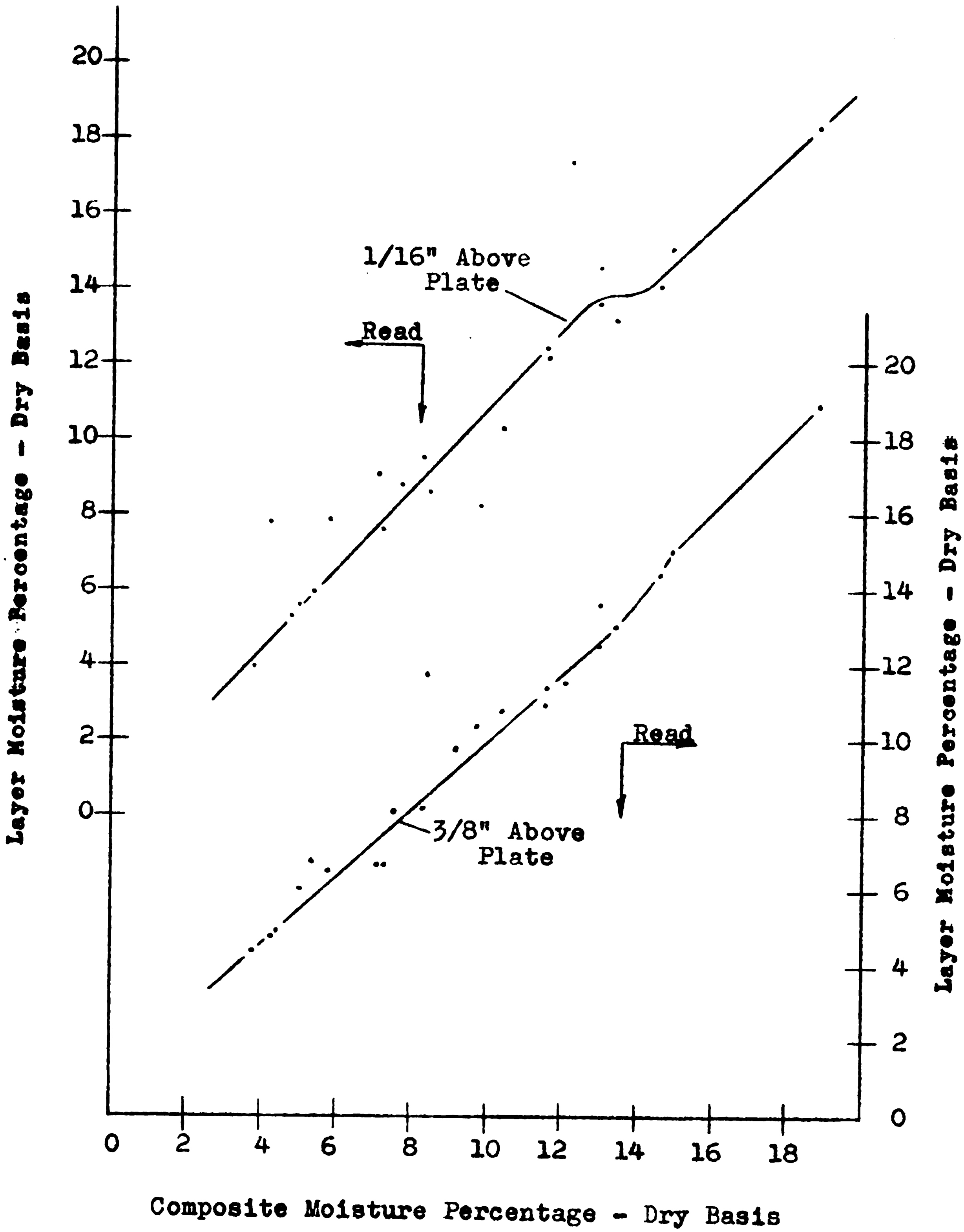
Graph No. 8
Layer Moisture vs.
Height Above Plate
1 inch Sand Bed



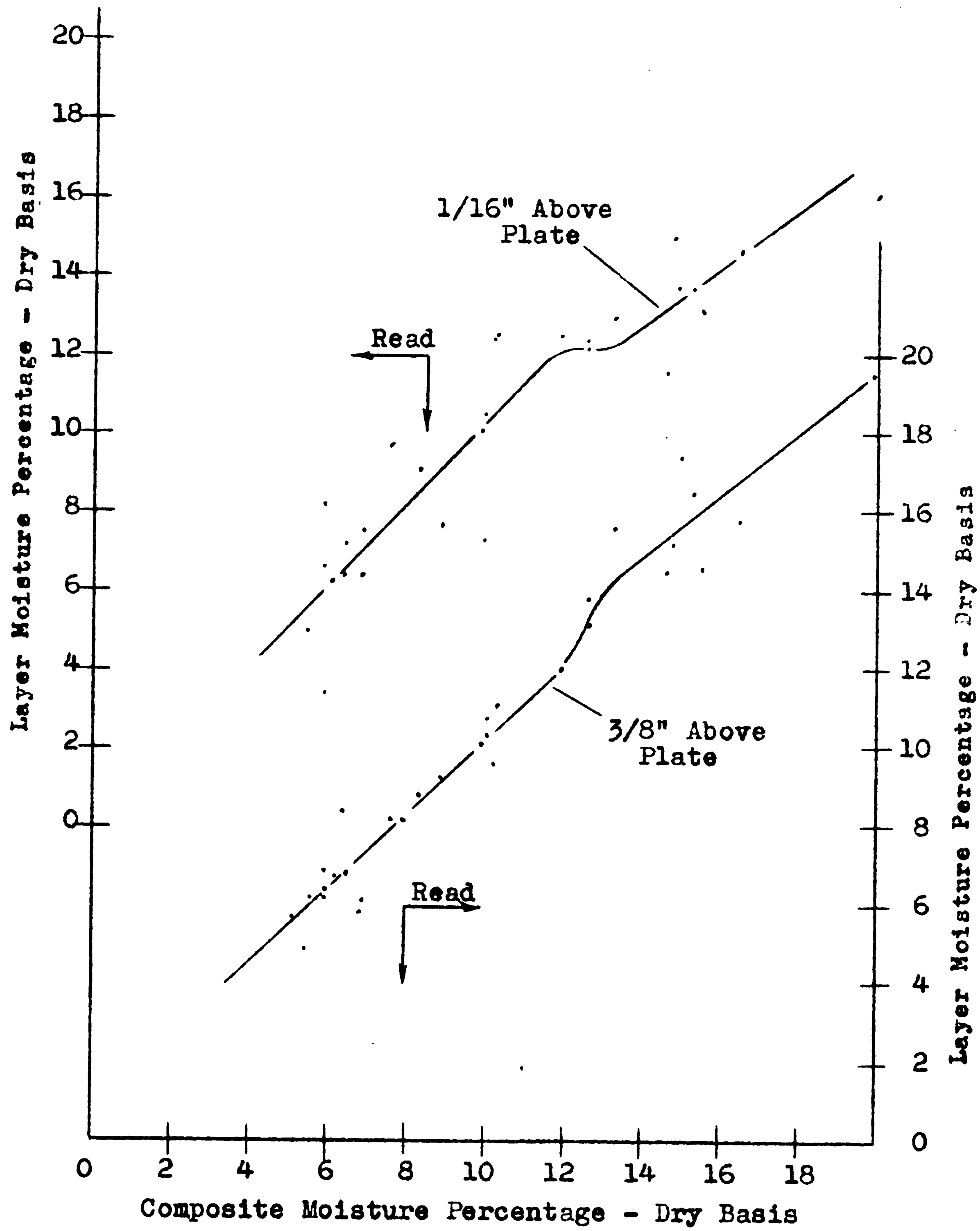
Graph No. 9
Layer Moisture vs.
Height Above Plate
1½ inch Sand Bed



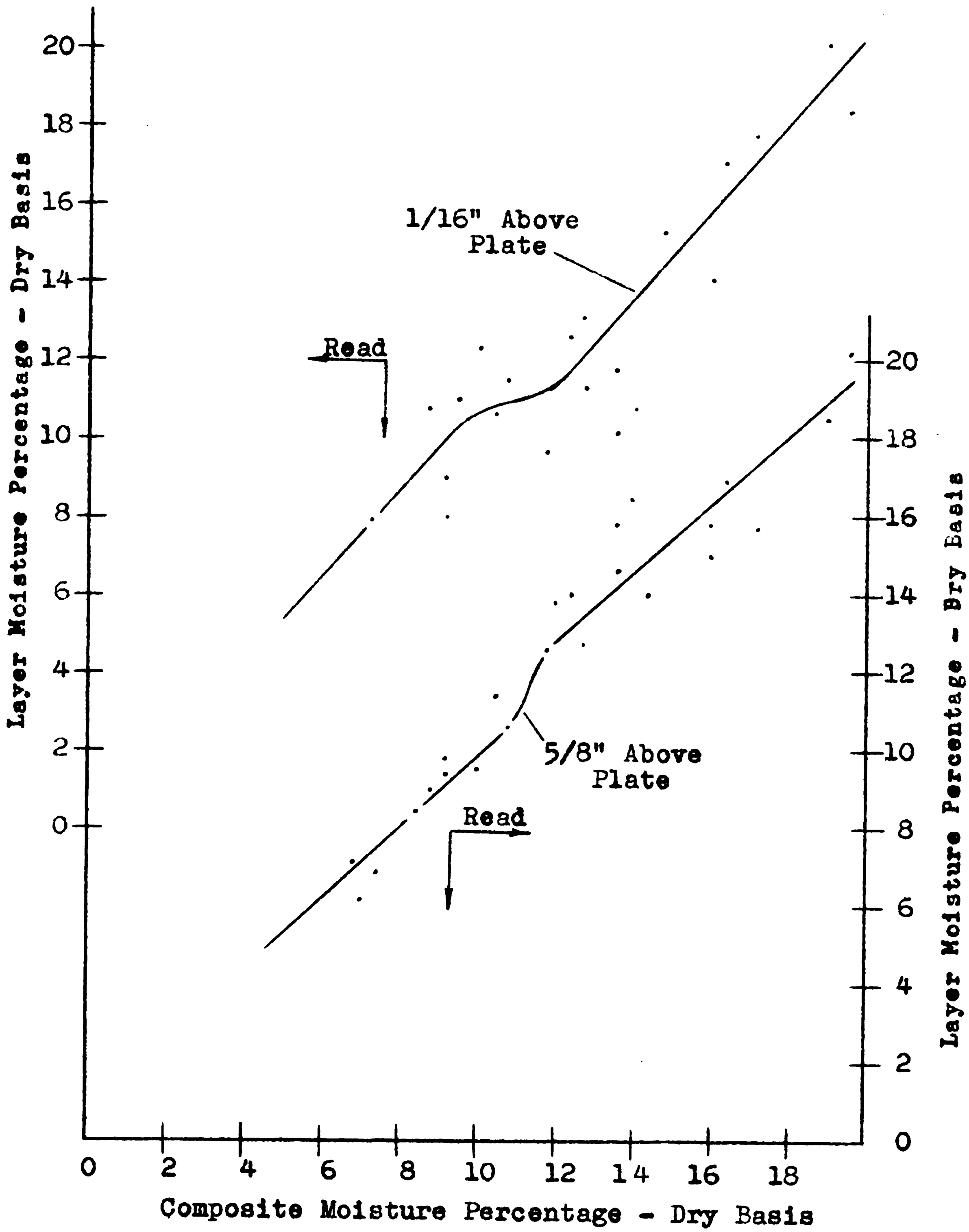
Graph No. 10
Layer Moisture vs.
Composite Moisture
½ inch Sand Bed



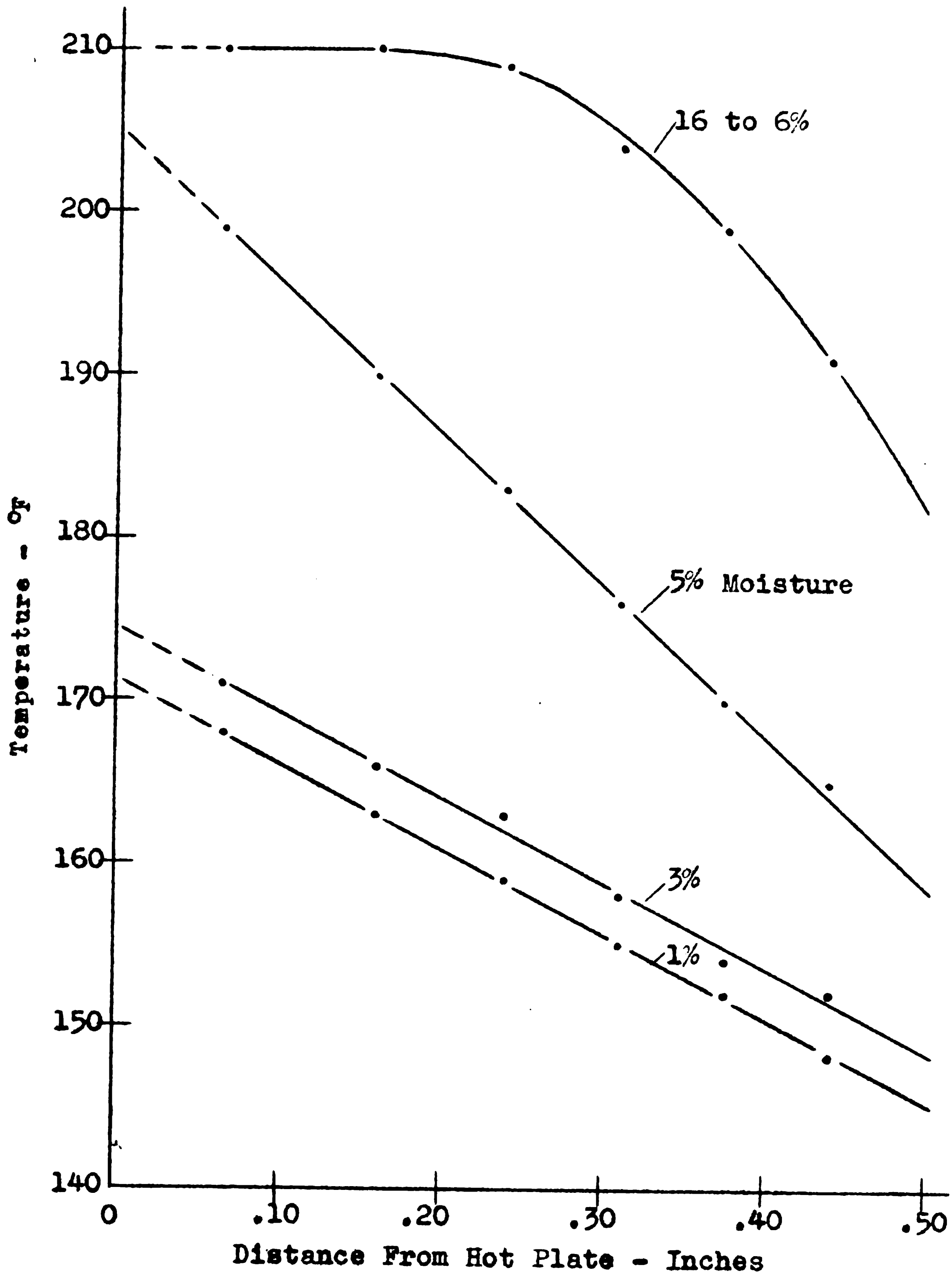
Graph No. 11
Layer Moisture vs.
Composite Moisture
1 inch Sand Bed



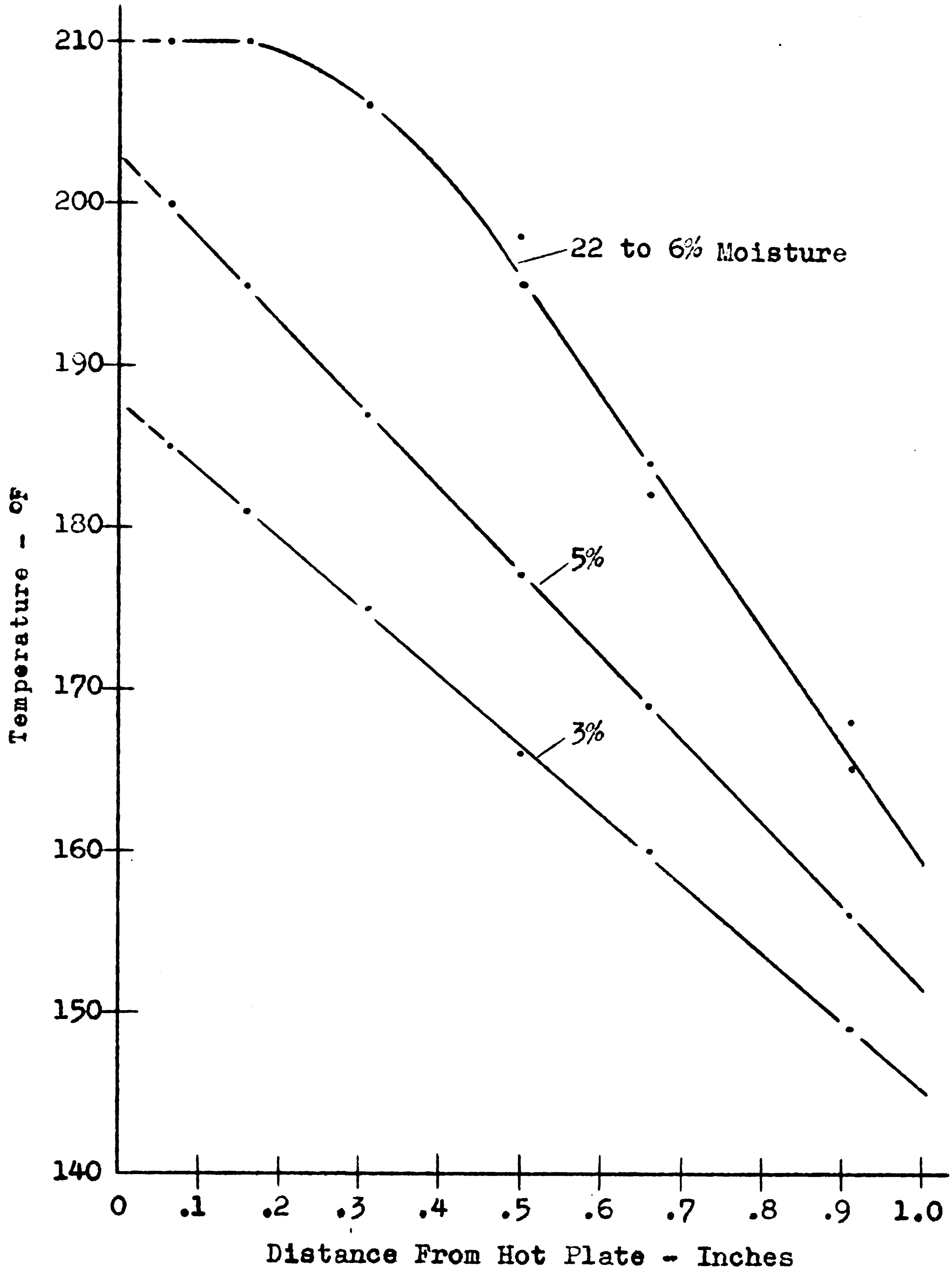
Graph No. 12
Layer Moisture vs.
Composite Moisture
1½ inch Sand Bed



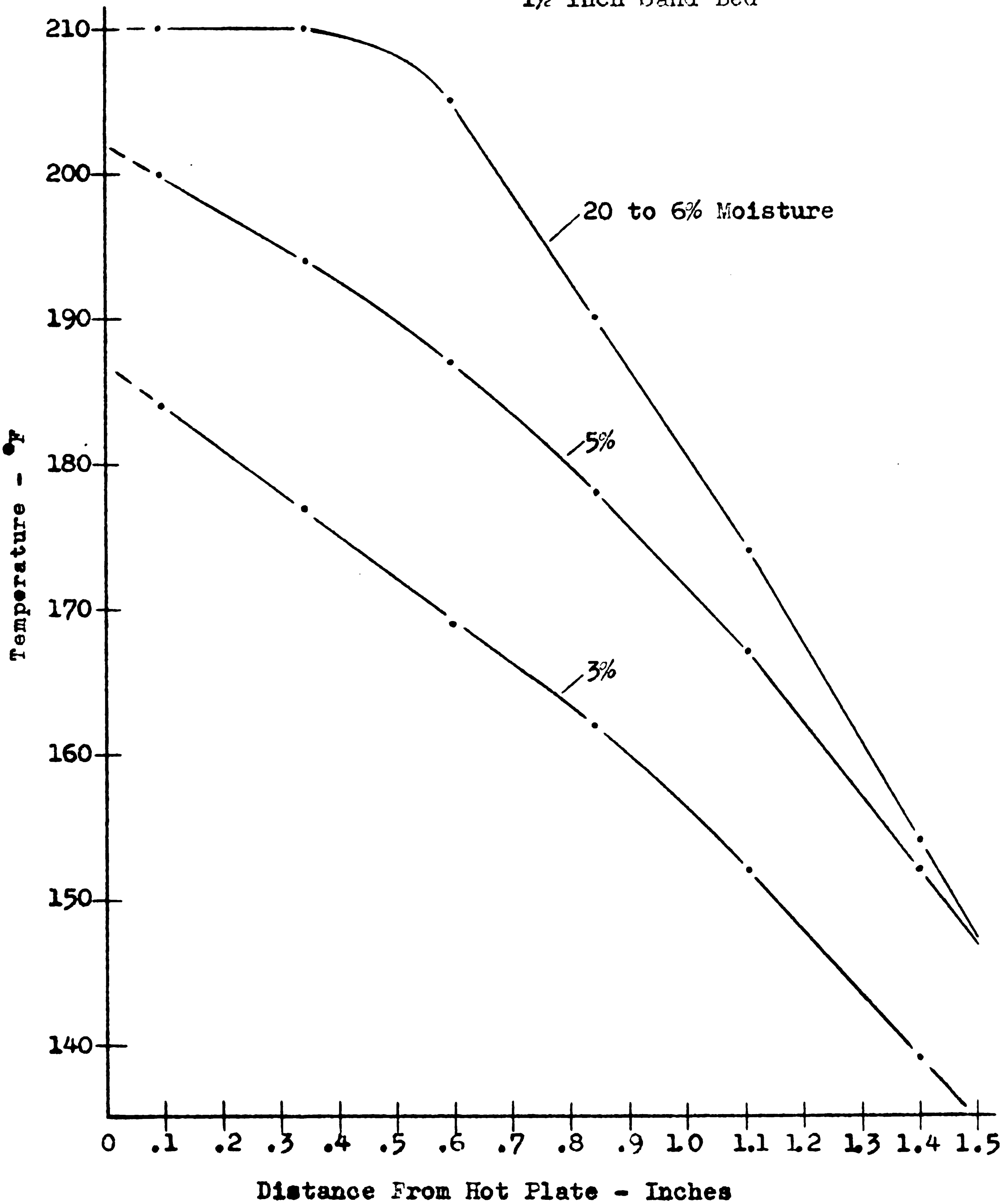
Graph No. 13
Temperature vs. Height
Above Plate
½ inch Sand Bed



Graph No. 14
Temperature vs. Height
Above Plate
1"inch Sand Bed

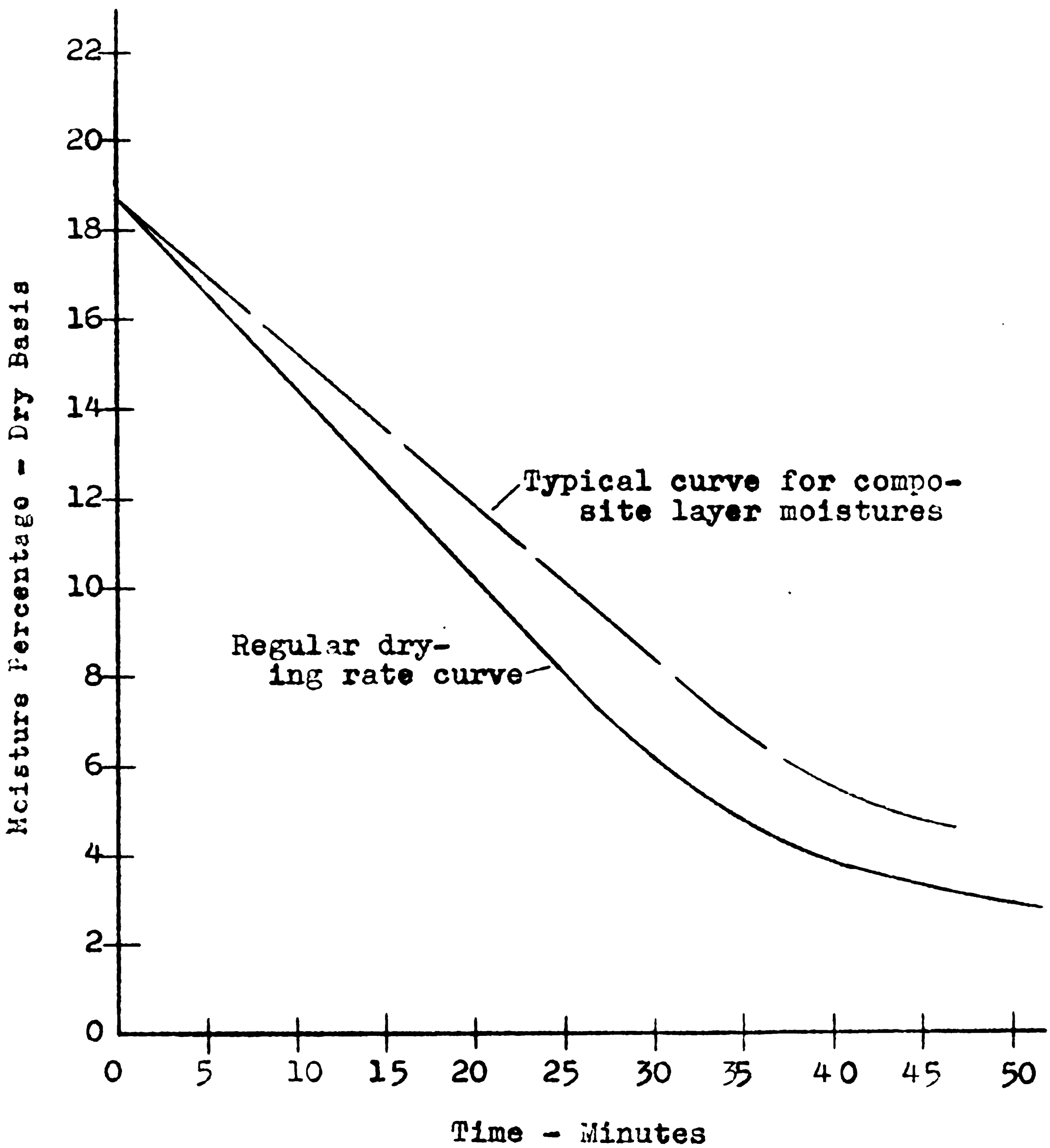


Graph No. 15
Temperature vs. Height
Above Plate
1½ inch Sand Bed



Graph No. 16
Moisture Content vs. Time
1½ inch Sand Bed

(To illustrate discrepancy in drying time when using micarta bushings for layers)



DISCUSSION OF RESULTS

DISCUSSION OF RESULTS

Hot Surface Layer Moistures

The hot surface moisture content approached a constant value during constant rate of drying (between approximately 8 and 16 per cent moisture), for each bed thickness studied. A constant value of moisture content was also observed for the layer one-eighth' of an inch above the plate, for moisture contents corresponding to the constant hot surface moisture contents. Maximum moisture contents within the bed were observed at heights approximately 40 per cent of the total bed height above the hot surface. Table A lists these values as observed from graphs No. 7, 8, 9, 10, 11 and 12.

TABLE A

Bed Thickness inches	Hot Surface Moisture #Water / #Dry Sand	Layer Moisture 1/8" Above Plate #Water / #Dry Sand	Distance From Plate to Maximum Moisture inches
½	.138	.136	.1875
1	.122	.122	.375
1½	.102	.110	.625

The hot surface moisture content and the distance to the maximum moisture content for the three beds were inversely related; namely, the hot surface moisture content increased as the distance decreased.

It has been explained in the literature that the hot surface was supplied with water by the small capillaries. The resistance to this flow of water would be largely determined by the length of travel in these capillaries; assuming the viscosity of the fluid, the number and diameter of the capillaries and the friction per unit length of capillary remained fairly constant. From this, it would follow that the greater the length of the capillary, the greater the resistance to the flow of water. This explained why the moisture content at the hot surface of the one and one-half inch bed was less than the moisture content at the hot surface of the one inch bed and also why the moisture content at the hot surface of the one inch bed was less than the moisture content at the hot surface of the one-half inch bed.

As mentioned in the chapter on Equipment and Procedure, the resin in the micarta bushings used to measure the layer moistures broke down at the temperatures used for this study. This resin deposited a thin film on the hot surface, impeding heat transfer. This meant the temperature drop across the film at the hot surface was greater for the iron-micarta units than for the glass sampling tubes. As observed previously, the deviation in drying rate increased with time. It followed that the greatest deviation resulted from the samples that were in the bed the longest length of time and this is substantiated by graph No. 16. Since this deviation increased, the heat transfer decreased for the iron-micarta units and the effective hot surface temperature also decreased.

Ludt observed a decrease in hot surface moisture content with an increase in hot surface temperature. Therefore, the error that developed using micarta bushings increased the measured hot surface moisture content for the longer runs; namely, the one and one-half inch bed. For this reason, the true value of the hot surface moisture content would be expected to be even lower than recorded.

Drying Rates and Heat Transfer Coefficients

The drying rate of the one-half inch bed was the highest of the three beds studied. During the constant rate period, the rate dropped when the bed thickness was increased from one-half inch to one inch. No significant rate change was observed when increasing the bed thickness to one and one-half inches.

The heat transfer coefficients during the same period were also greater for the one-half inch bed. Table B lists the drying rates and the heat transfer coefficients for the three beds as observed from graphs No. 4, 5 and 6A.

TABLE B

Bed Thickness Inches	Drying Rate $\frac{\#\ Water}{Hr.-Ft.^2}$	Heat Transfer Coefficients $\frac{BTU}{Hr.-{}^{o}F-Ft.^2}$
½	5.4	355
1	3.3	245
1½	3.3	235

The higher heat transfer coefficients for the one-half inch bed indicated a greater heat transfer for that bed. The reason for the increased heat transfer, might have been due to the area of the wetted surface at the hot surface. Graph No. 6B showed the heat transfer coefficient increased as the hot surface moisture content increased. It also showed that at low moisture contents, the heat transfer coefficients became fairly constant. Therefore, a partial explanation of the increased drying rate for the one-half inch bed would be the result of higher heat transfer coefficients due to a greater area of wetted surface at the hot surface.

However, other factors also entered into the rate of drying. As observed from the data of the one inch bed, Run #21, lower heat transfer coefficients and slower drying rates occurred when on heat up to the constant plate temperature, the bed rose from the plate. During the course of the tests, it became evident that the one inch bed was the most difficult to keep from rising.

During heat-up, the one-half inch bed rose from the edges near the ring, the vapor escaped and the bed commenced to dry normally. The one and one-half inch bed had to be punctured a few times to allow the excess vapor to escape and it too settled down to normal drying. However the one inch bed, even though punctured, persisted on rising from the plate. At times, as with run #21, the entire bed appeared to be riding on a cushion of vapor. This vapor decreased the heat transfer coefficient and slowed down the drying rate. Perhaps, this strange phenomena was responsible for the drying rates of the one inch bed being as low as they were.

The average vertical deviation of experimental points from the moisture-time curves showed that data for the one inch bed deviated the most. Table C lists the maximum deviation and the standard deviation for the three beds studied.

TABLE C

Bed Thickness Inches	Maximum Deviation $\frac{\text{\# Water}}{\text{\# Dry Sand}}$	Standard Deviation $\sigma = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n}}$
½	.0205	.0095
1	.0370	.0163
1½	.0425	.0152

Although, the critical moisture content was very difficult to pin-point for the three beds, it appeared to vary with thickness, as observed from graphs No. 1, 2 and 3. The critical moisture contents appeared to occur around four, six and seven per cent for the one-half, one and one and one-half inch beds respectively.

Sand Bed Temperatures

Sand bed temperatures were shown by graphs No. 13, 14 and 15. It was necessary to determine the temperature of the sand at the hot surface, to calculate the heat transfer coefficients. These temperatures were determined by extrapolating the temperature vs. height above plate graphs to zero height. This showed that the temperature of the sand at the plate surface was 210^{o}F for all three bed thicknesses during the constant rate period. The temperature distribution was similar for all three beds, although, the open surface temperature of the thinner beds were the greatest. These temperatures reached a constant value during the constant rate period. However, when the critical moisture content was reached, the temperatures throughout the bed started to fall off sharply.

Retford reported slightly different results; namely, higher heat transfer coefficients, higher drying rates and temperature distributions. The only difference in the equipment used for this study and his study was the thickness of the hot surface plate. The three-quarter inch plate used by Retford was turned down to one-quarter inch. It was inconceivable that the thinner plate made this difference, but perhaps the condition of the surface was different in the two cases.

CONCLUSIONS

CONCLUSIONS

1. The highest heat transfer coefficients were obtained with the one-half inch sand bed.
2. The greatest drying rates were obtained with the one-half inch sand bed.
3. The higher heat transfer coefficients and greater drying rates with the thinnest bed appeared to be the direct result of the greater area of wetted hot surface.
4. The critical moisture content appeared to vary with bed thickness; the thinnest bed had the lowest critical moisture content.

APPENDIX

APPENDIX

Sample Calculations

1. Drying Rate - The drying rate was expressed in pounds of water evaporated per square foot of area per hour. It was obtained by multiplying the slope of the moisture content-time line by the density of the sand, the height of the bed and conversion of time (minutes to hours).

$$R = m'h\rho\,(60)$$

For a slope of -.00425 for the 1½ inch bed, determined by the method of least squares, the drying rate would be:

$$R = (0.00425)\frac{\#\ \text{Water}}{\#\ \text{Dry Sand - min.}} \times (0.125)\ \text{ft} \times (102.6)\frac{\#}{\text{ft.}^3} \times (60)\frac{\text{min.}}{\text{hr.}} = 3.27\ \frac{\#\ \text{Water}}{\text{Hr.-ft}^2}$$

2. Heat Transfer Coefficient - The heat transfer coefficient was expressed in BTU.'s per hour per square foot of area per degree Fahrenheit. It was obtained by dividing the heat transferred per unit area by the temperature drop across film at the hot surface, according to the following formula: $H = Q_a/\Delta t$

The heat transferred per unit area (Q_a) was calculated by determining the amount of heat given off by the milliliters of steam condensed per unit time.

$$Q_a = \frac{60\ c\ \rho_w \overline{H}_v}{A_f}$$

Q_a for an interval when 39.2 milliliters of steam condensed and was collected in four minutes would be:

$$Q_a = \frac{60\ \frac{\text{min.}}{\text{hr.}} \times 39.2\ \frac{\text{ml.}}{4\ \text{min.}} \times 0.00211\ \frac{\#}{\text{ml.}} \times 958.6\ \frac{\text{BTU}}{\#}}{0.30656\ \text{ft.}^2} =$$

$$= 3{,}880\ \text{Btu./Hr.-ft.}^2$$

The temperature drop across the film at the surface was determined by subtracting the extrapolated surface temperature of the sand from the plate surface temperature. The surface temperature of the sand was determined by extrapolating the plot of bed temperatures (Graph No. 13) to zero height above the plate surface. The plate temperature was constant at 220°F.

Therefore, $H = Q_a/\Delta t = \frac{3{,}880\ \text{Btu./Hr.-ft.}^2}{(220 - 210)^\circ\text{F}} =$

$$= 388\ \text{Btu./Hr.-ft.}^2\text{-}^\circ\text{F.}$$

Nomenclature

A_f - Area of plate over funnel ($ft.^2$)

c - Milliliters of condensate per time (ml/min.)

h - Height of Bed (ft.)

H - Heat transfer coefficient (Btu./hr.-$ft.^2$-^oF)

$\overline{H}_v$ - Latent heat of vaporization of steam (Btu./#)

m - Slope of drying curve (#Water/#Dry Sand - min.)

ρ_s - Density of sand (#/cubic foot)

ρ_w - Density of water at 212^oF (#/ml.)

Q_a - Total heat transferred by steam (Btu./hr.-$ft.^2$)

R - Rate of vaporization (#Water/hr.-$ft.^2$)

Δt - Temperature drop between plate and sand (^oF)

θ - Time interval (min.)

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Babbitt, J. D., American Society of Testing Materials Bulletin, No. 212, 58, (1956).
2. Ceaglske, N. H. and O. A. Hougan, Transactions of the American Institute of Chemical Engineers, Vol. 33, 283, (1937).
3. Coulson, J. M. and J. F. Richardson, Chemical Engineering, Vol. 2, (1955).
4. Dreshfield, A. C. Jr., Chemical Engineering Progress, Vol. 53, 174, (April, 1957).
5. Ernst, R. C., D. B. Ardern, O. K. Schmied, and F. M. Tiller, Industrial & Engineering Chemistry, Vol. 30, 1119, (1938).
6. Ernst, R. C., J. W. Ridgway and F. M. Tiller, ibid., Vol. 30, 1122, (1938).
7. Hadley, W. A. and R. Eisenstadt, Transaction of the American Geophysical Union, Vol. 36, 615, (1955).
8. Haines, W. B., Journal of Agricultural Science, Vol. 17, 264, (1927); Vol. 20, 97, (1930).
9. Harbert, W. D., D. C. Cain and R. L. Huntington, Transactions of the American Institute of Chemical Engineers, Vol. 37, 267, (1941).
10. Hougan, O. A., H. J. McMauley and W. R. Marshall, ibid., Vol. 36, 183, (1940).
11. King, A. R. and D. M. Newitt, Transactions of the Institute of Chemical Engineers, Vol. 33, 64, (1955).

12. Ludt, R. W., American Institute of Chemical Engineers Journal, Vol. 3, 343, (September, 1957).

13. McCready, D. W., Paper Trade Journal, Vol. 101, 66, (1935).

14. Newitt, D. M. and M. Coleman, Transactions of the Institute of Chemical Engineers, Vol. 30, 30, (1952).

15. Oliver, T. R. and D. M. Newitt, ibid., Vol. 27, 9, (1949).

16. Pearse, J. F., T. R. Oliver and D. M. Newitt, ibid., Vol. 27, 1, (1949).

17. Retford, D. T., M. S. thesis, Michigan State University, East Lansing, (1957).

18. Sherwood, T. K., Transactions of the American Institute of Chemical Engineers, Vol. 32, 150, (1936).

19. Tambling, T. N., M. S. thesis, Michigan State University, East Lansing, (1953).