A STUDY OF THE MECHANISM OF DRYING SAND ON A HEATED SURFACE

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Thomas Noel Tambling

1953

This is to certify that the

thesis entitled

A Study of the Mechanism
of Drying Sand on a Heated Surface

presented by

Thomas Noel Tambling

has been accepted towards fulfillment
of the requirements for

Master's degree in ~~Chemical~~ Engineering

Randall W Ludt
Major professor

Date August 14, 1953

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A STUDY OF THE MECHANISM OF

DRYING SAND ON A HEATED SURFACE

BY

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1953

ACKNOWLEDGMENTS

The author wishes to express his sincere thanks to Dr. Randall W. Ludt, under whose guidance, help, and consideration this investigation was undertaken.

He also wishes to thank Mr. William Clippinger for his help with mechanical details, and thanks also to the author's wife for her moral support and help.

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INTRODUCTION

The purpose of this study lies in an attempt to secure a better understanding of the mechanism of drying on a heated surface. This paper has been limited to the investigation of the factors and mechanism involved in the process of drying sand on a heated plate.

Drying itself is perhaps one of the oldest unit processes used by man. He has used it in the drying of hides, foods, clay-ware, etc., throughout the ages. Although drying has a long history, serious studies into the mechanism of drying have been left to recent years.

As a process in our present day world, it occurs in many of our chemical and industrial operations. Drying is a principal operation in the manufacture of rayon, cellophane, pigments, dyes, insecticides, fine chemicals, textiles, leather, wood products, ceramics, dried foods, soap, and paper (5). As a principal operation or some part of a process, drying can be an appreciable fraction of the total investment and processing cost.

Many studies have been advanced in an effort to determine the mechanism and controlling factors involved in drying in a hope of better understanding. Empirical equations (8), diffusion equations (5, 14), vapor pressure equations (6), suction equations (2, 7, 8), and/or capillary flow equations (2, 7) are used in an attempt to use known data in the development of driers or to determine drying conditions. A consideration of the many different properties of solids should lead one to realize that no one simple mechanism could be used to predict the movement of moisture and vapor in a solid during the drying process.

To date most of the work done towards determining the mechanism of drying has been done in the field of air drying (6). Some work has been done in the field of infra-red, dielectric, and heated surfaces drying. These last three methods of drying do not seem to have been covered to the extent as has air drying.

Some work on the drying mechanism has been published or written in the field of drying paper pulp on heated surfaces (6, 12). Lewis, McAdams, and Adams (4) analyzed data obtained on the drying of paper pulp on drum driers. Sherwood (10) presented a means of calculation of the influence of heat inflow through nondrying faces on the rate of drying. Stacey (13) and Sherwood and Cummings (11) have reported and discussed data on the drying of various materials in pans, a method which is similar to drying on heated surfaces. But little work seems to have been published dealing with the mechanism of drying granular solids on heated surfaces.

Kirschbaum (3) has presented material on the theoretical principles of evaporative drying with heated surfaces. He developed basic equations and related them to the Mollier diagram of enthalpy versus moisture content. Further analysis of his work has not been presented for the lack of a translation of the article.

McCready (6) has proposed two general cases for the drying of a wet slab on a heated surface.

Case I A continuously decreasing temperature gradient extends from the hot surface, through the slab to the drying air.

Case II The temperature gradient between the hot surface and the drying air passes through a minimum temperature in the slab and increases to the temperature of the hot surface and drying air.

Experimentally he has dried paper pulp under the conditions of Case I and Case II.

Under Case I drying, during the time of constant drying, local temperature in the slab remained constant until a critical moisture content was approached, and then the temperatures decreased.

In the falling rate period, a zone of vaporization which was originally formed beneath the closed face of the slab advanced toward the open face. Between this zone of vaporization and the open face, there was a free water zone. In the first part of the falling rate, the temperatures in the slab decreased with a decreasing temperature gradient, and the temperature difference between the hot surface and the slab increased. In the latter part of the falling rate period, there was an increasing temperature difference across the zone of vaporization with a decreasing temperature difference between the hot plate and the interface. In the zone of free water the temperature difference decreased.

Under Case II drying, the drying process was similar to that in case I except that there were two zones of vaporization: one starting at the closed face and the other starting at the open face of the slab. These two zones of vaporization moved towards each other throughout the falling rate period.

McCready also made a study on influencing factors and concluded that the factors that have the greatest influence on the rate of drying of paper are the temperature of the hot surface and the thickness of the paper. The temperature of the drying air has little effect on the rate of drying, as most of the heat required for the drying process is supplied from the hot surface. Changing the relative humidity of the air has little effect on the rate of drying providing the difference between the hot surface and the drying air temperatures is large.

Pearse, Oliver, and Newitt (8) agree that during the constant rate period drying takes place at the exposed surface and is a function of the diffusion of water vapor through the air film. They apply empirical relationships which are found to hold for the evaporation of water from free surfaces.

They hold that the forces which are likely to affect the movement of free water in a solid are those due to gravity, friction, convection, and capillarity. The relative magnitude of these forces depends upon the structure of the bed and of its component parts, and upon any factors which may cause a change in the physical properties of the water such as temperature. Also, if the bed is exposed to a temperature gradient, movement of water by distillation may occur. Any unbalanced pressures would in effect cause a movement of water.

In a continuation of Ceaglske and Hougen's work (2), Pearse, Oliver, and Newitt have summarized the following conclusions as to particle size and controlling forces as a result of their experimental work in air drying:

Particle Size (cm.)	Forces Controlling
10^{-1}	Gravitational and Capillary.
10^{-2}	Gravitational and Capillary.
10^{-3}	Capillary.
10^{-4}	Capillary.
10^{-5}	Capillary and Frictional.
10^{-6}	Capillary and Frictional.

While the work of Pearse, Oliver, and Newitt (8) is more applicable to relatively coarse granular solids; Oliver and Newitt (7) continued the work with beds composed of fine particles. They came to the conclusion from the work with fine and relatively coarse granular solids composed of non-porous particles that the moisture movement is governed by the structure of the bed. There is a distinction of beds into two categories, namely (1) beds in which the movement of moisture is controlled solely by capillary forces, and (2) beds in which the capillary forces are limited by vaporization within the pores and moisture movement is largely by vapor diffusion. A third classification might be made in which the structure of the bed is such that, under one set of conditions, capillary forces are controlling and, under another set, vaporization effects become pronounced.

EXPERIMENTAL PROCEDURE

The sand used for the solid came from sandy lake beds near Caro, Michigan. The screen analysis with standard screens was as follows:

Screen No.	Cumulative percent retained
40	6.4
60	33.5
100	69.6
200	96.9

The sand collected on screen No. 60 was used for this study. This would place the diameter of the particles between the limits 0.25 - 0.42 mm.

About one and seven tenths of a pound of 40-60 sand was weighed out on a beam balance. To this sand was added enough water to bring the total weight to two pounds. This placed the original moisture content at approximately 15 percent.

In the first series of runs when the plate temperature was below the boiling point of water, the water added was at its boiling point. The purpose was an attempt to reduce the time to heat the sample to a constant drying rate.

The sand and water were mixed thoroughly together. The mixed sand sample was then placed in a mold consisting of an annular ring for the sides and a sheet of clear plastic for the bottom. The ring was one inch high and had an internal diameter of seven inches. The ring was made of galvanized iron sheet. The depth of the sand in this mold was 0.75 inches.

The sand in this mold was then placed on a heated plate, and the plastic sheet was removed. A brass ring with an one inch internal diameter, 1.5 inches external diameter, and two legs 1.5 inches long, holding six thermocouples evenly spaced around the ring, was placed in the middle of the sand slab.

These thermocouples, Leeds and Northrup, No. 20, copper-constantan, duplex, glass insulated, were spaced 1/16, 1/8, 5/16, 1/2, 11/16, and 15/16 inches from the heated plate. The thermocouple 15/16 of a inch from the plate was 3/16 inches from the open or top surface of the sand slab. Its purpose was to give one some idea of the temperature of the air layer above the surface of the slab.

An electric hot plate was used as the source of heat. It was connected through three variable rheostats so that the temperature could be controlled throughout a run.

Two circular steel plates one foot in diameter and each one 0.75 inches thick were placed on the hot plate. The steel plates were used in hopes to get a better distribution of heat. The electric plate itself was subject to hot spots, and the steel plates placed upon it were an attempt to remove this fault.

Six thermocouples were placed half way between the two faces of the top two circular plates. One was at the center, and the others at a distance of 1, 2, 3, 4, and 5 inches respectively away from the center. A seventh thermocouple was placed about 1/16 of an inch from the top face and about one inch from the center.

These thermocouples were also Leed and Northrup, No. 20, copper-constantan, duplex, and glass insulated wires.

All thermocouples were connected through throw switches to a Leeds and Northrup potentiometer using an ice solution as the cold junction.

From a series of preliminary runs, it was observed that the temperature drop in the steel plate and in the sand at the same level from the center to the outside edges was within one degree F. at temperatures up to as high as 250 degrees F. As this temperature drop across the diameter of the steel plate and sand was small, it was not considered necessary to take the temperature at various distances from the center. So the temperatures recorded both in the steel plate and sand bed were from the center, and these were considered to be the average temperatures throughout the plate and sand slab.

To protect the drying slab from air currents and to help set up natural connection currents, the drying apparatus was shielded. This shield extended 14 inches above the drying surface. This was done in hopes that it would lead to more uniform results.

An one inch internal diameter copper tube machined down to a wall thickness of 0.031 inches was used to take samples. Samples were taken at various time intervals by dropping the copper tube down through the sand bed then removing it with the sample within its shell. This sample was then divided into 1/8 of an inch layers, and put into previously weighed weighing bottles. This procedure was reduced to a minimum time, and the time involved averaged approximately two minutes.

These weighing bottles with the sand samples were then weighed again and placed in an oven kept at 240 degrees F. for an overnight period. The weighing bottles were removed, allowed to cool, and weighed the final time.

To help determine the possible migration of water in the sand bed during the drying process, a five percent sodium chloride solution was used in Runs 23 and 24, and a two percent solution was used in Run 25 as the moisture mixed with the sand. Samples were taken in the previous way. After the drying and final weighing, the samples were mixed with 50 ml. of distilled water to dissolve the NaCl.

Mohr method for the determination of chloride was used to determine the chloride content in each sample.

Temperatures and moisture content were all recorded against time and against the distance from the heated surface.

DATA AND GRAPHS

TABLE - I

Run 12.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand						Total Aver.
	Distance from Plate - Inches						
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
90	16.7	16.1	15.8	15.6	15.9	15.4	15.9

No temperature gradient was imposed upon sand. It was allowed to stand for 90 minutes before samples were taken.

TABLE - II

Run 13.

Pressure 744 m.m.
Room temperature 82°F.
Wet bulb temperature 69°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	195						
1.5	180	147	142	129	118	112	92
5.	178	157	154	144	134	126	102
10.	179	160	158	143	140	132	114
15.	179	161	158	148	140	133	114
30.	178	160	158	150	142	134	117
40.	180	162	160	151	144	136	118
45.	181	163	161	152	144	136	119
60.	182	164	162	154	146	137	122

TABLE - III

Run 13.

Pressure 744 mm.
Room temperature 82°F.
Wet bulb temperautre 69°F.

Time min.	Percent Moisture Content - Gms. water / Gms. B. D. Sand						Total Aver.
	Distance from Plate - Inches						
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
15	12.7	12.71	12.3	11.6	11.43	11.44	12.03
30	9.02	9.60	9.34	9.62	9.53	9.70	9.47
45	6.72	7.05	7.03	7.36	6.92	7.80	7.13
60	3.78	4.26	4.18	4.33	4.32	3.77	4.11

TABLE - IV

Run 14.

Pressure 742mm.
Room temperature 90°F.
Wet bulb temperature 78°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	15/16
0	195						
1.5	178	152	147	135	126	119	100
5	178	160	156	148	139	131	111
10	178	161	160	152	144	135	118
20	177	164	160	152	144	137	124
30	178	164	160	152	145	136	121
50	179	164	161	153	146	137	121
60	178	164	160	152	145	136	121
70	176	162	160	152	144	136	120
80	176	164	161	154	147	138	123
90	179	157	154	149	143	136	122

TABLE V

Run 14.

Pressure 742 mm.
Room temperature 90° F.
Wet bulb temperature 78° F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches						Total Aver.
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
0							19.9
30	10.20	11.02	10.25	11.30	11.40	10.40	10.76
60	4.20	4.43	5.47	5.40	5.10	4.96	4.93
90	0.135	0.40	1.82	2.10	0.85	0.85	.834

TABLE - VI

Run 15.

Pressure 736 mm.
Room temperature 89°F.
Wet Bulb temperature 77°F.

Time min.	Plate	Temperature - °F. Distance from plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	192						
1.5	175	153	148	136	126	119	100
5	176	161	157	148	138	128	109
10	176	162	159	150	142	134	117
20	174	162	159	151	142	134	120
30	175	162	159	151	142	132	118
40	177	164	160	152	142	134	118
50	176	163	160	152	143	134	122
60	176	162	160	152	142	132	118
70	174	162	159	152	143	134	120
80	176	158	157	150	141	132	120

TABLE - VII

Run 15.

Pressure 736 mm.
Room temperature 89°F.
Wet bulb temperature 77°F.

Time min.	Percent Moisture Content - $\frac{\text{Gms. Water}}{\text{Gms. B. D. Sand}}$ Distance from Plate - Inches						Total Aver.
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
0							20.3
20		12.90	10.60	11.00	12.50	13.10	
40	10.40	6.77	8.25	8.36	8.15	8.32	8.38
60	4.02	4.40	4.47	1.70	4.47	1.04	3.35
80	0.76	1.70	1.74	1.54	0.46	0.27	1.08

TABLE - VIII

Run 16.

Pressure 729 mm.
Room temperature 83°F.
Wet bulb temperature 77°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	183						
1	174	144	138	125	116	109	95
5	172	156	152	142	133	125	105
10	172	157	154	146	137	120	109
15	172	158	155	146	138	130	113
25	172	159	155	147	139	130	115
30	173	159	156	147	140	132	115

TABLE - IX

Run 16.

Pressure 729 mm.
Room temperature 83°F.
Wet bulb temperature 77°F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches: 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Total Aver.
0							14.2
15	11.60	10.40	10.50	11.00	11.50	12.30	11.22
17	11.50	10.80	10.60	10.50	10.80	11.50	11.12
30	8.76	9.14	9.45	9.43	9.40	10.00	9.36
33	7.71	7.80	8.50	8.50	8.90	9.02	8.41

TABLE - X

Run 18.

Pressure 736 mm.
Room temperature 78°F.
Wet bulb temperature 70°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	232						
0.5	218	161	154	132	112	102	83
2.5	206	177	173	158	138	123	96
5.0	207	186	181	167	149	130	103
10.0	208	189	185	172	153	135	111
20.0	205	188	185	172	154	136	118
25.0	205	188	185	173	154	136	120

TABLE - XI

Run 18.

Pressure 736 mm.
Room temperature 78°F.
Wet bulb temperature 70°F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Total Aver.
11	10.30	10.30	10.20	10.60	10.70	10.20	10.72
13	9.80	9.60	9.97	9.80	9.77	9.75	9.78
27	4.83	5.30	5.50	5.58	5.60	5.20	5.34
29	3.75	4.40	4.63	4.50	4.74	4.65	4.45

TABLE - XII

Run 19.

Pressure 733 mm.
Room temperature 79°F.
Wet bulb temperature 67°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	237						
1.5	208	175	169	154	137	125	101
5	209	185	180	166	154	141	112
10	209	188	183	170	158	146	120
15	208	188	184	171	160	148	124
20	209	190	186	174	162	150	126
25	210	192	188	176	164	150	127
30	212	196	192	180	166	151	122
35	221	184	180	170	160	149	125
40	225	175	172	164	155	146	125

TABLE - XIII

Run 19.

Pressure 733 mm.
Room temperature 79 °F.
Wet bulb temperature 67 °F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Total Aver.
0							17.1
10	11.4	11.6	11.3	11.2	11.20	12.8	11.58
20	7.35	8.25	7.67	8.3	9.02	9.5	8.35
30	1.93	4.01	4.34	4.72	4.22	4.95	4.03
40	0.	1.51	2.65	3.06	2.98	0.83	1.84

At about 34 min. a sample was taken from the surface.

Moisture equaled .8 .

TABLE - XIV

Run 21.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0.	267						
.33	240	176	166	144	126	116	102
2.5	223	194	190	174	156	141	110
5.0	221	201	197	183	166	150	117
10.	221	203	199	187	171	154	123
15.	222	203	201	189	170	153	129
20	226	196	192	180	161	146	127
25.	229	180	178	170	158	146	127
30.	230	170	169	162	152	142	122
35.	230	165	164	158	143	136	122
40.	229	163	161	155	146	133	120

Pressure 740 mm.
Room temperature 87°F.
Wet bulb temperature 72°F.

TABLE - XV

Run 21.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Total Aver.
5	9.8	9.1	8.65	8.7	9.7	9.96	9.33
10	6.9	7.15	6.3	6.4	6.4	6.8	6.66
15	4.2	4.45	4.3	4.32	4.11	4.13	4.25
20	2.12	2.82	3.01	3.04	3.1	2.83	2.82
0							16.1

Pressure 740 mm.
Room temperature 87°F.
Wet bulb temperature 72°F.

TABLE - XVI

Run 22.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	259						
.75	229	180	171	153	138	128	111
3.0	219	195	190	174	159	142	120
5.	218	201	196	181	166	148	120
10.	216	200	196	183	164	145	124
15.	215	197	192	180	161	145	123
20.	216	192	189	175	156	142	126
25.	217	177	174	165	152	140	124
30.	217	168	166	157	146	131	118
35.	216	163	160	153	144	127	119
40.	215	161	158	150	143	124	117
45.	215	158	155	148	141	126	117
50.	215	154	150	140	137	121	117
55.	215	158	154	143	130	124	119
60.	216	160	156	145	130	123	119
65.	214	162	157	146	133	124	120
70.	214	162	157	146	136	126	120

Pressure 744 mm.
Room temperature 82°F.
Wet bulb temperature 72°F.

TABLE - XVII

Run 22.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand						Total Aver.
	Distance from Plate - Inches						
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
0							16.28
5.	10.2	10.3	10.0	10.2	10.6	10.8	10.35
10	5.95	6.8	6.7	6.8	6.65	7.0	6.66
15	4.6	5.1	5.2	5.15	5.6	5.2	5.16
20	2.7	3.2	3.3	3.7	3.1	3.4	3.24

Pressure 744 mm.
Room temperature 82°F.
Wet bulb temperature 72°F.

TABLE - XVIII

Run 23.

Time min.	Percent NaCl Dry Basis Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Aver.
0.							1.337
5.	4.940	.480	.564	.612	.620	1.080	
10.	4.480	.375	.419	.478	.535	1.275	
15.	5.500	.362	3.72	.484	.425	1.380	
20.	5.960	.216	1.96	.288	.372	1.885	

Pressure 739 mm.

TABLE - XIX

Run 24.

Time min.	Percent NaCl Dry Basis Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Aver.
0.							.705
5.	2.05	.385	.363	.302	.341	.938	
10.	2.11	.190	.139	.164	.255	1.120	
15.	2.46	.122	.105	.169	.143	1.08	
20.	3.97	.131	.0904	.0904	.154	1.395	

Pressure 737 mm.
Room temperature 85°F.
Wet bulb temperature 78°F.

TABLE - XX

Run 25.

Time min.	Percent NaCl Dry Basis Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Aver.
0.							.233
10.	.397	.105	.084	.125	.149	.504	
20.	.767	.046	.050	.064	.079	.362	

Pressure 733 mm.
Room temperature 83°F.
Wet bulb temperature 77°F.

TABLE - XXI

Run 20.

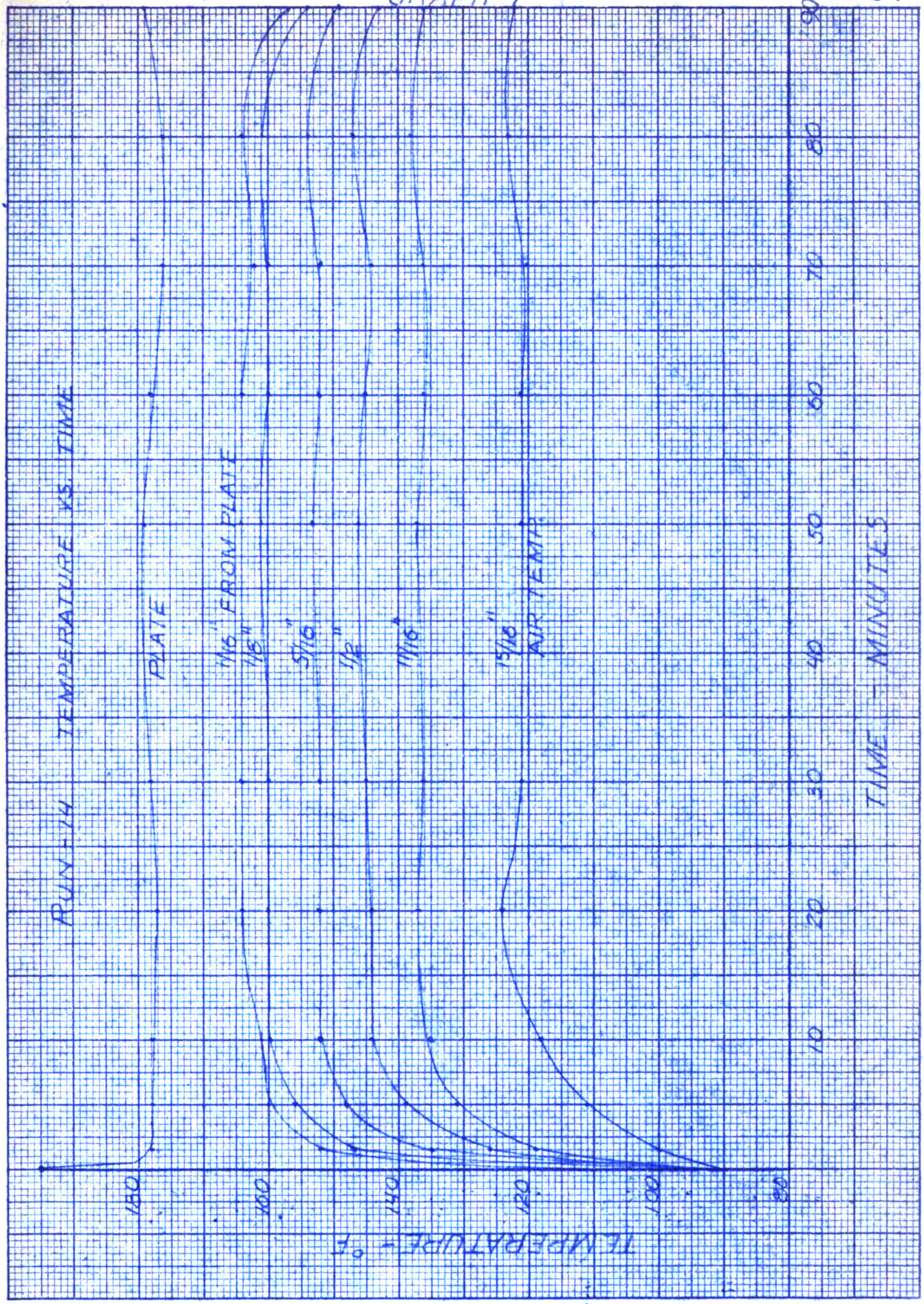
Time min.	Temperature °F. Plate	Interface	Temp. Diff.
.5	228	170	58
3.	213	193	20
5.	212	194	18
10.	211	198	13
15.	210	198	12
20.	211	200	11
25.	214	202	12
30.	222	190	32
40.	231	171	60
50.	233	160	73
65.	230	161	69
80.	227	169	58

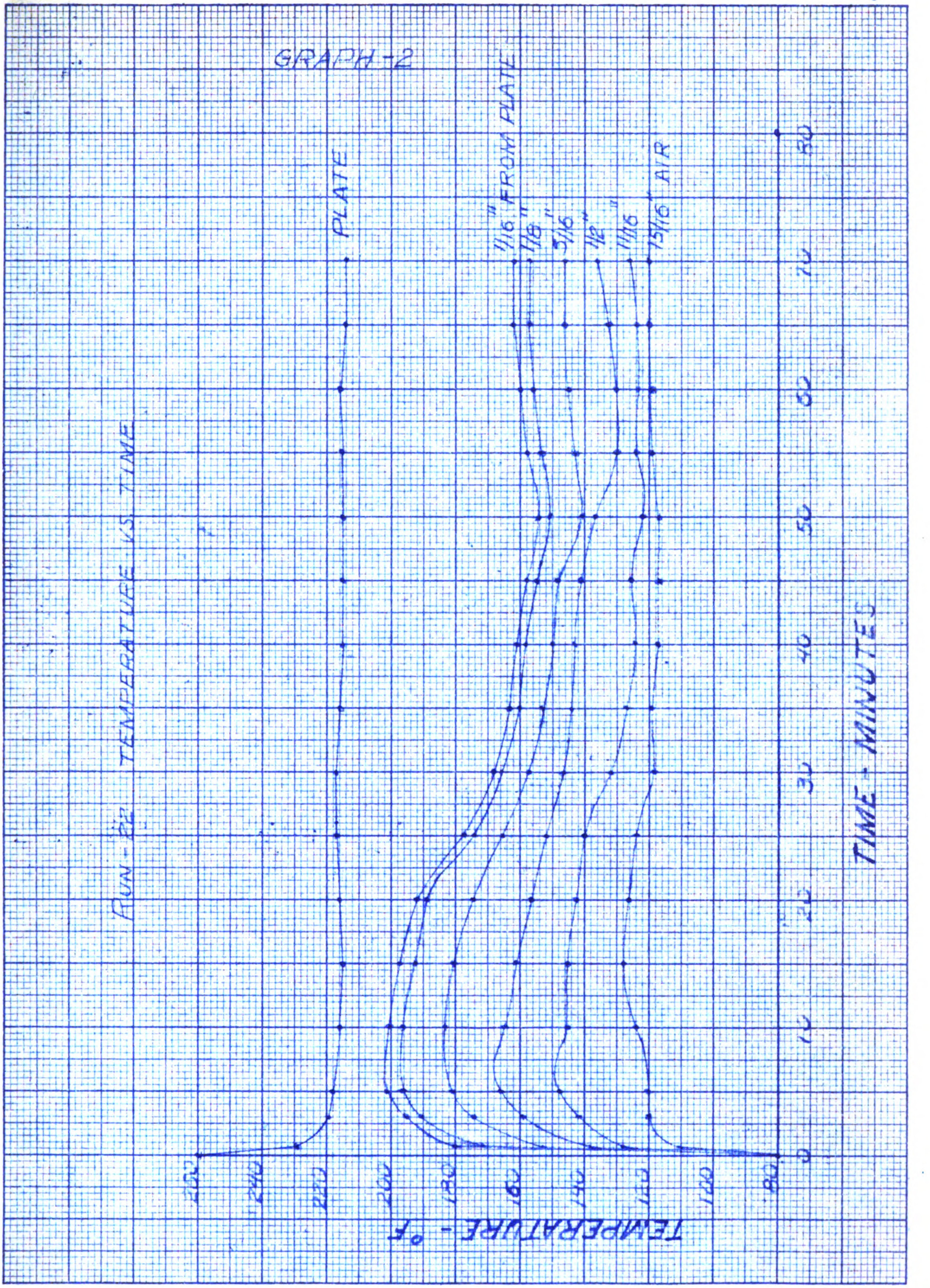
TABLE - XXII

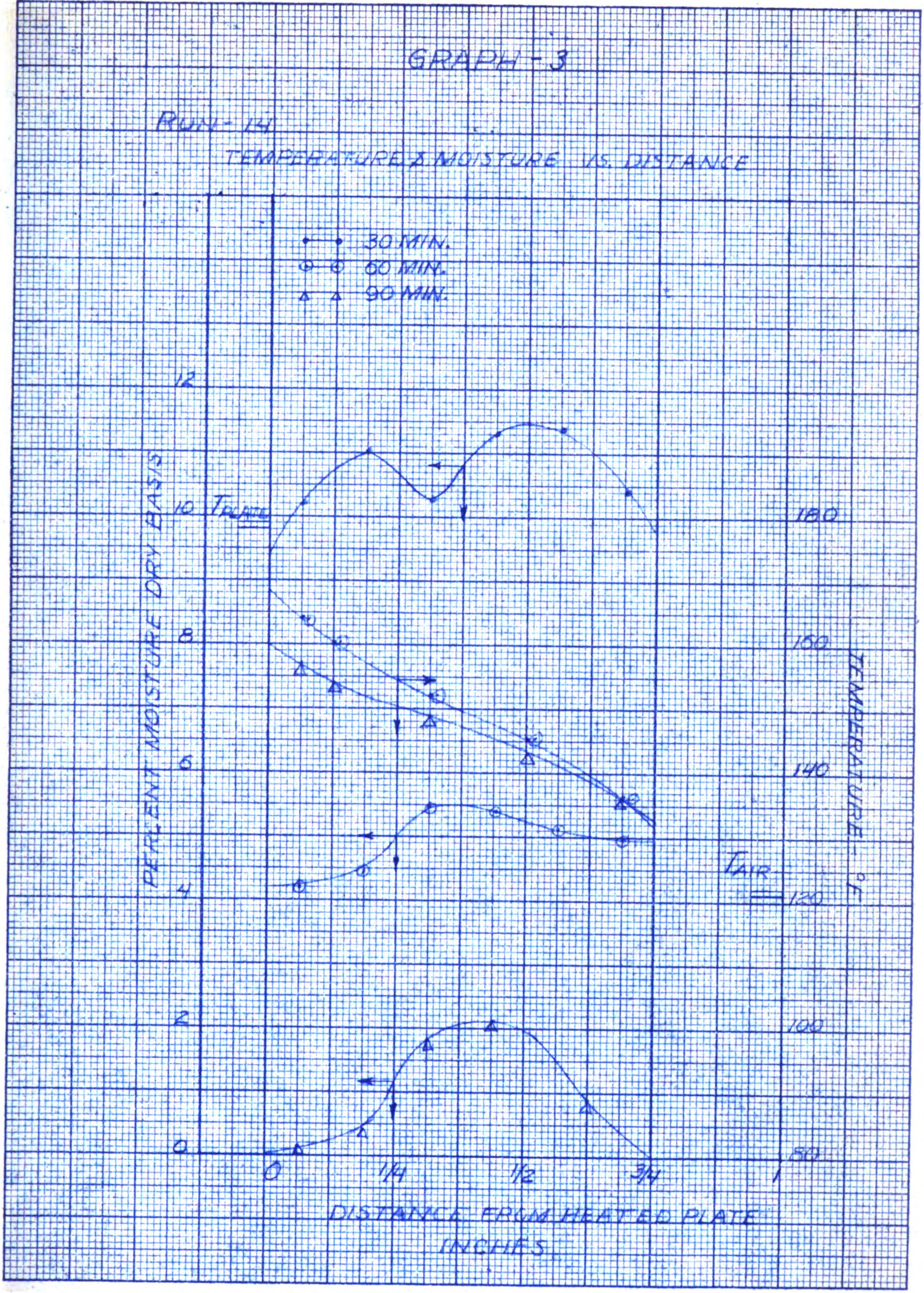
Run 22.

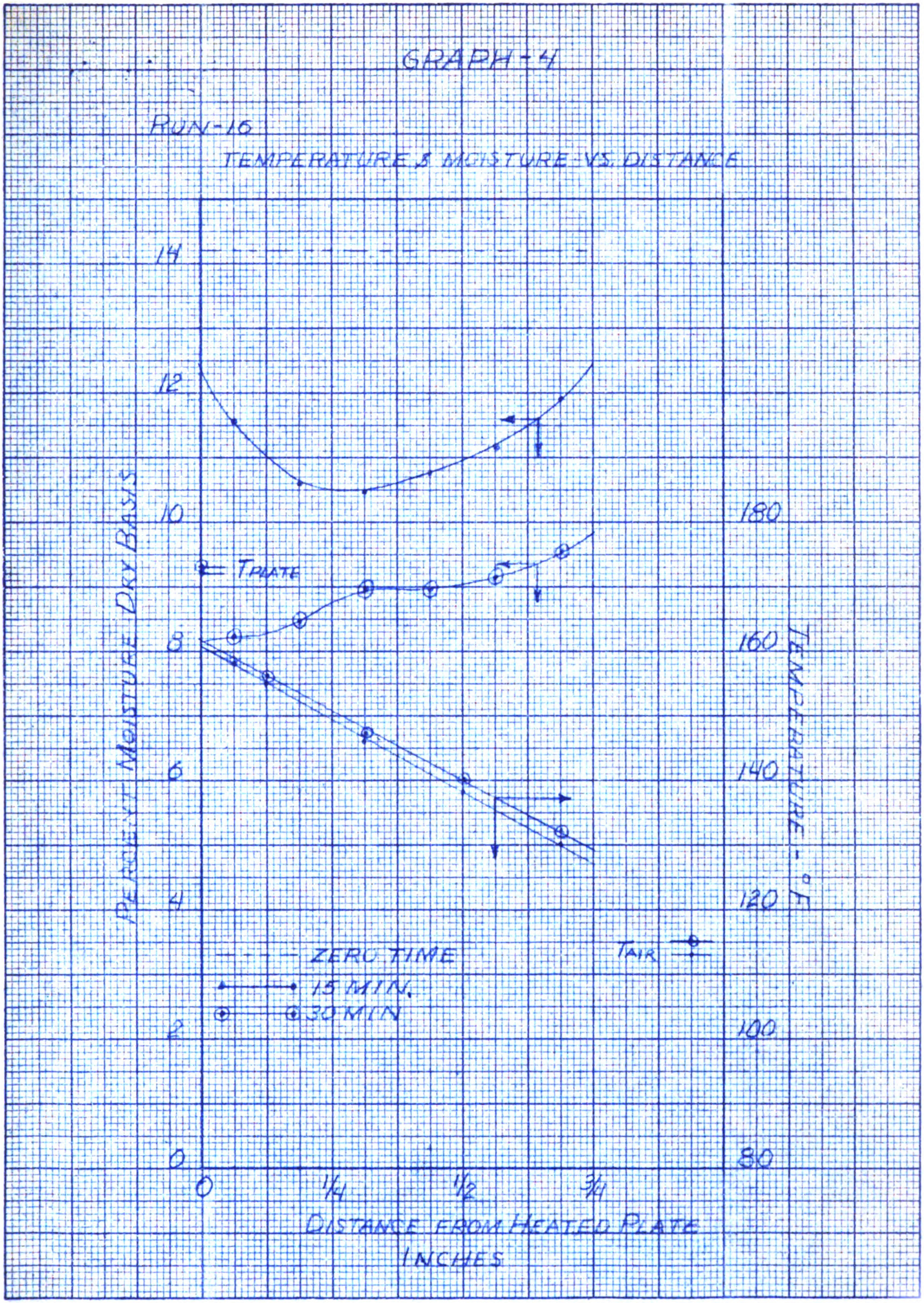
Time min.	Temperature °F. Plate	Interface	Temp. Diff.
.75	230	190	40
3.0	215	196	19
5.	218	206	12
10.	216	203	13
15.	215	202	13
20.	216	195	21
25.	217	180	37
30.	217	170	47
40.	215	163	52
45.	215	161	54
50.	215	158	57
55.	215	161	54
60.	216	163	53
70.	214	166	48

GRAPH-1

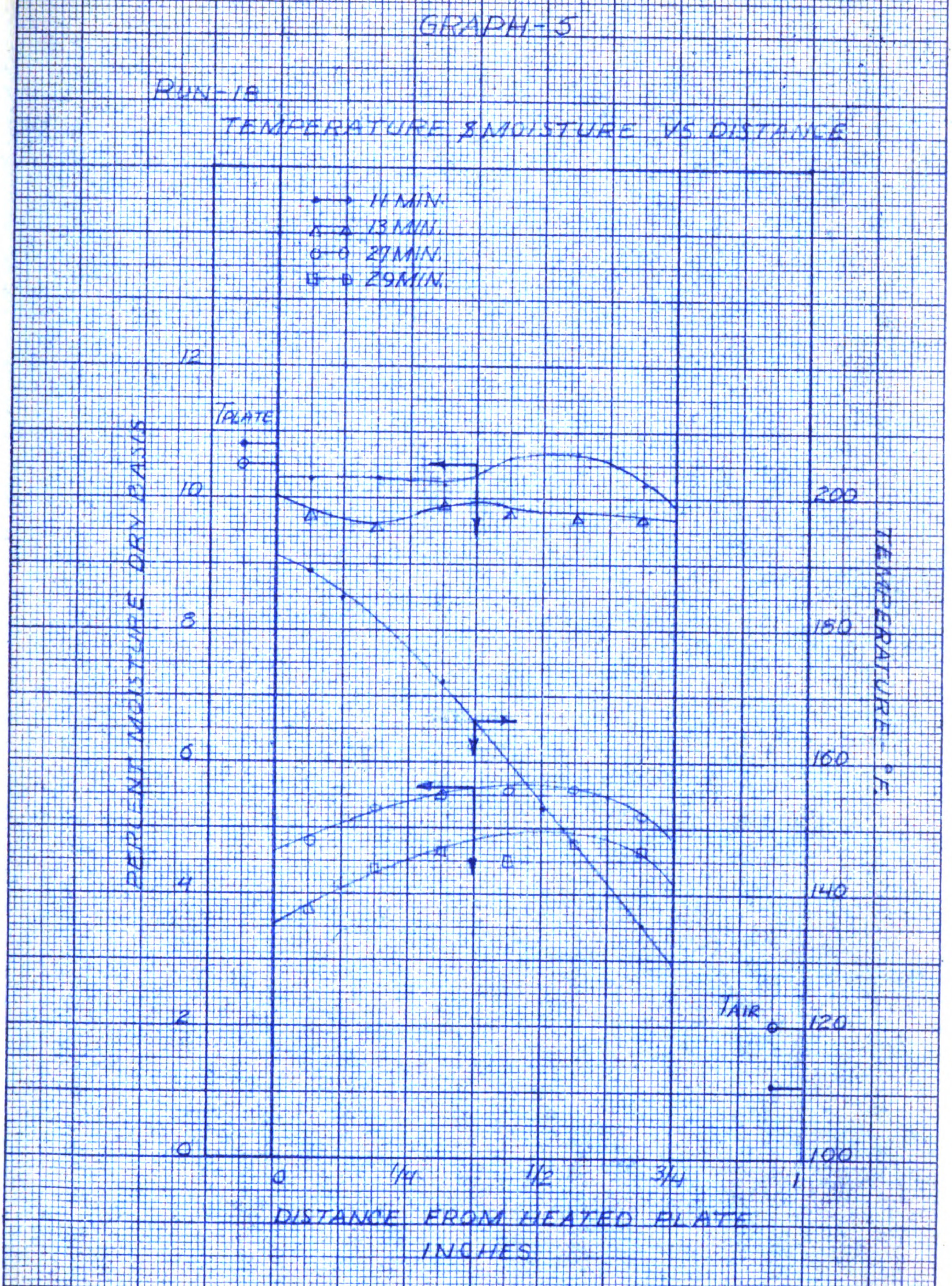

RUN-14 TEMPERATURE VS TIME
PLATE
1/16" FROM PLATE
1/8"
5/16"
1/2"
11/16"
15/16"
AIR TEMP.
TIME - MINUTES
10
20
30
40
50
60
70
80
90
TEMPERATURE - °F
80
100
120
140
160
180

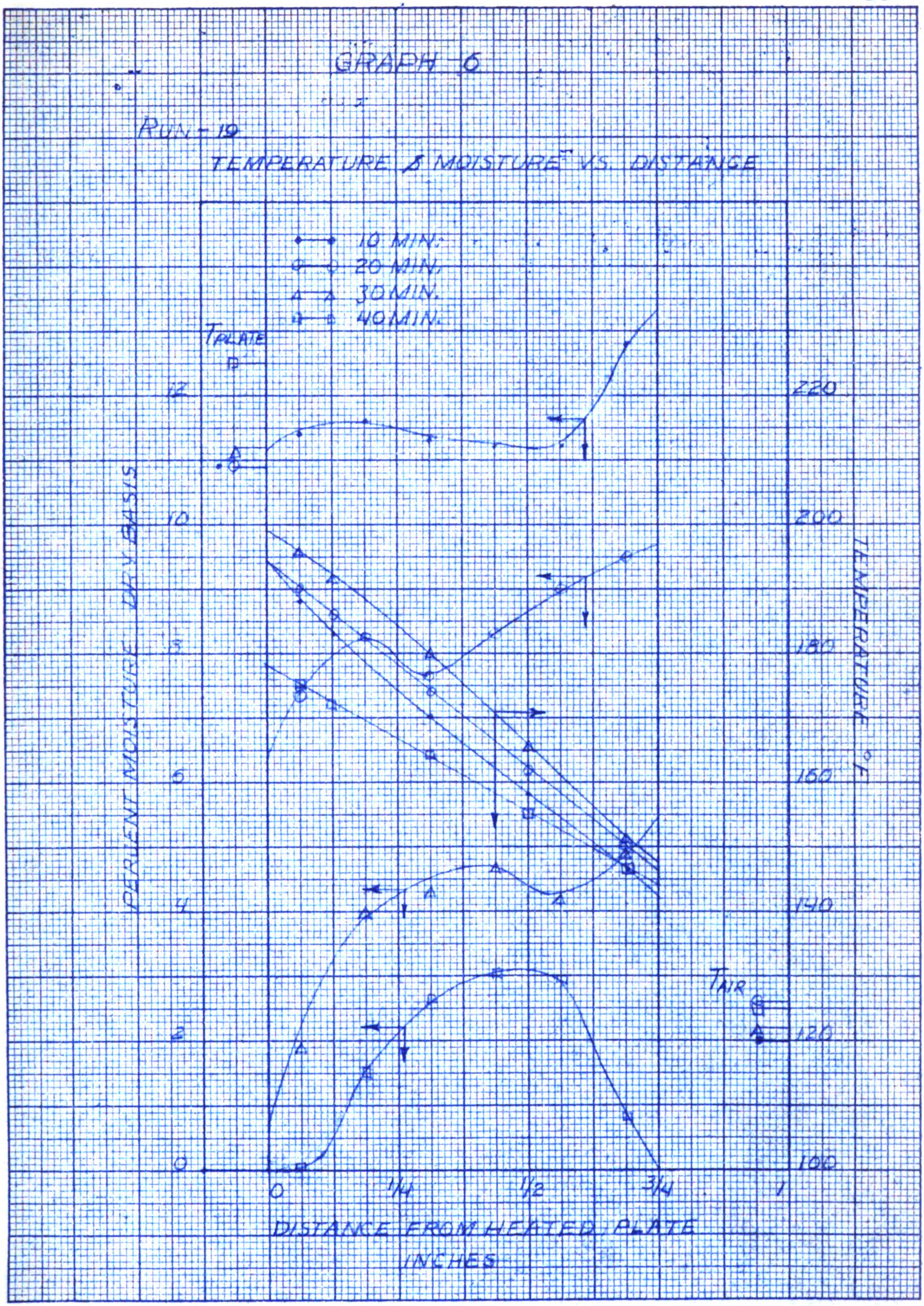

GRAPH - 2
RUN - 22 TEMPERATURE VS. TIME
PLATE
1/16" FROM PLATE
1/8"
5/16"
1/2"
11/16"
15/16" AIR
TEMPERATURE - °F
260
240
220
200
180
160
140
120
100
80
TIME - MINUTES
0
10
20
30
40
50
60
70
80

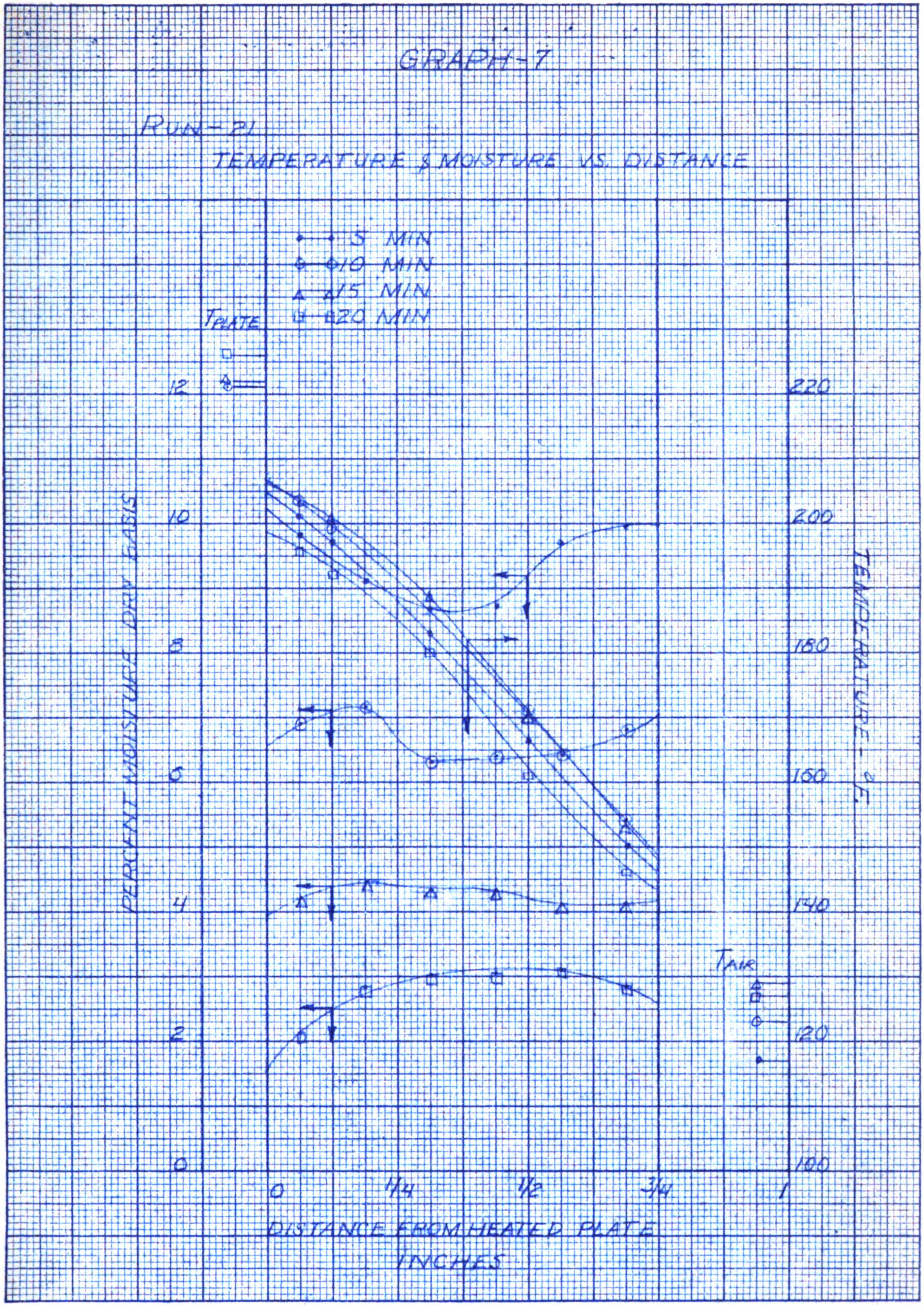

GRAPH - 3
RUN - 14
TEMPERATURE & MOISTURE VS. DISTANCE
30 MIN.
60 MIN.
90 MIN.
PERCENT MOISTURE DRY BASIS
TEMPERATURE - °F
T_{PLATE}
T_{AIR}
12
10
8
6
4
2
0
180
160
140
120
100
80
0
1/4
1/2
3/4
1
DISTANCE FROM HEATED PLATE
INCHES

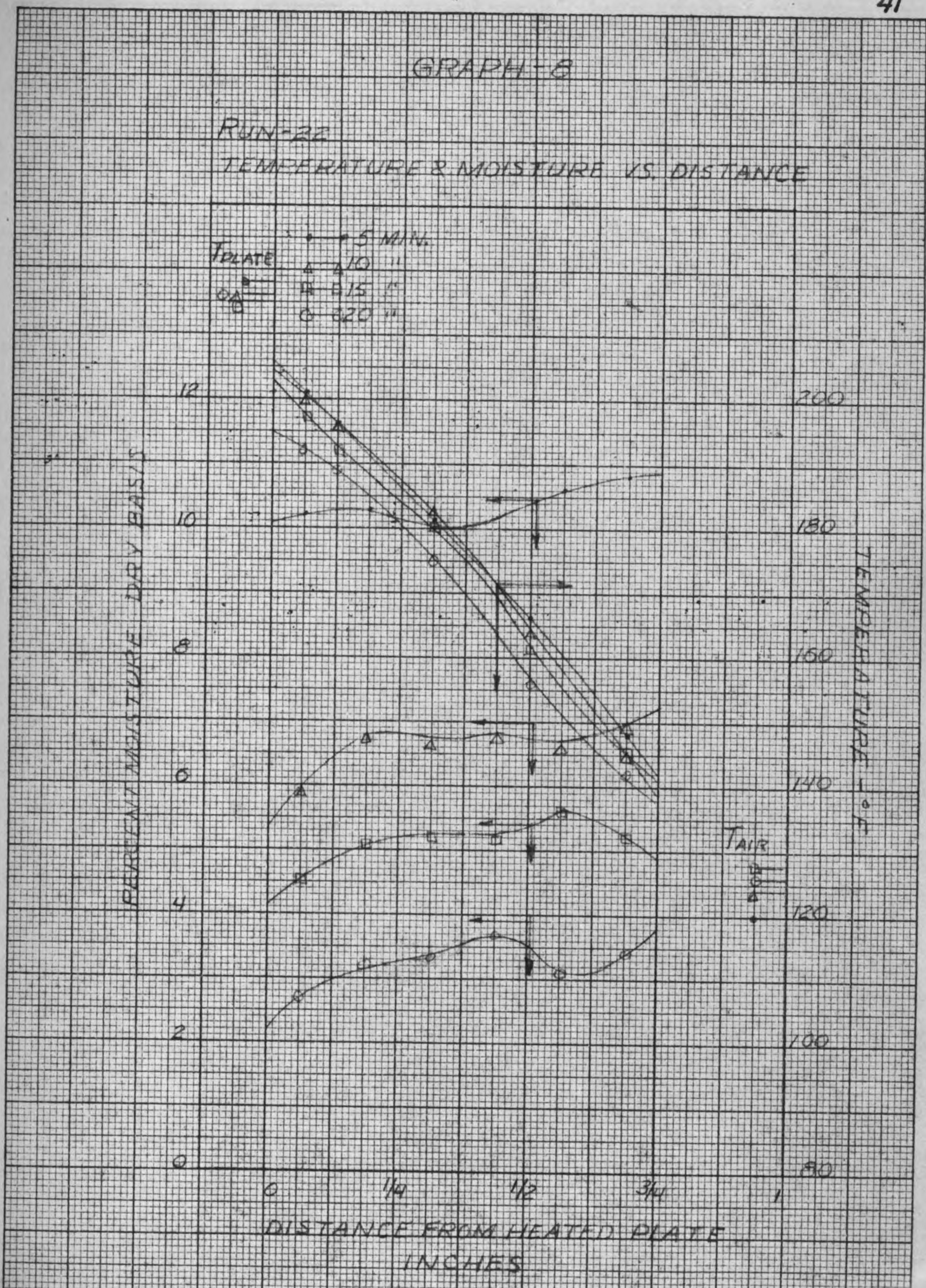


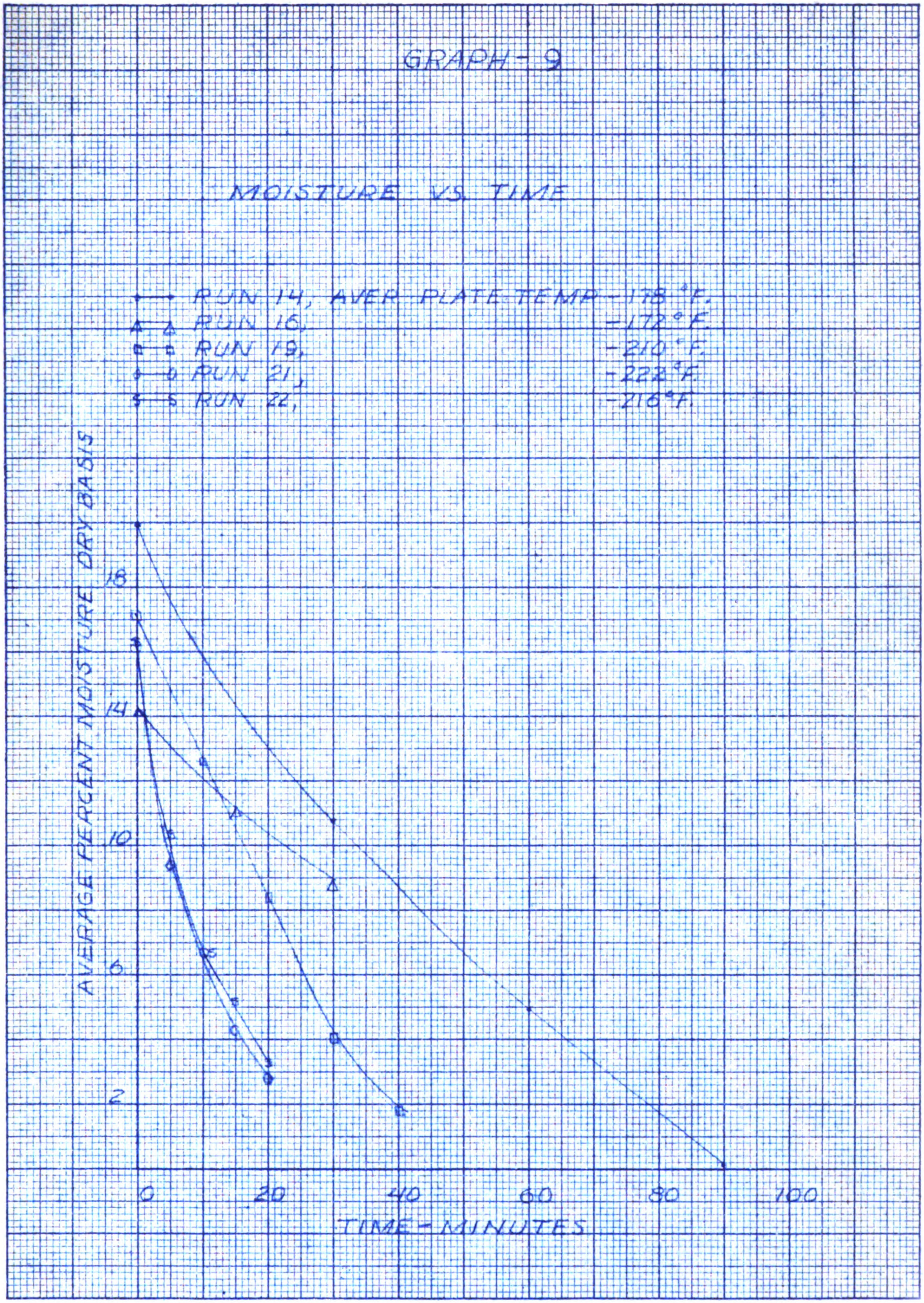
GRAPH - 4
RUN-16
TEMPERATURE & MOISTURE VS. DISTANCE
PERCENT MOISTURE DRY BASIS
TEMPERATURE - °F
TPLATE
TAIR
ZERO TIME
15 MIN.
30 MIN
0
2
4
6
8
10
12
14
80
100
120
140
160
180
1/4
1/2
3/4
DISTANCE FROM HEATED PLATE
INCHES

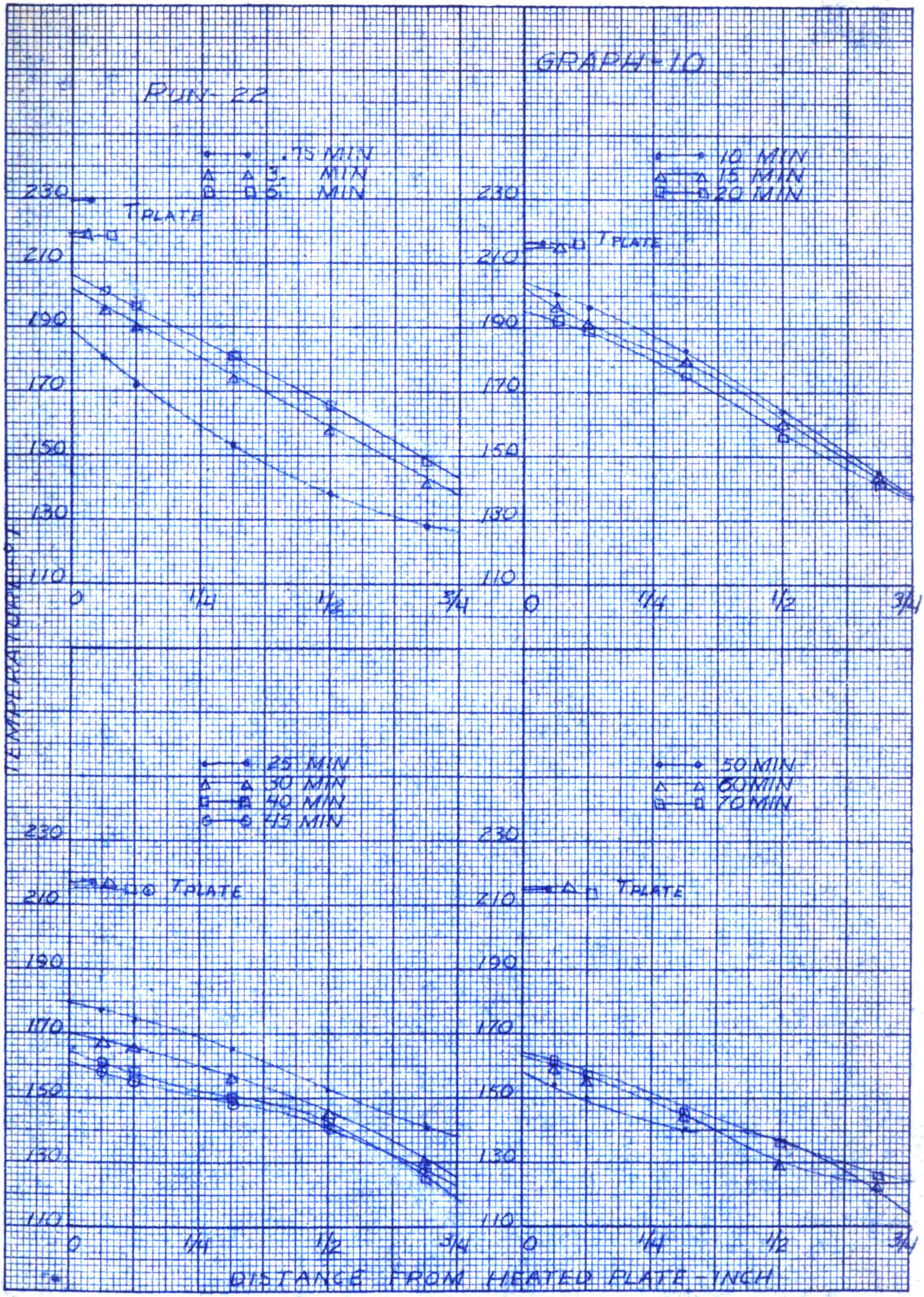

GRAPH-5
RUN-18
TEMPERATURE & MOISTURE VS DISTANCE
11 MIN.
13 MIN.
27 MIN.
29 MIN.
TPLATE
TAIR
PERCENT MOISTURE DRY BASIS
TEMPERATURE °F.
0
2
4
6
8
10
12
100
120
140
160
180
200
0
1/4
1/2
3/4
1
DISTANCE FROM HEATED PLATE
INCHES

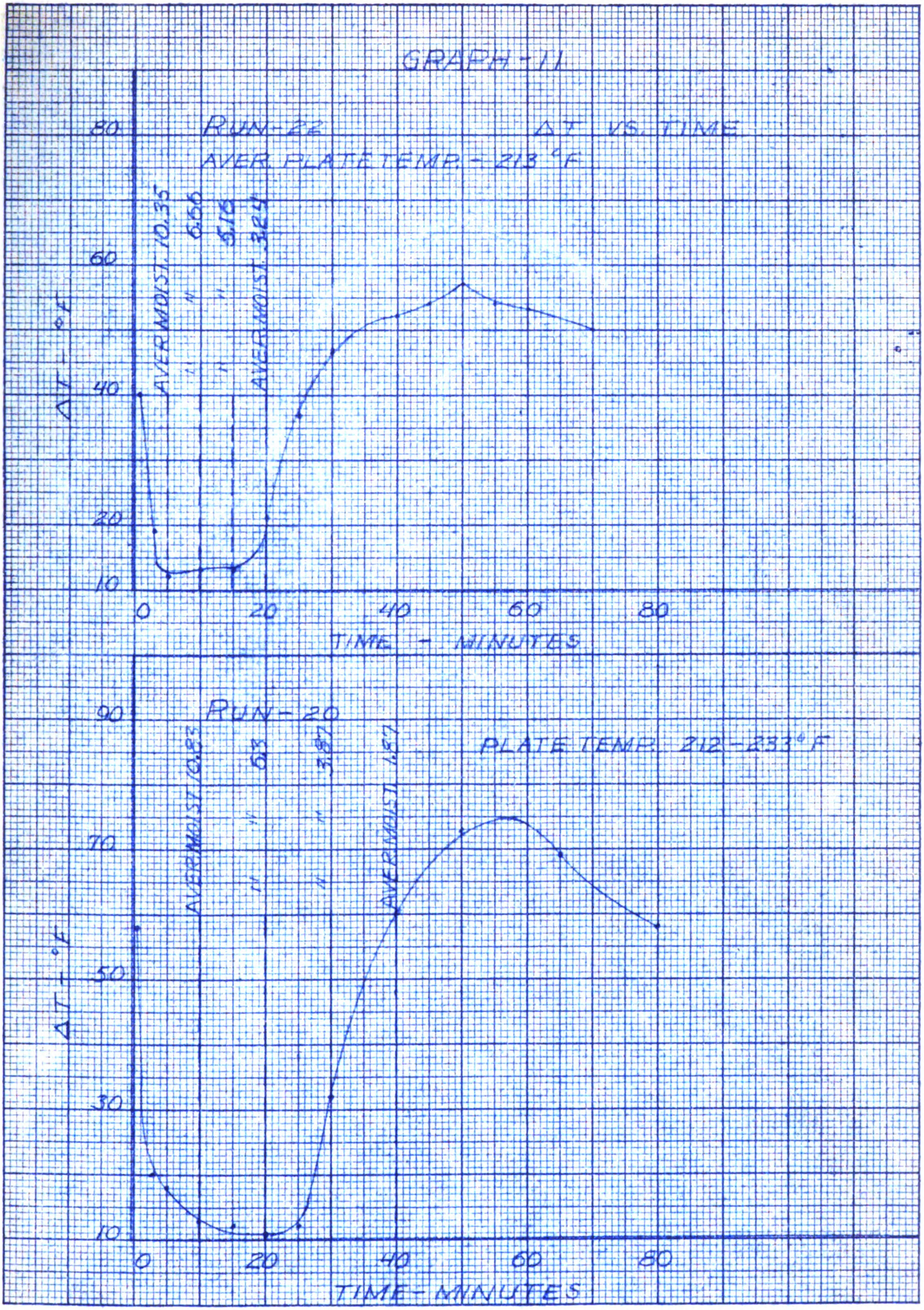

GRAPH 6
RUN - 19
TEMPERATURE & MOISTURE VS. DISTANCE
10 MIN.
20 MIN.
30 MIN.
40 MIN.
TPLATE
TAIR
PERCENT MOISTURE DRY BASIS
TEMPERATURE °F
0
2
4
6
8
10
12
100
120
140
160
180
200
220
0
1/4
1/2
3/4
1
DISTANCE FROM HEATED PLATE
INCHES

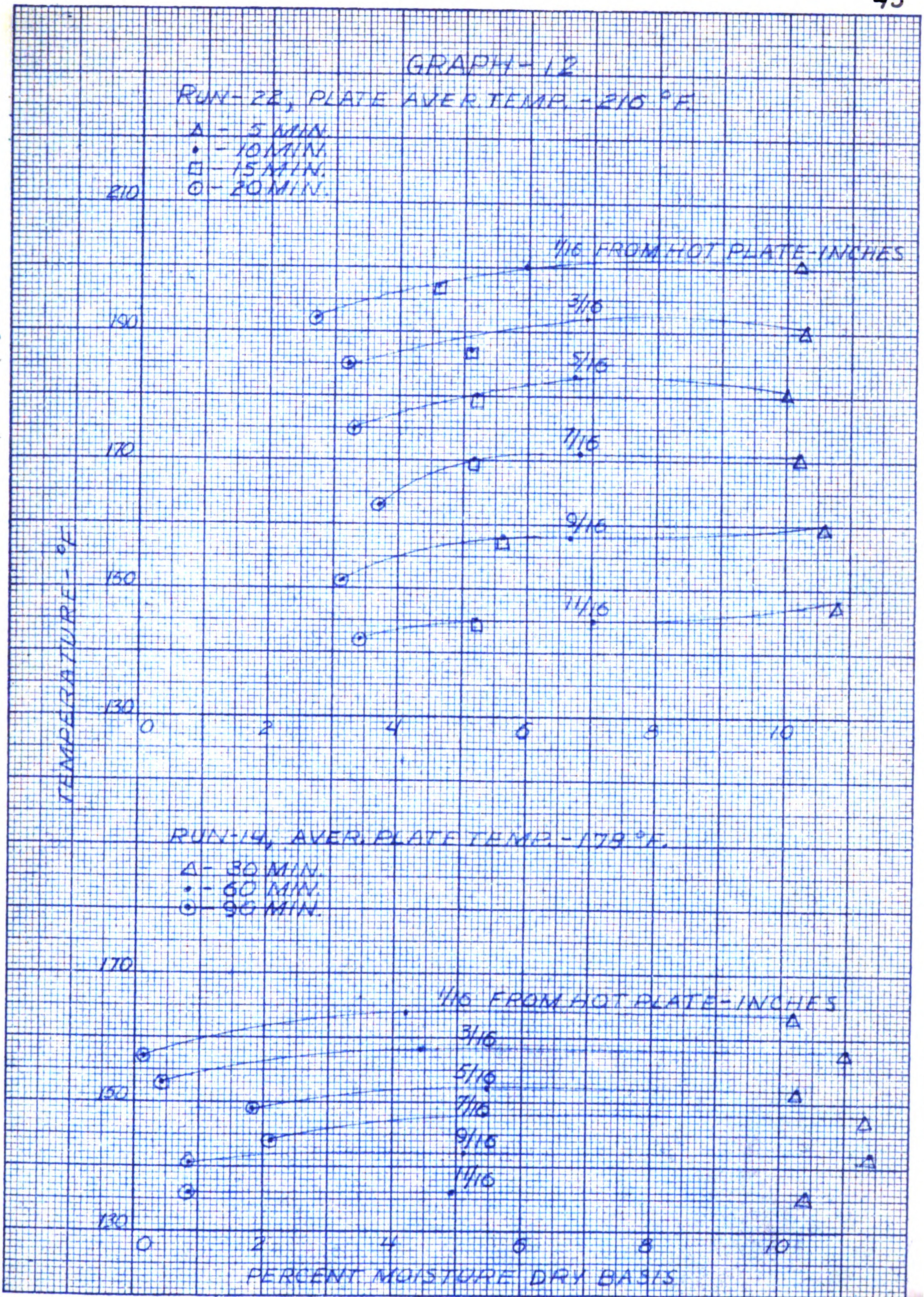

GRAPH - 7
RUN - 21
TEMPERATURE & MOISTURE VS. DISTANCE
5 MIN
10 MIN
15 MIN
20 MIN
TPLATE
TAIR
PERCENT MOISTURE DRY BASIS
TEMPERATURE - °F
12
10
8
6
4
2
0
220
200
180
160
140
120
100
0
1/4
1/2
3/4
1
DISTANCE FROM HEATED PLATE
INCHES

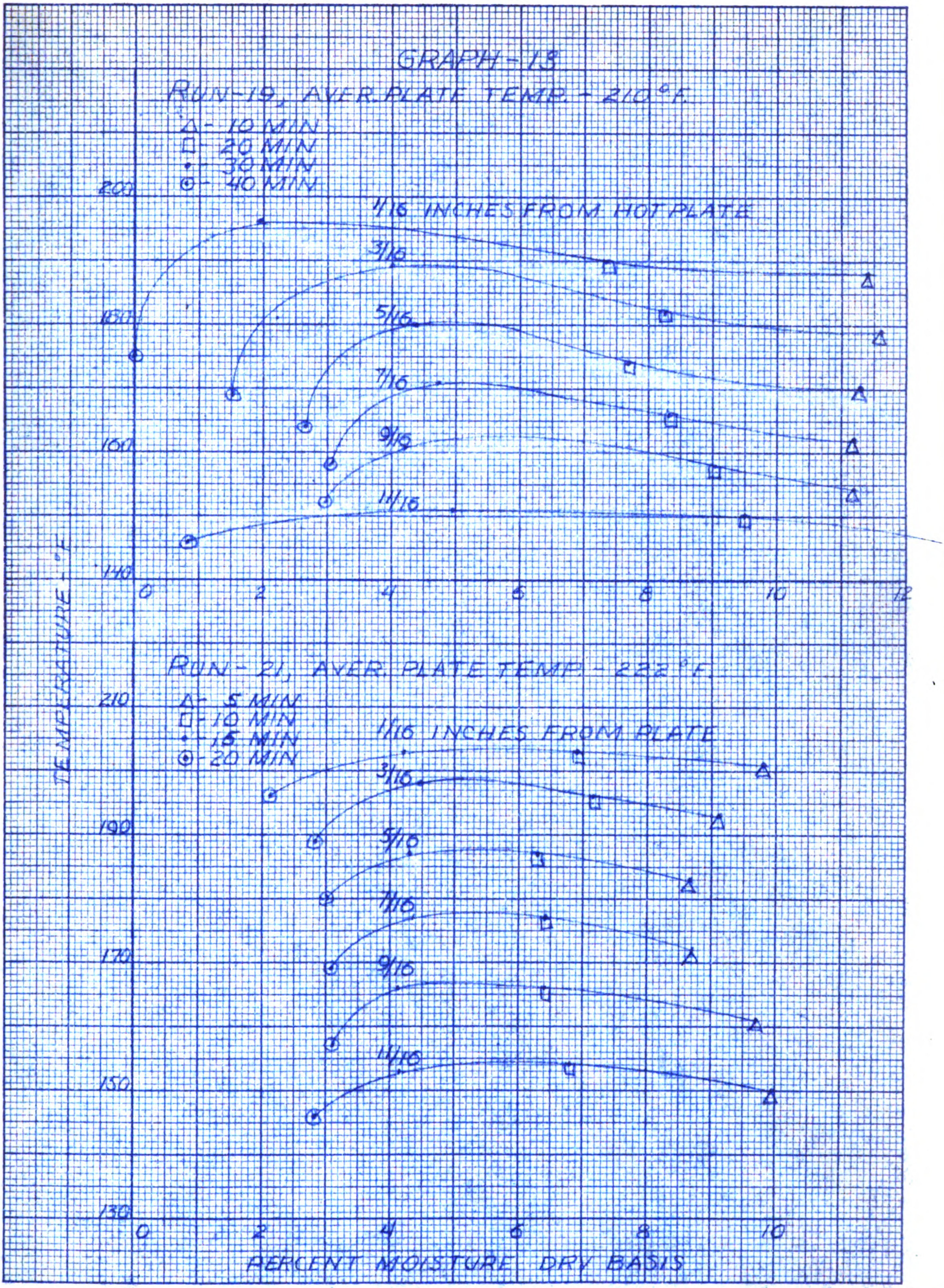

GRAPH-8
RUN-22
TEMPERATURE & MOISTURE VS. DISTANCE
5 MIN.
10 "
15 "
20 "
TPLATE
TAIR
PERCENT MOISTURE DRY BASIS
TEMPERATURE - °F
0
2
4
6
8
10
12
80
100
120
140
160
180
200
0
1/4
1/2
3/4
1
DISTANCE FROM HEATED PLATE
INCHES


GRAPH - 9
MOISTURE VS. TIME
RUN 14, AVER. PLATE TEMP. - 178 °F.
RUN 16, - 172 °F.
RUN 19, - 210 °F.
RUN 21, - 222 °F.
RUN 22, - 216 °F.
AVERAGE PERCENT MOISTURE DRY BASIS
18
14
10
6
2
0
20
40
60
80
100
TIME - MINUTES

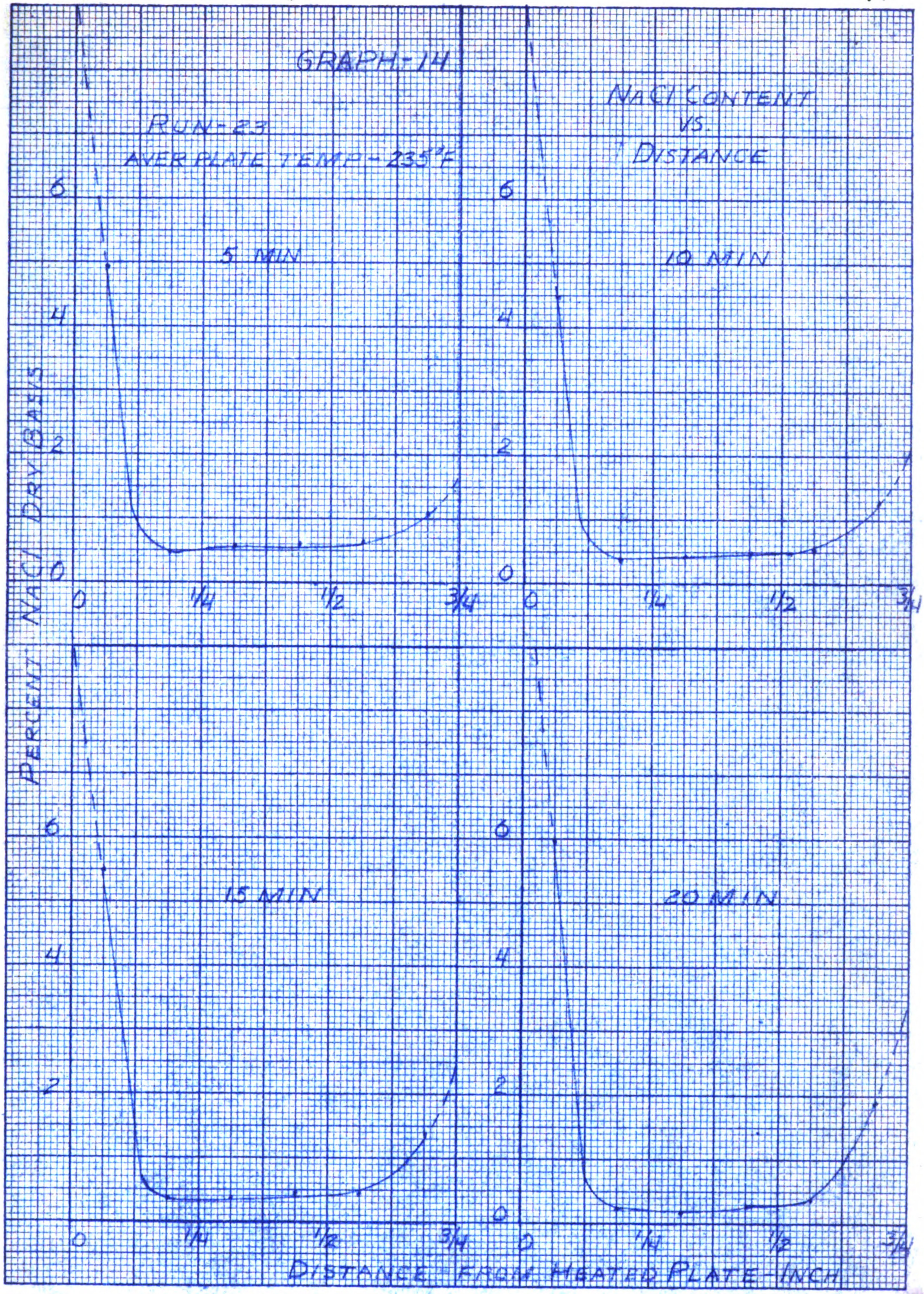

GRAPH-10
RUN-22
.75 MIN
3. MIN
5. MIN
TPLATE
10 MIN
15 MIN
20 MIN
TPLATE
25 MIN
30 MIN
40 MIN
45 MIN
TPLATE
50 MIN
60 MIN
70 MIN
TPLATE
230
210
190
170
150
130
110
0
1/4
1/2
3/4
TEMPERATURE - °F
DISTANCE FROM HEATED PLATE - INCH

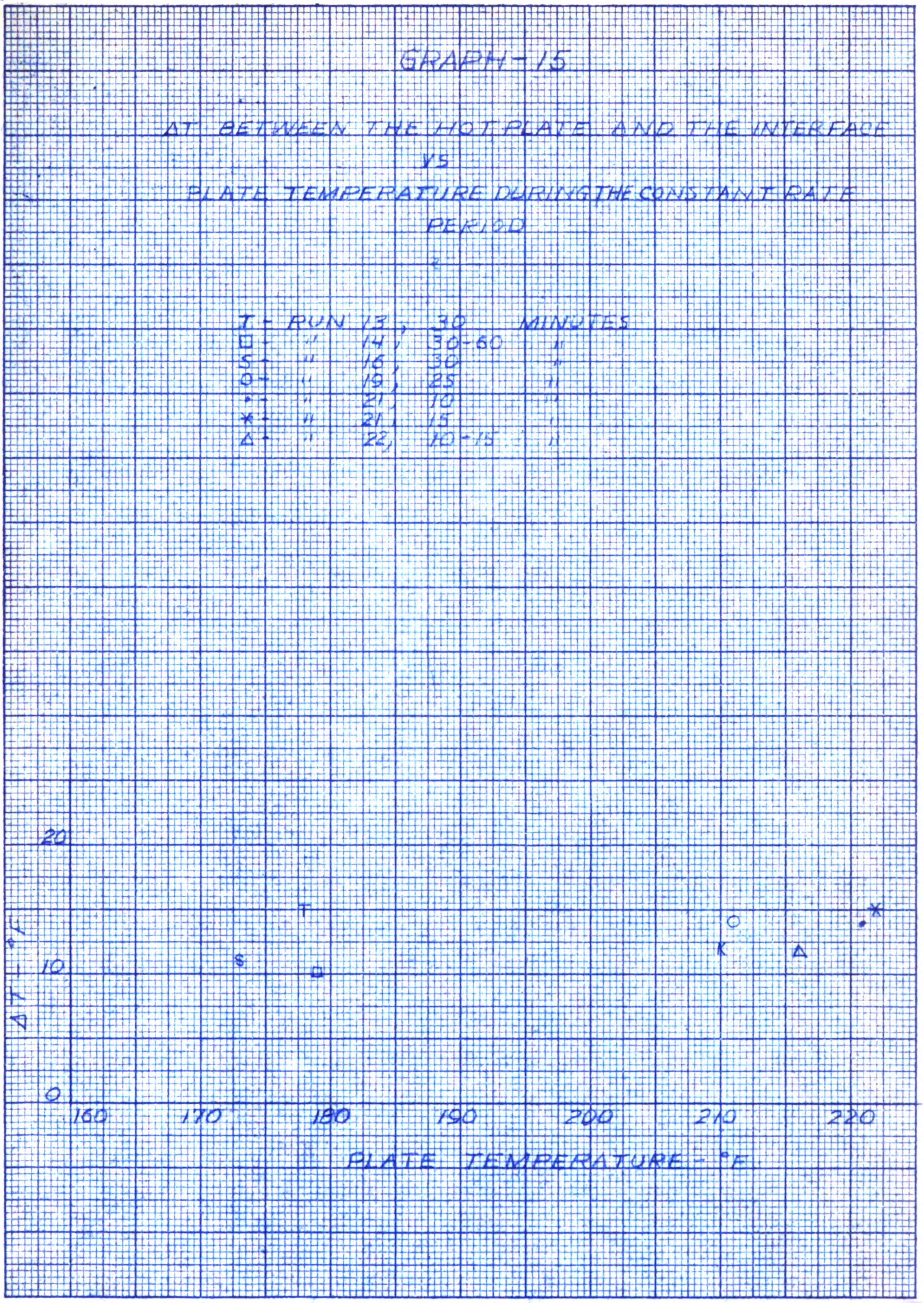

GRAPH - 11
RUN - 22
ΔT VS. TIME
AVER. PLATE TEMP. - 213 °F
AVER. MOIST. 10.35
" 6.66
" 5.16
AVER. MOIST. 3.24
ΔT - °F
80
60
40
20
10
0
20
40
60
80
TIME - MINUTES
RUN - 20
PLATE TEMP. 212 - 233 °F
AVER. MOIST. 10.83
" 6.3
" 3.87
AVER. MOIST. 1.87
ΔT - °F
90
70
50
30
10
0
20
40
60
80
TIME - MINUTES


GRAPH - 12
RUN - 22, PLATE AVER. TEMP. - 216 °F.
Δ - 5 MIN.
• - 10 MIN.
□ - 15 MIN.
⊙ - 20 MIN.
1/16 FROM HOT PLATE - INCHES
3/16
5/16
7/16
9/16
11/16
210
190
170
150
130
0
2
4
6
8
10
TEMPERATURE - °F
RUN - 14, AVER. PLATE TEMP. - 179 °F.
Δ - 30 MIN.
• - 60 MIN.
⊙ - 90 MIN.
170
150
130
1/16 FROM HOT PLATE - INCHES
3/16
5/16
7/16
9/16
11/16
0
2
4
6
8
10
PERCENT MOISTURE DRY BASIS



GRAPH - 13
RUN-19, AVER. PLATE TEMP. - 210°F.
△ - 10 MIN
□ - 20 MIN
• - 30 MIN
⊙ - 40 MIN
1/16 INCHES FROM HOT PLATE
3/16
5/16
7/16
9/16
11/16
200
180
160
140
0
2
4
6
8
10
12
RUN - 21, AVER. PLATE TEMP. - 222°F.
△ - 5 MIN
□ - 10 MIN
• - 15 MIN
⊙ - 20 MIN
1/16 INCHES FROM PLATE
3/16
5/16
7/16
9/16
11/16
210
190
170
150
130
TEMPERATURE - °F
PERCENT MOISTURE DRY BASIS


GRAPH-14
RUN-23
AVER PLATE TEMP-235°F
NaCl CONTENT
VS.
DISTANCE
5 MIN
10 MIN
15 MIN
20 MIN
PERCENT NaCl DRY BASIS
0
2
4
6
0
1/4
1/2
3/4
DISTANCE FROM HEATED PLATE-INCH


GRAPH - 15
ΔT BETWEEN THE HOT PLATE AND THE INTERFACE
VS
PLATE TEMPERATURE DURING THE CONSTANT RATE
PERIOD
T - RUN 13, 30 MINUTES
□ - " 14, 30-60 "
S - " 16, 30 "
O - " 19, 25 "
• - " 21, 10 "
* - " 21, 15 "
Δ - " 22, 10-15 "
0
10
20
ΔT - °F
160
170
180
190
200
210
220
PLATE TEMPERATURE - °F

DISCUSSION

There are three periods of drying: (1) a heating-up period where the solid is being heated to a constant rate; (2) the constant rate period during which the water is being vaporized at a constant rate, and (3) the falling rate period in which the drying rate is continuously decreasing. Drying includes all three periods providing that the critical moisture content has not been reached before the constant rate is involved.

The Heating-up Period

Moisture content was higher at the bottom of the slab before the slab was placed on the hot surface (see Table I). In this type of distribution, gravitational forces were controlling, and this accounted for the greater concentration of water at the bottom of the slab.

When the wet slab was placed on the hot surface, flash vaporization took place at the interface between the hot plate and the closed face of the sand slab. There was a great deal of vaporization. In fact, the system functioned as a packed distillation column. The vapor passed up through the bed condensing as it traveled. The use of sodium showed the effects of this heating-up period. In Run 23, the original sodium chloride content was 1.337 percent. During the five minutes before a sample was taken, the sodium was depleted to an average of 0.675 percent for the top

5/8 inches of the slab. The total thickness of the slab was 3/4 inches.

The migration of sodium chloride must be accompanied by a similar movement of liquid water. If the water is traveling downward as shown by the data, there must be a diffusion of water vapor up through the bed from the heated surface. This vapor condensed, diluting the solution of salt, and in turn carried the salt back to the bottom surface. This explains the high concentration of salt at the hot plate.

A rapid heating-up period followed placing the slab on the heated surface. The temperature increased to a maximum, at which time constant drying started. The diffusion of water vapor through the slab accounted for the relatively rapid heating-up period.

The plate temperature decreased to a minimum during the heating-up period. If the electric power was not controlled at this minimum point, the plate temperature started to increase. This decrease was caused by the vaporization of the water when the wet slab was placed on the plate. Also, the slab was at room temperature and had to be heated up until it was in equilibrium with the hot plate.

During this heating-up period, the moisture was distributed in an inverted bell shape manner. That is, the moisture was in greater concentration at the two faces. This type of curve was characteristic of samples taken during the heating-up period as shown by the data. When the curvature of the moisture distribution gradient reached a relatively flat position, the heating-up period ceased and the constant rate period started.

The Constant Rate Period

The constant rate period was characterized by constant conditions. The temperature reached a maximum in the slab and remained relatively constant. The temperature gradient was also constant during this period. The temperature difference between the hot plate and the closed face remained constant. Also, the moisture during this period was distributed evenly across the slab. There was very little moisture gradient.

The temperature in this period remained constant until the falling rate period was approached. There were slight variations caused by external conditions such as the plate temperature and air currents.

The temperature difference at the hot surface interface was constant. The temperature differences remained within the limits of ten and fifteen degrees for the constant rate period regardless of the plate temperatures that were used. Graph 15 shows this correlation between temperature difference and plate temperature when one was plotted against the other. These temperature differences and plate temperatures were taken from different runs during the constant rate period.

Transitional Period

There was no definite break between the constant rate period and the falling rate period. Rather there was a transitional period during which the closed face started to dry out faster than the rest of the slab. In other words, there was a lower moisture concentration at the heated surface.

In this period between the constant and falling rate periods, the zone of vaporization started to move upward toward the top surface of the slab. The graphs of moisture versus distance show that this movement of the zone of vaporization was characterized by a parabola type curve. The curve extends from a low at the hot surface interface, to a high point, and then to a low concentration of moisture. This movement of the zone of vaporization towards the open face is also supported by McCready (6).

The Falling Rate Period

In the falling rate period, the temperature declined. It decreased until the minimum was reached and then started to rise. The temperature gradient decreased in such a manner that the temperature near the hot plate decreased the most. The temperature at the open face remained constant for a period of time and then decreased also. As in Run 22, the temperature at the air interface remained constant for twenty minutes (see graph 10).

The temperature difference between the plate and the interface increased during the falling rate period. It increased to a maximum and then decreased. This increased temperature difference was caused by increased thermal resistance. The increased thermal resistance was due to the drying out of the sand at the interface. Graph 11 shows how this temperature difference changed during the drying process.

The moisture distribution during the falling rate period was a bell shaped curve. The moisture concentration was the greatest in the center portion of the sand slab. The slab was drying out at both surfaces. As drying proceeded, the two surfaces became completely dry.

The temperature decrease of the falling rate period occurred between the limits of 3.4 to 6 percent moisture, dry basis. A correlation of the moisture content and the temperature showed that the temperature in the slab decreased at a critical moisture content. Graphs 12 and 13 show that this critical point occurred within the same range for four different plate temperatures.

Drying Rates

The drying rate was the greatest for the higher plate temperature. When average moisture content was plotted against time, the slope of the curve gave the drying rate. Graph 9 shows that the slope of the curve for the higher plate temperatures is greater than the slopes for lower temperatures. The steeper the slope of the curve, the greater the drying rate.

Zones of Vaporization

Vaporization of moisture was taking place at both surfaces of the sand bed. This was indicated by the drying out of the two surfaces. Also, the data on the movement of sodium chloride showed that water was moving towards both surfaces. The greatest movement of water was in the direction of the heated surface. This movement of water to these surfaces indicated that vaporization was taking place there.

Sources of Possible Error

A certain amount of error was probably introduced while taking samples of sand. Vaporization of moisture most likely continued even after the sample was removed from the slab. To reduce this source of inaccuracy, the time element was reduced to a minimum.

It was felt that the temperatures recorded were within the limit of plus or minus one degree. It is possible that there may have been several occasions when this did not hold true.

Probably some error may have resulted in the construction and extension of curves.

CONCLUSION

Heating-up Period

1. Moisture content was higher at the bottom of the slab before the slab was placed on the hot surface.

2. On placing the sand slab on the hot plate, flash vaporization took place.

3. A rapid heating-up period followed placing the slab on the heated plate, and the temperature increased to a maximum at which time constant drying started.

4. The plate temperature decreased to a minimum.

5. The moisture was distributed in an inverted bell shape manner.

The Constant Rate Period

1. The temperature reached a maximum in the slab and remained relatively constant.

2. The temperature gradient was constant.

3. The temperature difference between the hot plate and the closed face remained constant.

4. The moisture was distributed evenly across the slab.

Transitional Period

1. There was no definite break between the constant rate period and the falling rate period.

2. The zone of vaporization started to move toward the top surface of the slab.

The Falling Rate Period

1. The temperature reached a minimum and then increased.

2. At first the temperature decreased faster at the heated surface than the open face.

3. The temperature difference between the plate and the interface increased to a maximum and then decreased.

4. The moisture distribution was a bell shaped curve.

5. The temperature decrease of the falling rate period occurred between the limits of 3.4 to 6 percent moisture, dry basis.

Drying Rates

1. The drying rate was the greatest for the higher plate temperature.

Zones of Vaporization

1. There were two zones of vaporization. One starting at the hot plate interface, and the other starting at the open face.

2. The greatest movement of liquid water was toward the heated surface.

BIBLIOGRAPHY

1. Badger, W. L. and McCabe, W. B., Elements of Chemical Engineering, 2nd ed., McGraw-Hill (1936).

2. Ceaglske, N. H. and Hougen, O. A., "The Drying of Granular Solids", Trans. Am. Inst. Chem. Eng., 33, 283-314 (1937).

3. Kirschbaum, Emil, Z. Ver. deut. Ing., Verfahrenstech, No. 3, 84-7 (1943).

4. Lewis, McAdams, and Adams, Pulp and Paper Mag. (Canada), 25, 122 (1927).

5. Marshall, W. R., Jr., "Drying" in Encyclopedia of Chemical Technology, The Interscience Encyclopedia, Inc., Vol. 5, 232-265 (1950).

6. McCready, D. W., "Drying of Pulp and Paper", Paper Trade J., 101, No. 13, 66-71 (1935).

7. Oliver, T. R. and Newitt, D. M., "The Mechanism of Drying Solids, Part II", Trans. Inst. Chem. Eng., 27, 9-18 (1949).

8. Pearse, J. F., Oliver, T. R., and Newitt, D. M., "The Mechanism of Drying of Solids, Part I", Trans. Inst. Chem. Eng., 27, 1-8 (1949).

9. Perry, J. H., Chemical Engineers Handbook, 3rd ed., McGraw-Hill (1950).

10. Sherwood, T. K., Ind. Eng. Chem., 24, 976 (1929).

11. Sherwood and Cummings, "Mechanism of Drying of Clay", Ind. Eng. Chem., 25, 311-316 (1933).

12. Shroff, P. D., "Drying of Paper Pulp on a Heated Surface," Unpublished M.S. Thesis, Mich. State College (1949).

13. Stacey, A. E., "Drying Rate Efficiency", Trans. Am. Inst. Chem. Eng., 16, 169-81 (1924).

14. Walker, et. al., Principles of Chemical Engineering, 3rd ed., McGraw-Hill (1937).

APPENDIX

TABLE - XXIII

Run 11.

Pressure 733
Room temperature 80°F.
Wet bulb temperature 74°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0	187						
2.	169	141	138	127	120	116	104
4.	170	150	147	138	132	125	108
5.	170	153	150	142	135	127	108
10.	170	155	153	145	139	131	112
15.	170	155	153	146	139	132	114
20.	170	155	153	146	140	133	115
30.	170	155	153	146	140	133	114

TABLE - XXIV

Run 11.

Time min.	Percent Moisture Content - $\frac{\text{Gms. Water}}{\text{Gms. B. D. Sand}}$ Distance from Plate - Inches 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Total Aver.
0							15.95
15	13.7	11.95	13.5	14.	14.1	14.1	13.45
30	10.7	9.85	10.5	10.93	11.9	12.93	11.14

Pressure 733 mm.
Room temperature 86°F.
Wet bulb temperature 74°F.

TABLE - XXV

Run 20.

Pressure 741 mm.
Room temperature 78°F.
Wet bulb temperature 66°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air 15/16
0.	248						
.5	228	165	160	134	117	109	96
3.	213	183	182	165	146	132	107
5.	212	190	186	171	155	140	114
10.	211	193	189	176	161	145	122
15.	210	194	191	178	162	143	124
20.	211	196	192	180	164	156	125
25.	214	199	189	186	166	150	126
30.	222	185	181	170	157	145	121
35.	229	171	168	160	150	137	113
40.	231	168	165	157	148	139	122
50.	233	158	156	150	141	128	113
65.	230	160	158	146	130	123	117
80.	227	166	163	151	137	122	118
95.	224	166	163	152	140	130	117

TABLE - XXVI

Run 20.

Pressure 741 mm.
Room temperature 78 °F.
Wet bulb temperature 66 °F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches: 0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	Total Aver.
10.	10.7	10.2	9.93	10.45	11.38	12.3	10.83
20.	5.13	5.96	6.3	6.75	7.1	7.15	6.3
30.	2.34	3.54	4.1	4.36	4.52	4.39	3.87
40.	0.63	1.8	2.54	2.76	2.54	.96	1.87

TABLE - XXVII

Run 23.

Pressure 739 mm.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air Temp. 15/16
0	282						
.5	247	176	166	147	132	119	107
5.0	234	205	205	188	164	157	121
10.	235	206	205	193	171	148	128
15.	239	204	202	191	172	148	131
18.	229	199	198	189	169	148	131

TABLE - XXVII

Run 23.

Pressure 739 mm.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air Temp. 15/16
0	282						
.5	247	176	166	147	132	119	107
5.0	234	205	205	188	164	157	121
10.	235	206	205	193	171	148	128
15.	239	204	202	191	172	148	131
18.	229	199	198	189	169	148	131

TABLE XXVIII

Run 23.

Pressure 739 mm.

Time min.	Percent Moisture Content – Gms. Water / Gms. B. D. Sand — Distance from Plate – Inches						Total Aver.
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
0.							
5.	11.40	11.30	11.40	11.40	11.67	12.8	11.66
10.	5.90	10.00	10.00	10.20	10.23	11.17	9.58
15.	7.92	9.05	9.03	9.40	8.53	7.38	8.55
18.	4.92	6.38	6.85	7.38	6.44	5.84	6.30

TABLE - XXIX

Run 24.

Pressure 737 mm.
Room temperature 85°F.
Wet bulb temperature 78°F.

Time min.	Plate	Temperature - °F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air Temp. 15/16
0.	296						
1.5	247	203	188	166	164	134	106
3.5	240						
5.	240	208	208	194	180	152	120
10.	243	208	203	195	180	157	134
15.	242	208	206	195	180	159	137
20.	243	202	198	186	172	154	138
30.	242	177	176	163	154	134	125

TABLE - XXX

Run 24.

Pressure 737 mm.
Room temperature 85°F.
Wet bulb temperature 78°F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand						Total Aver.
	Distance from Plate - Inches						
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
0							
5	7.72	8.28	8.55	8.85	8.13	8.74	8.39
10	4.90	5.96	7.61	6.01	6.25	6.11	6.13
15	2.52	3.34	3.86	3.91	4.33	4.55	3.75
20	0.45	1.67	2.55	2.69	2.63	2.36	2.07

TABLE - XXXI

Run 25.

Pressure 733 mm.
Room temperature 83°F.
Wet bulb temperature 77°F.

Time min.	Percent Moisture Content - Gms. Water / Gms. B. D. Sand — Distance from Plate - Inches						Total Aver.
	0-1/8	1/8-1/4	1/4-3/8	3/8-1/2	1/2-5/8	5/8-3/4	
0							16.2
10	9.45	9.00	9.54	10.26	9.61	10.40	9.7
20	4.94	5.82	6.04	6.45	6.20	6.40	5.98

TABLE - XXXII

Run 25.

Pressure 738 mm.
Room temperature 83°F.
Wet bulb temperature 77°F.

Time min.	Plate	Temperature - ° F. Distance from Plate - Inches 1/16	1/8	5/16	1/2	11/16	Air Temp. 15/16
0.	276						
1.	259	195	186	159	124	114	97
5.	236	206	203	190	168	147	115
10.	236	206	206	194	172	148	121
15.	235	206	204	193	169	148	126
20.	232	202	196	187	166	148	126