DRYING OF PAPER PULP ON A HEATED SURFACE

Thesis for the Degree of M. S.

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THESIS

This is to certify that the

thesis entitled

THE DRYING OF PAPER PULP
ON A HEATED SURFACE

presented by

PHIROZE DHUNJISHAW SHROFF

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Randall W Ludt
Major professor

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DRYING OF PAPER PULP ON A HEATED SURFACE

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INTRODUCTION

Drying is one of the most important processes used in the production of paper. It is important because the heat requirement is a major item in determining manufacturing costs and because low drier capacity may limit production. Machine speed and production can frequently be increased by increasing the capacity of the drier section.

The object of studies on the process is to obtain data upon which to base the design and operation of equipment. Developments in the theory and mechanism of drying can be expected to lead to economies both in operating and capital costs. Generally these factors have been based on the results from previous installations or on established procedures. Very little scientific information is now available.

Several different types of driers are used in the manufacture of paper, but they employ the same general principles. The web formed on the wet-end of the machine is passed over a wire mesh, then across suction boxes and finally through press rolls. In this way most of the water is removed, and the sheet now containing about 60 per cent moisture is dried on steam heated rolls.

The drier section may consist of a series of steam heated drums, 48 inches in diameter. The paper passing over the rolls has alternately one of its faces and then the other, in contact with the drier surface. This method of drying is known as drum drying. Another method commonly employed makes use of a single large drum, 10-12 feet in diameter which is called a Yankee drier. This is also a continuous process, the sheet is pressed on to the drum so that during the entire drying period only one of its

faces is in continuous contact with the heated surface.

Thus it is seen that air drying is not applicable to drier sections of paper machines while continuous drying on a heated surface applies specifically only to Yankee driers and not to a series of drum driers.

Most of the experimental work on the drying of paper has been done with air drying. A small amount of work has been done with heated surfaces which corresponds to conditions on a Yankee drier. However, apparently only plant tests have been made on a series of drum driers. Some of the conditions found in air drying have been shown to exist when the material is dried on a hot surface. It is to be expected that the results obtained with heated surfaces can be corelated with the drying of paper on a series of drum driers. This work is being directed towards a better understanding of the mechanism existing on Yankee paper driers.

HISTORY

Many investigators have reported data on air drying processes, but few have investigated drying by a heated orifice. The important hypotheses on the air drying mechanism have been advanced by Lewis (12,13) and Sherwood (29,30,31,33). Four possible mechanisms of drying have been postulated and their characteristics given. They are:

(i) Saturated Surface Drying: The flow of water within the solid keeps the surface saturated so the equivalent of a film of water was presented to the drying air. The mechanism of drying was similar to the evaporation of water from a free liquid surface as described by Badger & McCabe (6) and Walker et. al. (45). All factors remain constant so the rate of drying is constant. This was the mechanism of drying in the internal of constant rate drying.

(ii) Unsaturated Surface Drying: The flow of water in the solid was sufficient to keep the hollows in the surface saturated with water, the high points being dry. The rate of drying decreases in proportion to the decrease in saturated area. The over-all coefficient of heat transfer remained constant and equal to the value in the internal of constant rate drying which indicated that water was evaporating at the surface of the solid.

(iii) Rate of Liquid Water Diffusion Through the Solid is the Controlling Factor: Water was evaporated at the surface of the solid as rapidly as it could diffuse to the surface from the interior. The rate of drying decreased as the rate of diffusion of liquid water decreased and the latter was a function of the thickness of the sample.

(iv) Evaporation of Water in the Interior of the Solid: The zone of vaporization of water was in the interior of the solid and its location depended upon a balance of the rate of flow of water into and the water vapor out of it. The rate of drying and the over-all coefficient of heat transfer decreased and a layer of dried solid was formed beneath the surface, as the zone of vaporization retreated into the interior of the solid.

Sherwood (29) has mentioned that mechanism (iii) applies to relatively non-porous materials and (iv) to porous materials but has not suggested at what porosity the mechanism changes. The mechanism of pulp drying has been showen to be of type 4.

McCready (15) has pointed out that the formulation of the drying mechanism could be based on the rates of flow of heat and water vapor between the air and the zone of vaporization or on the rate of transfer of liquid water through the solid. These are of little value as they did not include the rate of drying as a function of the water content of the solid.

Lewis, McAdams, and Adams (13) analyzed data on the drying of pulp and paper on drum driers. Sherwood (33) presented a means of calculating the influence of heat in flow through non-drying faces on the rate of drying. Stacey (40) and Sherwood and Cummings (38,39), have reported and discussed data on the drying of various materials in pans, a method which is similar to drying on heated surfaces. Diffusion equations analogous to those for unsteady heat conduction have been developed for application to the drying of solids (35). Sherwood (34) has discussed the application of theoretical diffusion equations to the drying of solids, which appeared to give reasonably close agreement with experimental data. However since some of the postulates were subject to criticism, Newman (21,22) suggested a new hypothesis. In support of it he obtained the liquid concentration-time-location relations in the interior of porous solids, together with equations developed for various shapes. The equations were integrated to give the average liquid concentration as a function of drying time. On the basis of his hypothesis he has derived diffusion and surface emission equations for the drying of porous solids.

Sherwood (29) performed experiments on the drying of various solids and the case of drying by internal diffusion of the liquid to the surface with negligible resistance to the removal of vapor was discussed in detail. The Fourier equations of heat conduction in solids have been showen to apply to the drying of solid slabs by this mechanism, and a method was described by which the equation may be used in the analysis of drying data.

In another paper, Sherwood (30) has described the effect of adjoining dry surfaces. Radiation from the surroundings and air velocity on the rate of drying of solids in the constant rate of drying period. He has derived a simple emperical equation to fit the data reasonably well in the falling rate period and to afford a simple basis of calculation in drier design.

McCready (15) has summarized the effect of density on the mechanism of drying. Increasing the density or decreasing permeability of the solid for water vapor resulted in a change in the distribution of water vapor through the zone of vaporization.

Two mechanisms of drying were found for the air drying of pulp and paper by McCready (15). Drying data on pulp slabs of varying permeability to water vapor have been presented as proof of the two mechanisms of drying, which also illustrated the effect of permeability on the water distribution in the solid.

Collins and Fisher (5) have showen that the over-all coefficient of heat flow remains constant druing the constant rate period but decreases rapidly after the critical moisture is reached; the decrease in the coefficient during the falling rate period corresponds to an increase in the over-all thermal resistance which must be due to the occurrence of the actual evaporation of water beneath the surface.

Sherwood (36) also found that internal liquid diffusion was controlling throughout the falling rate period for the case of thick pulp slabs, and evaporation has been shown to take place at points within the pulp structure.

This information has been based on air drying of porous solids. It does not apply directly to drying on a heated surface. The mechanisms found, however, do show some corelation with those which are found during drying on heated surfaces.

McCready (15,16) has reported data on the rate of drying of pulp slabs in contact with hot surfaces under experimental conditions similar to those in drum drying processes. However, his experimental data are based on a hot plate temperature of 80 deg. C. which corresponds to a steam pressure of 6.9 psia. This pressure is below that commonly used in industrial driers of pulp and paper. The mechanism of drying of the slab which described variations in the temperature and moisture content was presented. Effects of the slab thickness and supplementary drying air were investigated.

According to McCready, the slab dried at constant rate in the first interval of the drying process and then the rate of drying decreased. During the constant-rate period local temperatures in the slab remained constant until the indicated critical water concentration was approached and then the temperature decreased. The rate of drying decreased when the temperature decreased but the initial decrease in the rate was small.

In the first period of the interval of falling rate drying, the rate of drying and consequently the rate of heat transfer from plate to slab decreased, temperature in the slab decreased, temperature difference between plate and slab increased and temperature difference through the slab decreased. This indicated that thermal resistance between plate and slab increased due to drying out of the water film between slab and plate and that the thermal conductivity of the slab remained substantially constant and equal to the value of the wet slab in the interval of constant rate drying. In the second period temperature difference across the first ply beneath the closed face increased, indicating that the ply was drying. The temperature difference across the remainder of the slab decreased, indicating that, that part remained wet with substantially a constant thermal conductivity. In the third period the decrease in temperature difference between plate and slab indicated that thermal resistance between those points reached and remained at a constant value after the water had dried out.

He also showed that thick slabs dried at a slower rate than the thin slabs. The rate of heat and water vapor transfer through the slabs decreased as the thickness of the slab increased.

McCready (16) has shown that temperature of supplimentary air had very little effect on the rate. Increase in plate temperature increased greatly the rate of drying. Provided the difference between the hot surface and drying air temperatures was large, there was little effect of change of relative humidity of the air on the rate of drying. He suggested that thermal conductivity of the solid might be an important factor, since the heat absorbed by the dry surface must be conducted through the solid to the points where vaporization occurs.

It is possible from the preceding statements to predict the effect of some variables on the drying process. However there is still a wide field for further research on this important subject with regard to determining the exact mechanism of the drying process in order to operate on a more efficient basis in the inductrial drying of pulp and paper.

The present work presents, in the form of rate curves, new data on the drying of pulp sheets. All experiments were carried out in still air using a hot plate temperature of 240 deg. F. corresponding to a pressure of 25 pounds per sq. in. abs. which pressure corresponds closely to that which is used in the Yankee driers for pulp and paper.

EXPERIMENTAL PROCEDURE

The pulp used was of commercial can wrapper stock composed of sulphite and waste pulp. The slurry used in making the sheets was obtained by macerating a known quantity of the raw stock in a ball mill for one hour, followed by treating it in a mixer after further dilution with water.

It was observed that the ground pulp if kept in contact with water for any length of time, became hydrated, and as a result the sheets formed from it showed considerable shrinkage during the drying. In order to prevent this, freshly prepared pulp stock was used every time.

A definite quantity, each time the same, of this stock pulp was used to form the sheet. This ensured the sheet to be of uniform bone dry matter. The separate plies were first formed on a Buchner funnel and these plys were assembled to make the sheet. A silmanite Buchner funnel #H, 186 mm. in diameter was used. The sheets formed had a diameter of 7.1875 inches. Copper constantan thermocouples, 32 gage, enameled wire were placed between the plies and the whole was pressed to form a compact sample of the sheet. It was then wetted slightly and placed on the Buchner funnel, operated with a 26 inch vacuum to remove the water. This procedure was followed as closely as possible in order to ensure uniformity of the initial moisture contant of the sheets.

An electric hot plate was used as the source of heat. It was connected through several variable rheostats, so that the temperature could be controlled constant throughout the run. A type -TA Industrial Analyser was inserted in the circuit in order to keep an accurate check of the current supplied to the hot plate.

A circular steel plate one foot in diameter and 0.75 inches thick was placed on the hot plate. The upper surface of this steel plate was kept constantly polished. Six thermocouples, Leeds and Northrup, No. 20, copper-constantan, duplex wire, glass insulated, were inserted into the steel plate half way between the two faces of the slab, one thermocouple being at the center and the others at a distance of 1, 2, 3, 4, and 5 inches respectively away from the center.

These thermocouples, as well as those between the plies in the sheet, were connected through single-pole, single-throw switches to a Leeds and Northrup potentiometer.

In order to eliminate possible effects of shrinkage or curling at the edges of the sheet during drying, an annular ring was placed on the sheet. This ring was pressed down on the sheet by means of heavy lead weights placed around the rim of the annulus so as to allow free circulation of vapors. The ring 1.5 inches high had an internal diameter of 6.9375 inches and was made of number 14 B & S gage tin sheet. The area of the sheet covered by the annular ring was 0.00955 sq. ft. which was less than 3.5% of the total area of the sheet, and was therefore neglected in the calculations.

At the end of the run the thickness was measured with a dial indicator on a magnetic stand used with surface plate. The sample was then heated over night in an electric oven maintained at 100 deg. C. and the bone dry weight obtained.

From a series of preliminary runs carried out on the variation of temperature in the hot plate above, it was observed that the temperature drop across the plate from the center to the outside edges was within 1 degree F. at all temperatures up to as high as 400 degrees F. As the temperature across the plate was constant it was considered not necessary to take the temperatures at the various distances from the center to the outside to get an average temperature of the plate; only the temperature at the center of the plate was recorded as this represents the temperature of the plate.

The drying samples for the first series of runs were prepared as described above and were built up of four plies. Three thermocouples were inserted between the plies, and the temperatures were all measured at intervals of one minute.

In the first set of experiments of this series the sheets were kept intact at the end of the run. Determination of moisture content and thickness were carried out on the sheet as a whole. In the second set of this series the plies were separated at the end of the run and the thickness and moisture content of each ply separately determined.

In the second series of experiments, the drying samples were prepared identically as before but were composed for two plies. One thermocouple was inserted between the two plies and the temperatures recorded at intervals of one minute. Moisture content and thickness of the sample were obtained for the sheet as a whole.

The temperatures of the sample and of the hot plate were plotted against time, (Graphs 1, 2, 3, 14, 15, 16, and 25). The temperatures of the top and bottom of the sheet were obtained by extrapolating the lines joining the local temperatures of the plies, Graphs (4, 5, 6, 7, 17, 18, 19, 20).

Knowing the final and initial temperatures of the sheet, the final and initial moisture contents, the amount of vaporization, and the quantity of the bone dry material for various tests, the quantity of heat transferred by the hot plate which was picked up by the sheet together with that lost by radiation and convection from the surface were calculated for different intervals of time.

For any particular interval of time and the corresponding temperature difference in the sheet in that interval, the quantity of heat (q_s in B.t.u.'s) required to raise the temperature of the sheet from the average initial to the average final temperature is given by:

$$\frac{q_s}{\Delta \theta} = W_1 C_p \Delta t$$

where W_1 = Bone dry weight of sheet (lb.).

C_p = Specific heat of pulp equals 0.32 B.t.u./(lb.)(°F).

Δt = Temperature difference between the final (Av) and initial (Av) temperature of the sheet (°F).

$\Delta \theta$ = Time interval (minutes)

The quantity of heat (q_w in B.t.u.'s) required to raise the temperature of the total water in the sheet through the same temperature difference is given by:

$$\frac{q_w}{\Delta \theta} = W_2 C_p \Delta t$$

where W_2 = Total water in the sample (lbs.).

C_p = Specific heat of water equals 1.0 B.t.u./#°F.

The latent heat contributed by the water evaporated is based on the mean temperature of the center of the sheet as measured by the middle thermocouple, in that interval of time. Thus the heat given by the latent heat (q_L in B.t.u.'s) is given by:

$$\frac{q_L}{\Delta\theta} = W_3 L$$

Where W_3 = Total grams of water evaporated in the interval, (lbs.).

L = Latent heat (B.t.u./lb.).

In order to estimate the quantity of heat lost by radiation and convection from the top of the sheet, an over-all coefficient of heat transfer between the sheet and air was assumed, as 4.0 B.t.u./(hr)(ft^2)($^\circ$F). Then the quantity of heat lost (q_R in B.t.u./hr) is given by:

$$q_R = U_1 A_s \Delta t_1$$

where U_1 = Over-all coefficient of heat transfer equals 4.0 B.t.u./(hr)(ft^2)($^\circ$F).

A_s = Area of sheet (ft^2).

Δt_1 = Temperature difference between the average temperature of the top of the sheet in the interval of time θ and the air temperature (T_A), ($^\circ$F).

The total quantity of heat transferred (Q in B.t.u.'s/hr) by the plate is given by:

$$Q = \frac{60}{\Delta\theta}(q_s + q_w + q_L) + q_r$$

Knowing the total heat transferred by the plate, the thickness of the plate and the temperature of the plate half way between the two faces, the temperature of the top of the plate is calculated as follows:

$$(T_P - T_{TP}) = \frac{QS}{KA_s}$$

where S = 1/2 thickness of plate (ft).

K = Thermal conductivity of steel equals 26.0 B.t.u./(hr)(ft^2)($^\circ$F/ft)

T_P = Temperature of plate (^{o}F)

T_{TP} = Temperature of the top of the plate (^{o}F).

Calculation for an estimate of the over-all coefficient of heat transfer between the sheet and plate is as follows:

$$U = \frac{Q}{A_s \, \Delta t_2}$$

where Δt_2 is the temperature difference between the top of the plate and the bottom of the sheet: $\Delta t_2 = (T_{TP} - T_{BS})$, ($^{o}F$).

The over-all coefficient U was plotted for the different intervals of time, and a smooth curve was drawn through the tops, so that the area between each top and the smooth curve was divided into segments of equal size. The curve (Graph 12) gives the over-all coefficient of heat transfer between the sheet and plate at any time during the drying period. A curve (Graph 13) was then drawn of the over-all coefficient vs moisture content in the sample.

The grams of water evaporated on the basis of bone dry pulp were plotted vs time and a curve drawn through the data points (Graphs 9 and 26). The instantaneous rate of drying of the sample at various times was readily calculated from the curve as shown below and the instantaneous rate vs average water concentration expressed as grams of water left per gram of bone dry material were plotted (Graphs 11 and 29). This is the drying rate curve.

The instantaneous rate of drying at any time was obtained by the method of graphical differentiation as proposed by Running (26). The grams of water evaporated for small intervals of time were obtained from the graphs (9 and 26). evaporation divided by the product of time and area of the sheet gave the differential rates in lbs./(hr)(ft^2) for the small intervals of time. The differential rates were then plotted for the various intervals and a smooth curve drawn through the tops as before. This is the differential curve which gives the instantaneous rate at any time during the period covered (Graphs 10 and 28). The water concentration on bone dry basis is obtained from graphs (8 and 27).

In order to illustrate the extent of drying at different levels of thicknesses in the sheet, curves were drawn for each ply of the evaporation on the basis of bone dry pulp vs time (Graph 22).

The per cent moisture content of each ply was corelated with the final moisture content expressed as lb. of water left per lb. of bone dry material, (Graph 21).

TABLE 5

Time (minutes)	2	3	4	5	10	15	20
Bone dry wt. (gms)	14.918	14.863	15.237	14.510	15.345	15.109	15.275
After drying wt. (gms)	26.405	21.120	18.741	16.200	16.800	16.257	16.207
Total wet wt. (gms)	39.100	39.000	39.950	38.000	40.210	39.600	40.020
Initial moist. content (gms)	24.182	24.137	24.713	23.490	24.865	24.491	24.745
Final moist. content (gms)	11.487	6.257	3.504	1.690	1.455	1.148	0.932
Moisture evap. (gms)	12.695	17.880	21.210	21.800	23.410	23.343	23.813
% Initial moisture	61.846	61.889	61.860	61.900	61.837	61.845	61.831
% Final moisture	43.503	29.626	18.696	10.432	8.660	7.061	5.750
gms. H_2O Evap/gm B.D. pulp	.850	1.203	1.392	1.502	1.525	1.545	1.559
Final moist. content/ gm. B.D. pulp	.770	.421	.230	.116	0.095	0.076	0.061
Initial moist. content/ gm. B.D. pulp	1.621	1.624	1.622	1.618	1.620	1.621	1.620
Total thickness (inches)	0.188	0.196	0.172	0.160	0.197	0.201	0.182
Approx. Thickness of each ply (inches)	0.047	0.049	0.043	0.040	0.049	0.052	0.046

TABLE 6

Time (min)	Final Moist. Cont. lbs H_2O left / lb B.D. pulp	Evaporation lbs H_2O evap. / lb B.D. pulp	Rate lbs H_2O evap. / (lb B.D. pulp)(hr)(ft^2)	(overall coef. of heat trans. between plate and sheet) B.t.u. / (hr)(ft^2)(°F)
0.00	1.621	0.00	98.00	121.5
0.50	1.415	0.212	94.70	118.7
1.00	1.180	0.442	91.10	115.0
1.50	0.990	0.642	87.20	110.5
2.00	0.770	0.850	82.20	104.0
2.25	0.655	0.959	78.80	95.0
2.50	0.560	1.045	73.10	79.0
2.75	0.490	1.125	64.30	59.5
3.00	0.421	1.203	55.60	45.8
3.25	0.360	1.260	47.00	38.4
3.50	0.310	1.310	40.00	33.5
3.75	0.270	1.352	34.00	29.0
4.00	0.230	1.392	29.40	24.5
4.25	0.190	1.430	26.60	20.5
4.50	0.160	1.460	23.70	17.0
4.75	0.135	1.485	18.00	13.2
5.00	0.116	1.502	10.00	10.0
6.00	0.108	1.510	1.00	2.0
8.00	0.101	1.518	0.90	1.1
10.00	0.095	1.525	0.90	2.2
13.00	0.083	1.536	0.85	4.5
15.00	0.076	1.545	0.85	6.0
17.00	0.070	1.551	0.64	7.9
20.00	0.061	1.559	0.43	10.9

TABLE 11
(5 minutes)

	P_T	P_2	P_3	P_B	S*
Bone dry wt. (grams)	3.774	3.819	3.827	3.852	15.272
After drying wt. (grams)	4.500	4.300	4.200	4.200	17.200
Total wet wt. (grams)	9.956	10.001	10.009	10.034	40.000
Initial moist. content (grams)	6.182	6.182	6.182	6.182	24.728
Final moisture content (grams)	0.726	0.481	0.373	0.348	1.928
Moisture evaporated (grams)	5.456	5.701	5.809	5.834	22.800
% Initial moisture	62.000	61.75	61.70	61.50	61.750
% Final moisture	16.150	11.200	8.880	8.290	11.200
grams H_2O Evap/grams B.D. pulp	1.449	1.495	1.510	1.515	1.496
Final moisture content/grams B.D. pulp	0.1925	0.126	0.0974	0.0905	.126
Initial moisture content/grams B.D. pulp	1.638	1.619	1.615	1.605	1.622
Total thickness (inches)	0.050	0.053	0.048	0.039	0.190

P_T .... top ply

P_2 .... 2nd ply from top

P_3 .... 3rd ply from top

P_B .... Bottom ply

S* .... Sheet

TABLE 12
(10 minutes)

	P_T	P_2	P_3	P_B	S*
Bone dry wt. (grams)	4.112	4.139	4.156	4.141	16.548
After drying wt. (grams)	4.700	4.600	4.370	4.230	17.900
Total wet wt. (grams)	10.800	10.827	10.844	10.829	43.300
Initial moisture content (grams)	6.688	6.688	6.688	6.688	26.752
Final moisture content (grams)	0.588	0.461	0.214	0.089	1.352
Moisture evaporated (grams)	6.100	6.227	6.474	6.599	25.400
% Initial moisture	61.900	61.600	61.550	61.610	61.350
% Final moisture	12.500	10.040	4.900	2.100	7.550
grams H_2O Evap/grams B.D.pulp	1.483	1.504	1.557	1.594	1.534
Final moisture content/grams B.D. pulp	0.143	0.111	0.052	0.021	0.082
Initial moisture content/grams B.D. pulp	1.626	1.615	1.609	1.615	1.616
Total thickness (inches)	0.050	0.440	0.046	0.052	0.192

P_T .... top ply

P_2 .... 2nd ply from top

P_3 .... 3rd ply from top

P_B .... Bottom ply

S* .... Sheet

TABLE 13
(15 minutes)

	P_T	P_2	P_3	P_B	S*
Bone dry wt. (grams)	3.790	3.858	3.809	3.834	15.291
After drying wt. (grams)	4.200	4.150	3.920	3.890	16.160
Total wet wt. (grams)	9.967	10.035	9.986	10.012	40.000
Initial moisture content (grams)	6.177	6.177	6.177	6.178	24.709
Final moisture content (grams)	0.410	0.292	0.111	0.056	0.869
Moisture evaporated (grams)	5.767	5.885	6.066	6.122	23.840
% Initial moisture	61.974	61.554	61.856	61.705	61.772
% Final moisture	9.761	7.036	2.831	1.439	5.377
grams H_2O Evap/grams B.D. pulp	1.522	1.525	1.592	1.596	1.559
Final moisture content/grams B.D. pulp	0.108	0.076	0.029	0.015	0.057
Initial moisture content/grams B.D. pulp	1.630	1.601	1.621	1.611	1.616
Total thickness (inches)	0.042	0.046	0.048	0.042	0.178

P_T .... top ply

P_2 .... 2nd ply from top

P_3 .... 3rd ply from top

P_B .... Bottom ply

S* .... Sheet

TABLE 14
(20 minutes)

	P_T	P_2	P_3	P_B	S*
Bone dry wt. (grams)	3.796	3.842	3.856	3.844	15.338
After drying wt. (grams)	4.151	4.031	3.922	3.896	16.000
Total wet wt. (grams)	10.004	10.050	10.064	10.052	40.170
Initial moisture content (grams)	6.208	6.208	6.208	6.208	24.832
Final moisture content (grams)	0.355	0.189	0.066	0.052	0.662
Moisture evaporated (grams)	5.853	6.019	6.142	6.156	24.170
% Initial moisture	62.055	61.771	61.685	61.758	61.817
% Final moisture	8.552	4.688	1.682	1.334	4.137
grams H_2O Evap/grams B.D. pulp	1.542	1.567	1.593	1.601	1.576
Final moisture content/grams B.D. pulp	0.093	0.049	0.017	0.014	0.043
Initial moisture content/grams B.D. pulp	1.635	1.616	1.610	1.615	1.619
Total thickness (inches)	0.042	0.044	0.042	0.048	0.176

P_T .... top ply

P_2 .... 2nd ply from top

P_3 .... 3rd ply from top

P_B .... Bottom ply

S* .... Sheet

TABLE 15

TOP PLY

Time (min)	Temperature °F	Moisture Content $\frac{\text{lbs. } H_2O}{\text{lb. B.D. pulp}}$
5	146.6	.1925
10	128.0	.1430
15	172.7	.1080
20	188.9	.0930
SECOND PLY FROM TOP		
5	148.5	.1260
10	132.0	.1110
15	175.5	.0760
20	190.6	.0490
THIRD PLY FROM TOP		
5	150.4	.0974
10	134.3	.0520
15	178.8	.0290
20	192.2	.0170
BOTTOM PLY		
5	152.0	.0905
10	138.0	.0210
15	182.1	.0150
20	193.7	.0140

TABLE 16

Thick Sheet Rate lb. H_2O evap./(hr)(ft^2)		Thick Sheet Moisture Content lb. H_2O/lb. B.D. Pulp	Thin Sheet Rate lb. H_2O evap./(hr)(ft^2)		Thin Sheet Moisture Content lb. H_2O/lb. B.D. Pulp
98.0	1480	1.621	108.0	775	1.624
94.7	1430	1.415	102.1	726	1.390
91.1	1376	1.180	97.0	690	1.160
87.2	1318	.990	91.9	654	0.947
82.2	1240	.770	86.8	616	0.710
78.8	1190	.655	84.0	596	0.610
73.1	1105	.560	80.0	569	0.510
64.3	971	.490	73.0	519	0.420
55.6	840	.421	62.8	446	0.334
47.0	710	.360	52.1	371	0.277
40.0	605	.310	43.1	306	0.225
34.0	514	.270	35.5	252	0.180
29.4	444	.230	28.2	200	0.137
26.6	401	.190	21.5	153	0.112
23.7	358	.160	15.1	107	0.080
18.0	272	.135	9.0	64	0.067
10.0	151	.116	3.0	21	0.052
0.90	13.6	.095	.972	6.9	0.031
0.85	12.9	.076	.723	5.1	0.016
0.43	6.5	.061	.340	2.4	0.007

TABLE 21

Time (minutes)	2	3	4	5	10	15	20
Bone dry wt. (gms)	7.138	6.994	6.751	6.697	7.065	7.136	7.119
After drying wt (gms)	12.205	9.330	7.676	7.045	7.248	7.250	7.169
Total wet wt. (gms)	18.730	18.373	17.728	17.573	18.552	18.753	18.701
Initial moisture content (gms)	11.592	11.379	10.977	10.876	11.487	11.617	11.582
Final moisture content (gms)	5.067	2.336	0.925	0.348	0.219	0.114	0.050
Moisture evap. (gms)	6.525	9.043	10.052	10.528	11.268	11.503	11.532
% Initial moisture	61.890	61.933	61.918	61.890	61.917	61.947	61.932
% Final moisture	41.52	25.04	12.05	4.94	3.01	1.57	0.700
gms H_2O Evap/gm B.D. pulp	0.914	1.293	1.489	1.572	1.595	1.612	1.620
Final moist. cont./gm B.D. pulp	0.710	0.334	0.137	0.052	0.031	0.016	0.007
Initial moist. cont./gm B.D. pulp	1.624	1.627	1.626	1.624	1.626	1.628	1.627
Total Thickness (inches)	0.036	0.034	0.038	0.034	0.037	0.032	0.038
Approx. Thickness of each ply (inches)	0.018	0.017	0.019	0.017	0.019	0.016	0.019

TABLE 22

Time (min)	Final Moist. Cont. lbs H_2O left / lb B.D. pulp	Evaporation lbs H_2O evap. / lb B.D. pulp	Rate Lbs H_2O evap. / (lb B.D. pulp)(hr)(ft^2)
0.00	1.624	0.000	108.90
0.50	1.390	0.240	102.10
1.00	1.150	0.480	97.00
1.50	0.940	0.690	91.90
2.00	0.710	0.914	86.80
2.25	0.610	---	84.00
2.50	0.510	1.135	80.00
2.75	0.420	---	73.00
3.00	0.334	1.293	62.80
3.25	0.277	---	52.10
3.50	0.225	1.412	43.10
3.75	0.180	---	35.50
4.00	0.137	1.489	28.20
4.25	0.112	---	21.50
4.50	0.080	1.538	15.10
4.75	0.067	---	9.00
5.00	0.052	1.572	3.00
10.00	0.031	1.595	0.972
15.00	0.016	1.612	0.723
20.00	0.007	1.620	0.340

DISCUSSION

Experimental work on the drying of sheets of the thickness of ordinary paper would be extremely difficult. In these experiments thicker sheets were used. The temperatures of the hot plate used corresponded to the steam pressure of commercial driers, and the drying itself was carried out in still air.

The temperatures of the hot plate were measured within 1 deg. F. and it can be considered that the temperatures of the sheet were accurate to the same degree. The variation in temperatures across the plate were within 1 deg. F. The sheets were weighed immediately before the test and immediately after the end of the experiment. This introduced a certain amount of inaccuracy in the measurements, but these errors were believed to have been reduced to a minimum. As the experimental procedures were difficult, the accuracy of the data does not warrant a critical examination.

Immediately on placing the sheet on the heated surface flash vaporization took place. The temperature of the sheet immediately rose to very near the atmospheric boiling point of water which the temperature of the plate dropped. The temperatures then continued to decrease until a minimum was reached, after which there was a continuous increase in both sheet and plate temperatures. The hot plate temperature continued to rise until it reached its original value and then it remained constant. After the minimum, the temperature of the sheet increased continuously. The temperature in the slab at any time decreased from the plate to the open face.

The period during which the temperature decreases includes the normal falling rate period. Drying apparently begins in this period. Pulp of 60%

moisture, which is the normal moisture content of commercial driers, can always be expected to dry in this manner. The interval corresponding to the increasing temperatures includes the rest of the falling rate period. The latter part of the falling rate interval includes the period during which, apparently, internal diffusion controls the rate. This is an important part of paper drying because it indicates the difficulty in removing moisture from a thick sheet which contains less than 10% moisture.

The data show that the temperature of thin sheets decreases to 163.4 deg. F. while in the thick sheets the temperature decreases to 125 deg. F. Moreover, this minimum was reached in a shorter time in the former case. For the thick sheets, the interval after the minimum point is reached, during which the temperature of the sheet rises, corresponds to the period wherein internal diffusion is controlling. During this period the moisture content of the sheet is reduced from 0.101 to 0.061 pounds of water per pound of bone dry pulp.

For the thin slabs, the minimum temperature of the sheet is reached when the falling rate period is only half completed. The period of temperature increase in the sheet corresponds to the latter half of the falling rate interval, during which time the moisture content of the sheet decreased from 0.334 pounds of water per pound of bone dry ply to 0.007 pounds of water per pound of bone dry pulp.

The moisture content of the sheets decreased very rapidly during the initial drying period. Evaporation was practically complete for both sheets in five minutes. At a moisture content of approximately 10%, for the thick sheets, a critical rate change occurred which was apparently due to a change in the mechanism of drying (Graph 8.). A similar critical rate was also

observed for the thin sheets at a moisture content of about 5%, (Graph 27). The mechanism of drying after this lower critical point corresponded to that occurring when diffusion within the fibers is controlling.

Thin sheets can be expected to dry down at a relatively high rate to 5% moisture, a concentration which is normally obtained in paper drying. On the other hand, the mechanism of drying of thick sheets changes to that in which diffusion is controlling before the paper has become dried to 5% moisture. When diffusion is controlling, the rate of drying is very slow. This condition would require the use of very extensive drying equipment.

The lower critical point was reached at different moisture contents and temperatures for the thick and thin sheets, but the time taken to reach them was approximately the same in both cases. During this five minute period of drying the amount of water vaporized from the thick sheet was almost twice as great as that from the thin sheets. This means that the overall rate was almost twice as great for the thick sheet as for the thin sheet, which indicates that a thick sheet with twice the quantity of water can be dried within the same period and on the same equipment, with twice the quantity of steam being used. It is to be noted that the amount evaporated per pound of bone dry material was less for the thick sheet as compared to that vaporized from the thinner material.

Considering each ply as a single sheet, it was observed that at any given time during the drying period the amount of evaporation on bone dry basis was least at the top ply which is at the open face of the slab and the greatest was at the bottom ply, (Graphs 21, 22, 23). In five minutes of drying time the moisture content of the bottom sheet was 8% while the top sheet still had 16% moisture on dry basis. At the end of the next five minute interval the bottom sheet had a moisture content of only 2.1%, while the top ply showed a moisture content of 12.5 %. This showed that the bottom ply was drying out much faster than the top ply. The ply immediately above the bottom one was also drying out much faster than the top most ply and the one below it. Since the two bottom plies were drying out faster, the thermal resistance must have increased and the thermal conductivity decreased in these plies with an increase in the drying time. As a result, as drying time continued less heat was supplied to the top two sheets and therefore the moisture content remained higher in them as compared to the bottom ones. This can more clearly be understood from Table 14, which gives the moisture analysis of the plies at the end of 20 minutes of drying time. It is seen that the percent moisture left in the top ply is 8.55 while at the same time the moisture left in the bottom two plies is 1.68 and 1.33 percent respectively.

No corelation was found between the temperature of the plies and the moisture content.

The data on the rate of drying as related to time and moisture content have been shown in (Graphs 10, 11, 28, and 29). Using the accepted mechanism of drying, the rate versus time curve can be divided into three distinct regions. They may be defined by the mechanisms controlling the drying:

(a) Unsaturated surface drying

(b) Internal liquid diffusion

(c) Diffusion from the interior of the fibre.

Heat must be transferred from the hot plate to the sheet. The amount of heat transferred depends not only on the overall coefficient of heat transfer between sheet and ply but also upon the resistance to the flow of heat within the sheet. Vapor forms in the region adjacent to the plate and passes up through the wet sheet to the outside air. As vaporization near the plate occurs the sheet is dried and becomes more resistant to the conduction of heat.

It is not possible from these graphs (28, 29) to state the exact time or moisture content at which the critical water concentration would be reached because sufficient water was not present in the sample.

During the falling rate interval the decrease in rate was rapid. This continued for a little over two minutes when the moisture content of the samples were about 0.6 pounds of water per pound of bona dry pulp. The rate-time and the rate vs average water concentration curves were practically straight lines. This corresponds to unsaturated surface drying. Between 0.6 pounds of water per pound of bone dry pulp and less than 0.1 pounds of water per pound of bone dry pulp the rate decreased more rapidly. Internal diffusion between the fibres is assumed to be controlling.

After this period there was another change in the mechanism of drying. In the interval from five minutes to twenty minutes of drying, the moisture content decreased from 0.52 pounds of water per pound of bone dry pulp for the thin sheets and from 0.95 pounds of water per pound of bone dry pulp for the thick sheets. It is believed that in this interval the mechanism of drying is suggestive of diffusion from the interior of the fibre controlling the rate. Besides it must be noted that this latter interval extends over a period of fifteen minutes during which very small amounts of water were evaporated. The rate is very low but remains quite constant. This is significant from the point that it is extremely more difficult and time consuming to remove the water below this lower critical moisture content.

The overall heat transfer coefficient between the sheet and the plate was determined for the thick sheets only. It was found to decrease very rapidly with time from 122 B.t.u./(hr)(ft^2)(°F) to reach a minimum of 0.9 B.t.u./(hr)(ft^2)(°F). This minimum was reached in seven minutes, at which point diffusion from within the fibers appeared to have been controlling. Beyond this point the accuracy of the values are doubtful. They appear to increase but the apparent increase may be due to approximations made in the calculations.

The corelation of the overall coefficient of heat transfer with moisture content indicates a gradual decrease in the overall coefficient as the evaporation continues during the period of unsaturated surface drying. The overall coefficient then falls sharply with further decrease in the moisture content to reach its minimum value.

The drying curves in general agree with those obtained by McCreedy (15). The methods of experimentation as well as of conditions of drying which include the hot plate temperature, and the range of moisture content of the samples, differ from that shown by McCreedy.

In drying, the moisture content was such that no constant rate period was obtained; the whole of the drying period corresponded to the falling rate period.

CONCLUSIONS

1. On placing the sheet on the hot plate flash vaporization took place. This immediately increased the temperature of the sheet to about the atmospheric boiling point of water while the temperature of the hot plate decreased. The temperatures of the sheet decreased to a minimum and then increased. The temperature of a commercial Yankee drier may be expected to decrease in the same manner as the hot plate.

2. Evaporation was practically complete for both sheets in five minutes. At a moisture content of ten percent for the thick sheets and five per cent of the thin sheets, a critical rate change occurred.

3. No corelation was found between the temperatures of the plies and the moisture content.

4. The entire period of drying corresponded to the falling rate interval. Three different mechanisms seem to prevail in this period. They are defined as follows:

(a) unsaturated surface drying

(b) internal diffusion

(c) diffusion from the interior of the fibre.

5. The overall rate was almost twice as great for the thick sheets as for the thin sheets.

6. The specific rate on the basis of one pound of bone dry material was greater for the thin sheets than for the thick sheets.

7. The slow rate encountered during the period when drying is contributed by diffusion from within the fibers is not encountered in thin sheets, in drying down to five percent moisture; however this type of drying is

encountered in the case of drying of thick sheets to five percent.

8. The overall coefficient of heat transfer between the sheet and the plate, as calculated for the thick sheets, varied from 122 B.t.u./(hr)(ft^2)(^oF) to 0.9 B.t.u./(hr)(ft^2)(^oF).

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APPENDIX

TABLE 1.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	---	71.2	71.2	71.2	---	238.6
1	185.3	187.3	189.3	191.1	193.2	228.9
2	178.5	181.5	184.5	187.5	190.5	222.4
3	165.3	169.1	173.9	178.4	183.2	217.4
4	153.4	156.9	160.0	163.4	166.7	212.4
5	141.0	142.5	144.1	146.3	148.5	200.2

TABLE 2.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	79.0	79.0	79.0	——	239.0
1	185.2	185.7	186.4	186.8	187.4	228.7
2	178.0	178.5	179.6	181.4	183.6	221.4
3	164.1	166.6	169.5	172.8	176.4	222.8
4	144.0	147.9	151.9	158.0	165.0	213.4
5	134.5	138.2	141.8	145.0	148.2	211.6
6	131.0	134.6	138.2	141.8	145.4	214.0
7	130.0	134.6	139.3	143.6	147.7	217.0
8	138.0	142.5	147.2	152.0	156.6	224.8
9	143.5	149.5	155.5	161.4	167.4	230.4
10	160.9	164.3	167.7	169.5	171.3	233.4

TABLE 3.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	81.1	81.1	81.1	——	239.0
1	184.0	186.4	188.6	191.0	193.2	222.2
2	178.0	180.0	181.9	186.0	190.2	217.4
3	173.4	175.5	178.9	183.0	188.0	211.6
4	147.2	153.9	160.5	167.0	173.6	209.5
5	131.0	135.0	138.9	141.4	143.8	208.0
6	128.4	131.7	135.1	138.6	141.9	209.8
7	124.0	128.5	132.8	136.4	140.0	212.9
8	123.5	128.0	132.4	135.7	139.0	214.9
9	128.0	132.0	136.0	138.2	140.4	221.0
10	135.0	137.8	140.5	145.0	150.0	224.6
11	138.0	141.8	145.8	149.0	152.0	229.6
12	144.0	147.5	150.8	154.0	157.0	230.7
13	152.5	156.2	159.8	163.5	169.0	233.2
14	160.5	163.4	166.1	171.0	175.7	234.0
15	168.7	171.0	173.1	177.4	181.5	235.2

TABLE 4.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	----	84.2	84.2	84.2	----	239.5
1	188.2	189.0	189.7	191.1	192.7	229.3
2	178.8	181.0	183.2	186.1	188.8	222.1
3	167.9	171.2	174.6	177.5	180.7	219.6
4	144.3	150.8	157.6	162.0	166.4	212.0
5	131.3	138.2	145.4	152.2	159.1	207.1
6	126.5	131.9	137.1	145.9	154.2	209.8
7	126.3	130.6	135.0	140.9	148.0	212.0
8	124.9	129.7	134.2	138.6	143.2	217.9
9	128.4	131.5	134.6	138.2	141.6	222.1
10	131.1	134.2	137.3	140.5	143.5	228.2
11	132.5	137.8	143.2	147.2	151.2	231.8
12	138.5	144.0	149.5	154.0	158.5	234.3
13	150.2	154.0	157.6	160.5	163.3	235.8
14	158.1	161.6	165.2	168.8	172.4	236.8
15	163.4	167.0	170.6	173.8	177.2	238.3
16	169.3	173.5	177.8	180.3	183.0	239.5
17	176.6	178.5	180.1	183.6	188.1	239.5
18	179.5	181.0	182.5	185.7	190.3	239.9
19	182.8	184.1	185.4	188.2	191.0	239.9
20	185.7	186.1	187.2	189.7	192.3	240.4

TABLE 7.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	----	79.0	79.0	79.0	----	239.5
1	181.2	182.5	183.7	186.7	189.0	219.2
2	169.5	174.0	178.0	181.0	183.5	214.9
3	155.5	160.5	165.2	168.8	171.7	212.9
4	148.5	150.1	155.5	159.9	163.8	211.3
5	145.7	147.6	149.5	151.2	152.7	216.0

TABLE 8.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	68.9	68.9	68.9	——	238.6
1	174.2	176.5	178.5	183.2	188.7	220.3
2	173.4	174.2	174.9	180.5	186.7	215.6
3	167.0	169.2	171.0	174.2	178.5	212.9
4	155.6	158.9	161.6	165.5	171.4	210.6
5	141.3	145.9	149.9	154.0	158.7	214.5
6	133.5	138.6	143.2	148.0	153.2	217.4
7	127.9	132.8	137.1	138.9	140.5	222.4
8	124.5	128.8	132.8	135.1	137.9	227.5
9	120.2	125.2	129.7	132.8	136.0	231.8
10	125.9	130.0	133.9	136.5	139.5	234.0

TABLE 9.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	71.6	71.6	71.6	——	239.0
1	182.5	184.1	185.4	187.3	188.5	223.5
2	175.0	178.2	181.4	183.7	185.8	216.1
3	170.5	172.7	175.3	177.4	179.0	212.0
4	149.0	153.1	157.5	162.0	165.9	209.5
5	140.4	144.1	147.9	152.4	156.0	212.0
6	133.7	136.4	139.3	144.7	149.5	216.0
7	129.4	131.9	134.6	140.0	144.7	221.7
8	124.9	128.5	132.6	137.3	141.4	225.5
9	125.6	129.6	134.2	139.6	144.1	230.0
10	130.0	133.2	136.9	144.1	150.5	233.6
11	135.5	138.9	142.5	150.1	158.2	236.1
12	142.0	146.7	151.9	157.3	162.0	237.2
13	156.0	158.0	161.1	165.7	169.9	238.3
14	165.0	168.0	171.3	174.9	177.8	238.6
15	171.5	174.0	176.9	180.5	183.7	239.5

TABLE 10.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	67.6	67.6	67.6	——	235.8
1	175.0	177.4	179.6	181.4	183.3	220.6
2	172.0	173.8	176.0	178.9	182.0	215.2
3	164.0	167.7	171.7	174.6	177.7	212.9
4	144.2	149.5	155.1	162.3	170.5	213.8
5	130.5	136.0	141.8	146.3	151.5	214.9
6	125.4	129.2	133.2	138.9	145.4	218.3
7	121.0	124.7	128.8	135.0	142.0	220.6
8	119.6	123.4	127.4	132.3	138.0	222.8
9	117.2	122.0	127.0	131.7	137.0	224.6
10	123.2	126.5	130.0	135.7	142.5	227.1
11	128.2	130.6	134.6	143.2	154.6	230.7
12	128.7	137.1	146.1	153.3	161.4	233.6
13	145.5	152.6	159.1	163.4	168.2	236.5
14	160.0	163.4	167.0	170.2	173.8	237.2
15	168.5	170.6	172.9	177.1	181.5	238.3
16	174.0	176.4	178.9	182.1	185.5	238.8
17	179.5	181.4	183.2	186.1	189.5	239.0
18	183.4	185.0	186.8	189.0	191.5	239.0
19	186.1	187.9	189.7	191.3	193.1	239.0
20	188.2	189.7	191.5	192.9	194.5	239.0

TABLE 4.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	----	84.2	84.2	84.2	----	239.5
1	188.2	189.0	189.7	191.1	192.7	229.3
2	178.8	181.0	183.2	186.1	188.8	222.1
3	167.9	171.2	174.6	177.5	180.7	219.6
4	144.3	150.8	157.6	162.0	166.4	212.0
5	131.3	138.2	145.4	152.2	159.1	207.1
6	126.5	131.9	137.1	145.9	154.2	209.8
7	126.3	130.6	135.0	140.9	148.0	212.0
8	124.9	129.7	134.2	138.6	143.2	217.9
9	128.4	131.5	134.6	138.2	141.6	222.1
10	131.1	134.2	137.3	140.5	143.5	228.2
11	132.5	137.8	143.2	147.2	151.2	231.8
12	138.5	144.0	149.5	154.0	158.5	234.3
13	150.2	154.0	157.6	160.5	163.3	235.8
14	158.1	161.6	165.2	168.8	172.4	236.8
15	163.4	167.0	170.6	173.8	177.2	238.3
16	169.3	173.5	177.8	180.3	183.0	239.5
17	176.6	178.5	180.1	183.6	188.1	239.5
18	179.5	181.0	182.5	185.7	190.3	239.9
19	182.8	184.1	185.4	188.2	191.0	239.9
20	185.7	186.1	187.2	189.7	192.3	240.4

TABLE 7.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	----	79.0	79.0	79.0	----	239.5
1	181.2	182.5	183.7	186.7	189.0	219.2
2	169.5	174.0	178.0	181.0	183.5	214.9
3	155.5	160.5	165.2	168.8	171.7	212.9
4	148.5	150.1	155.5	159.9	163.8	211.3
5	145.7	147.6	149.5	151.2	152.7	216.0

TABLE 8.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	68.9	68.9	68.9	——	238.6
1	174.2	176.5	178.5	183.2	188.7	220.3
2	173.4	174.2	174.9	180.5	186.7	215.6
3	167.0	169.2	171.0	174.2	178.5	212.9
4	155.6	158.9	161.6	165.5	171.4	210.6
5	141.3	145.9	149.9	154.0	158.7	214.5
6	133.5	138.6	143.2	148.0	153.2	217.4
7	127.9	132.8	137.1	138.9	140.5	222.4
8	124.5	128.8	132.8	135.1	137.9	227.5
9	120.2	125.2	129.7	132.8	136.0	231.8
10	125.9	130.0	133.9	136.5	139.5	234.0

TABLE 9.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	71.6	71.6	71.6	——	239.0
1	182.5	184.1	185.4	187.3	188.5	223.5
2	175.0	178.2	181.4	183.7	185.8	216.1
3	170.5	172.7	175.3	177.4	179.0	212.0
4	149.0	153.1	157.5	162.0	165.9	209.5
5	140.4	144.1	147.9	152.4	156.0	212.0
6	133.7	136.4	139.3	144.7	149.5	216.0
7	129.4	131.9	134.6	140.0	144.7	221.7
8	124.9	128.5	132.6	137.3	141.4	225.5
9	125.6	129.6	134.2	139.6	144.1	230.0
10	130.0	133.2	136.9	144.1	150.5	233.6
11	135.5	138.9	142.5	150.1	158.2	236.1
12	142.0	146.7	151.9	157.3	162.0	237.2
13	156.0	158.0	161.1	165.7	169.9	238.3
14	165.0	168.0	171.3	174.9	177.8	238.6
15	171.5	174.0	176.9	180.5	183.7	239.5

TABLE 10.

Time (min)	T_{TS} (graph)	T_T (exp)	T_M (exp)	T_B (exp)	T_{BS} (graph)	T_P (exp)
0	——	67.6	67.6	67.6	——	235.8
1	175.0	177.4	179.6	181.4	183.3	220.6
2	172.0	173.8	176.0	178.9	182.0	215.2
3	164.0	167.7	171.7	174.6	177.7	212.9
4	144.2	149.5	155.1	162.3	170.5	213.8
5	130.5	136.0	141.8	146.3	151.5	214.9
6	125.4	129.2	133.2	138.9	145.4	218.3
7	121.0	124.7	128.8	135.0	142.0	220.6
8	119.6	123.4	127.4	132.3	138.0	222.8
9	117.2	122.0	127.0	131.7	137.0	224.6
10	123.2	126.5	130.0	135.7	142.5	227.1
11	128.2	130.6	134.6	143.2	154.6	230.7
12	128.7	137.1	146.1	153.3	161.4	233.6
13	145.5	152.6	159.1	163.4	168.2	236.5
14	160.0	163.4	167.0	170.2	173.8	237.2
15	168.5	170.6	172.9	177.1	181.5	238.3
16	174.0	176.4	178.9	182.1	185.5	238.8
17	179.5	181.4	183.2	186.1	189.5	239.0
18	183.4	185.0	186.8	189.0	191.5	239.0
19	186.1	187.9	189.7	191.3	193.1	239.0
20	188.2	189.7	191.5	192.9	194.5	239.0

TABLE 17

Time	Sheet	Plate
0	68.5	237.6
1	169.7	231.8
2	167.0	219.6
3	164.1	215.6
4	166.3	217.4
5	175.6	219.6

TABLE 18

Time	Sheet	Plate
0	67.1	238.3
1	168.8	230.5
2	165.6	220.6
3	163.4	213.4
4	165.2	214.9
5	173.8	217.4
6	178.9	219.9
7	181.0	224.6
8	182.8	229.3
9	185.0	232.2
10	184.4	235.0

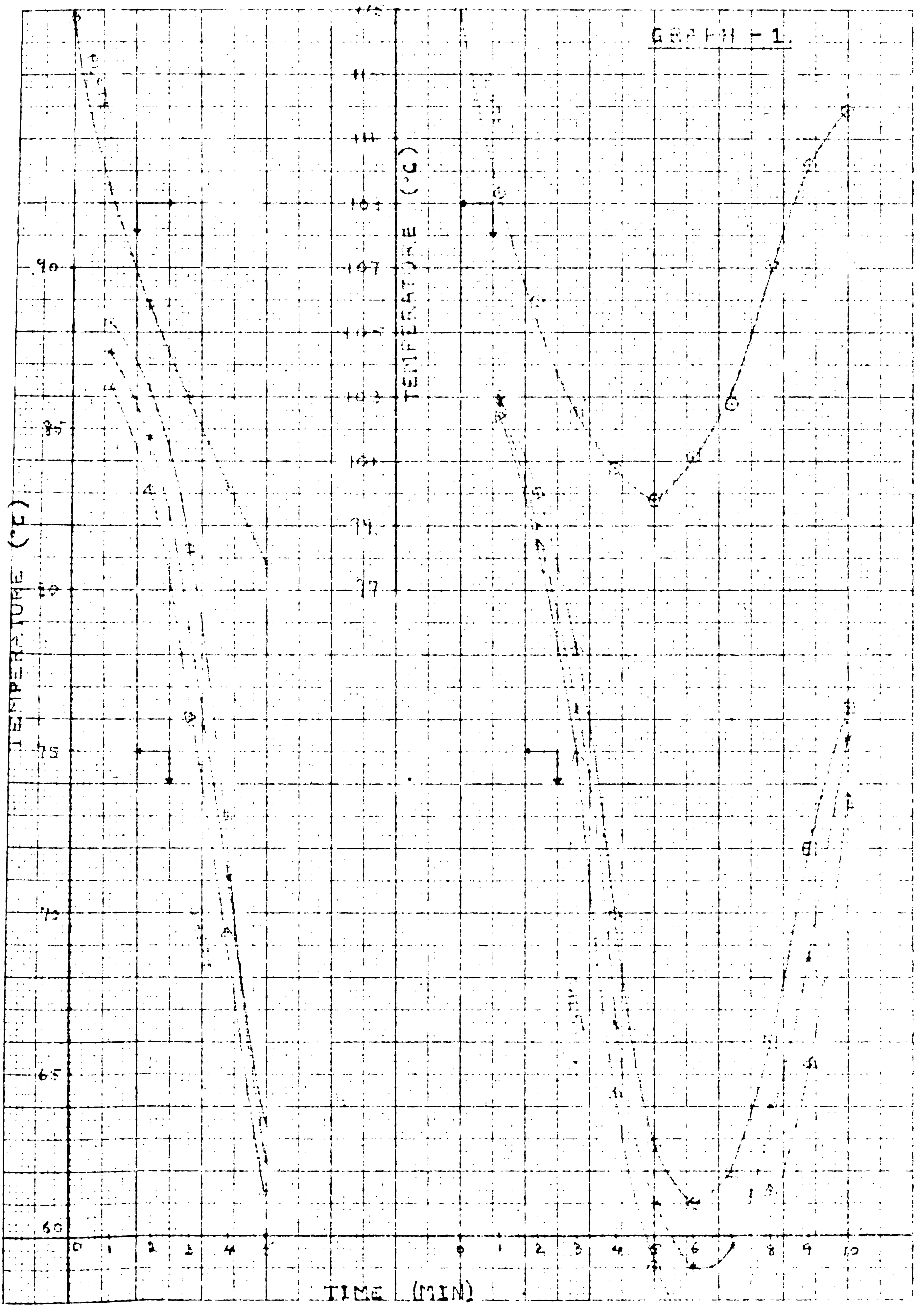
TABLE 19

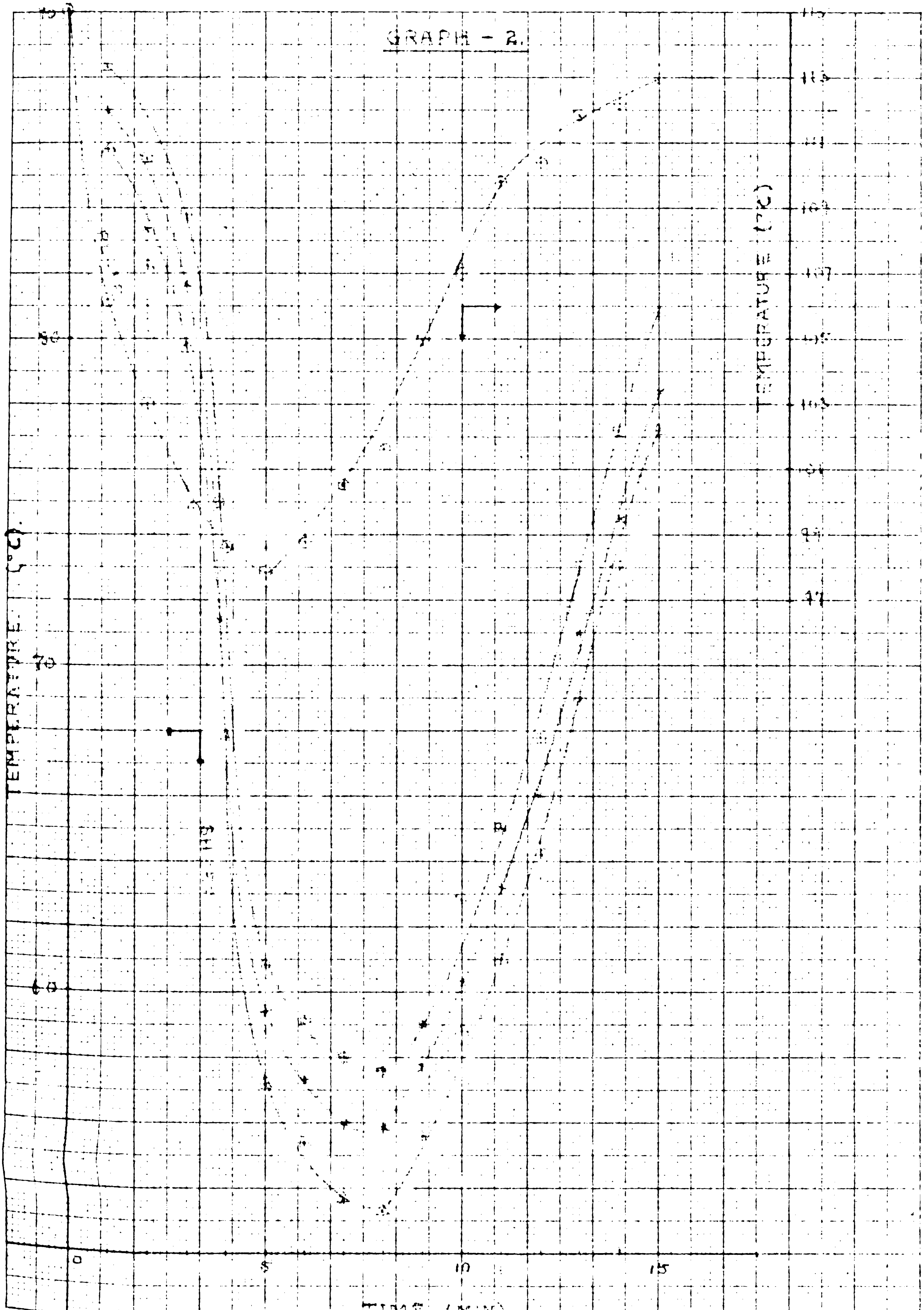
Time	Sheet	Plate
0	67.1	239.5
1	167.7	226.8
2	165.9	217.4
3	163.8	214.5
4	167.0	215.6
5	172.4	217.0
6	181.0	219.2
7	184.1	223.9
8	186.8	229.6
9	187.2	232.2
10	188.6	234.3
11	189.7	236.1
12	190.8	237.2
13	191.8	237.9
14	192.6	238.6
15	193.1	239.0

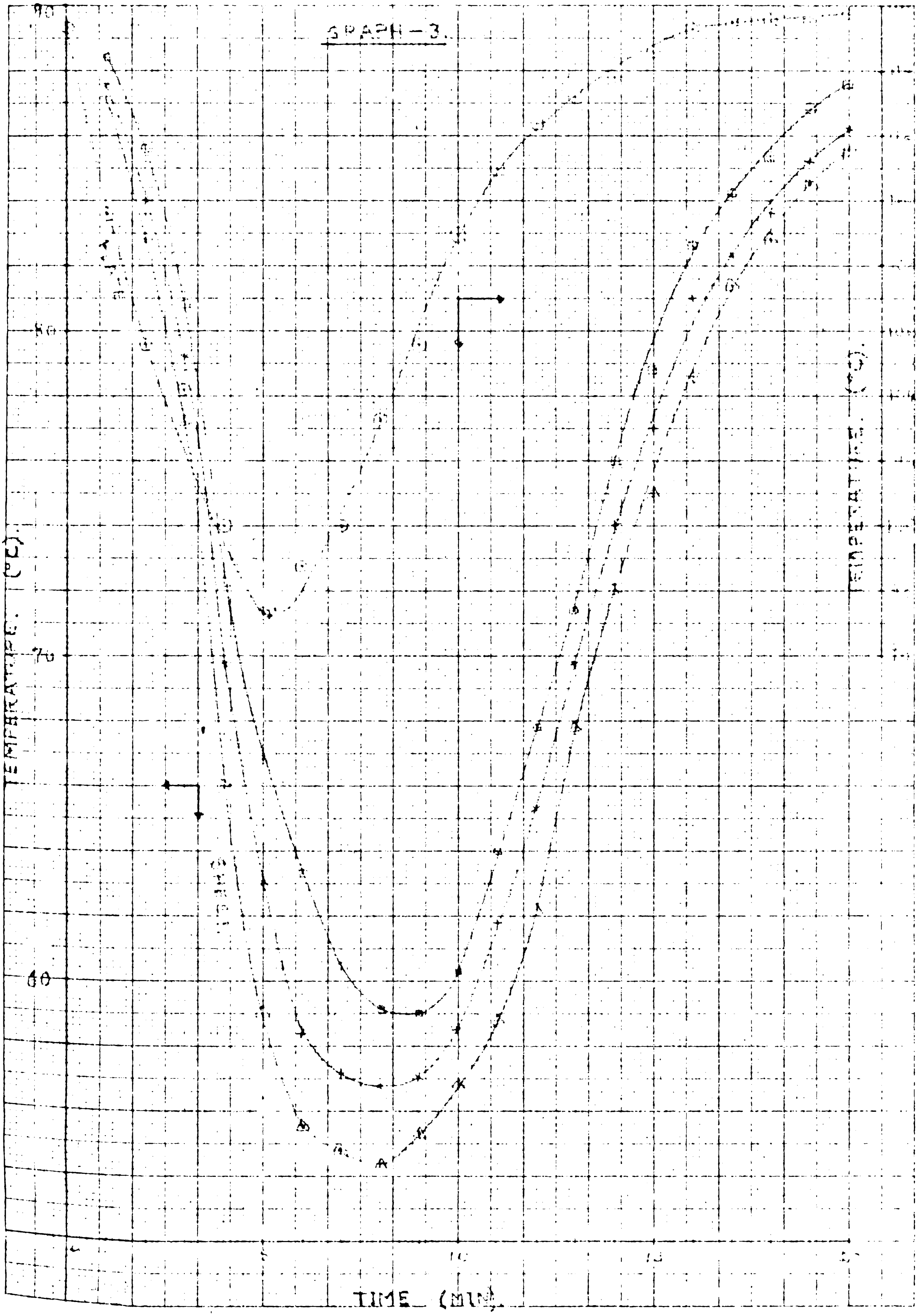
TABLE 20

Time	Sheet	Plate
0	67.6	239.0
1	171.0	229.3
2	168.4	221.7
3	165.2	216.3
4	170.2	217.0
5	176.5	218.3
6	179.6	221.7
7	181.9	225.5
8	184.3	228.9
9	186.4	231.4
10	187.9	233.2
11	188.6	235.4
12	189.3	236.8
13	191.1	237.9
14	192.6	238.6
15	194.0	239.5
16	194.7	239.5
17	195.4	240.4
18	195.8	240.8
19	196.3	240.8
20	196.5	240.8

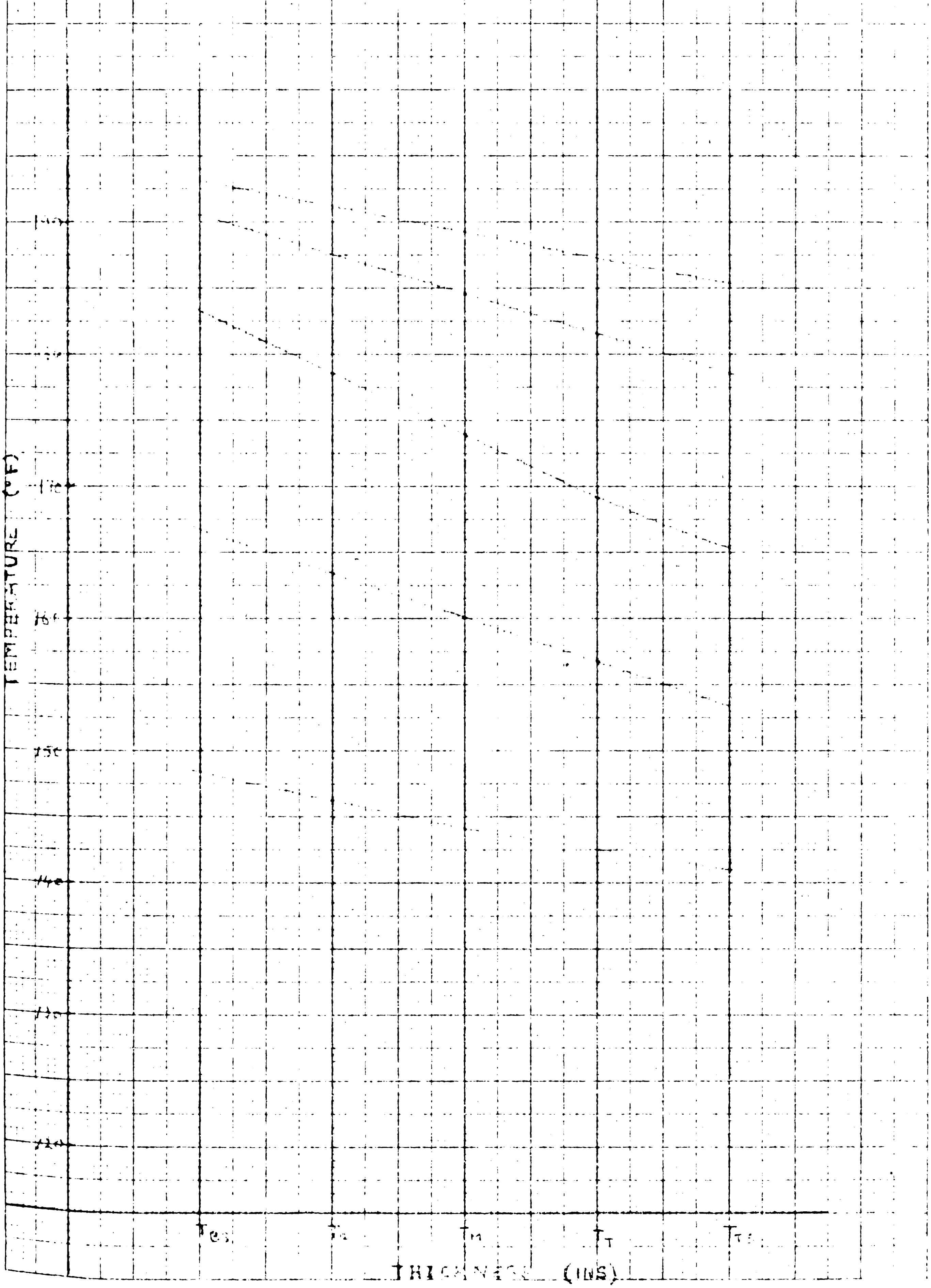
THICK SHEETS

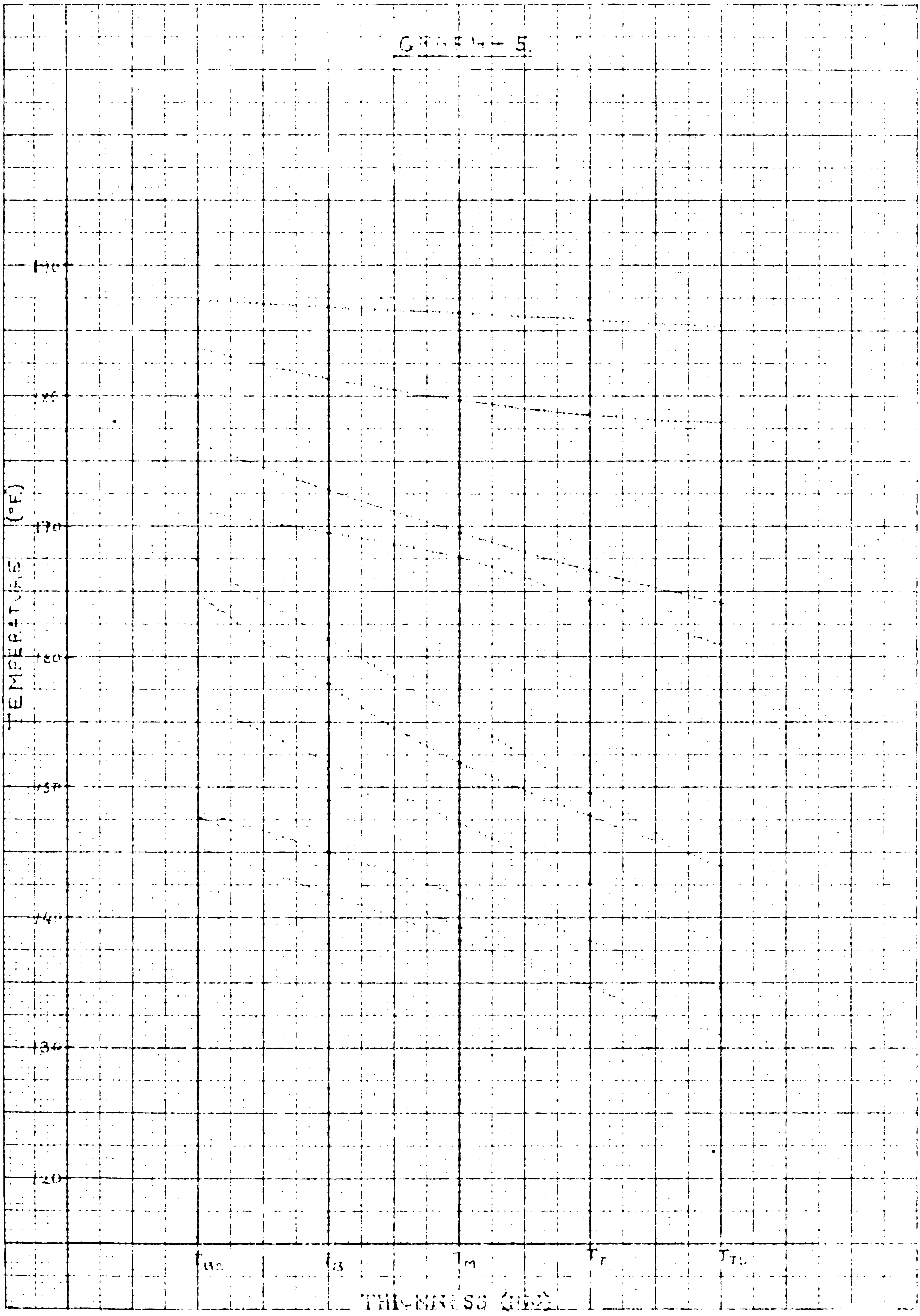

GRAPH - 1.
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (MIN)
90
85
75
65
60
0
1
2
3
4
5
6
7
8
9
10


GRAPH - 2.
TEMPERATURE (°C).
TEMPERATURE (°C)
TIME (MIN).
0
5
10
15
60
70
80

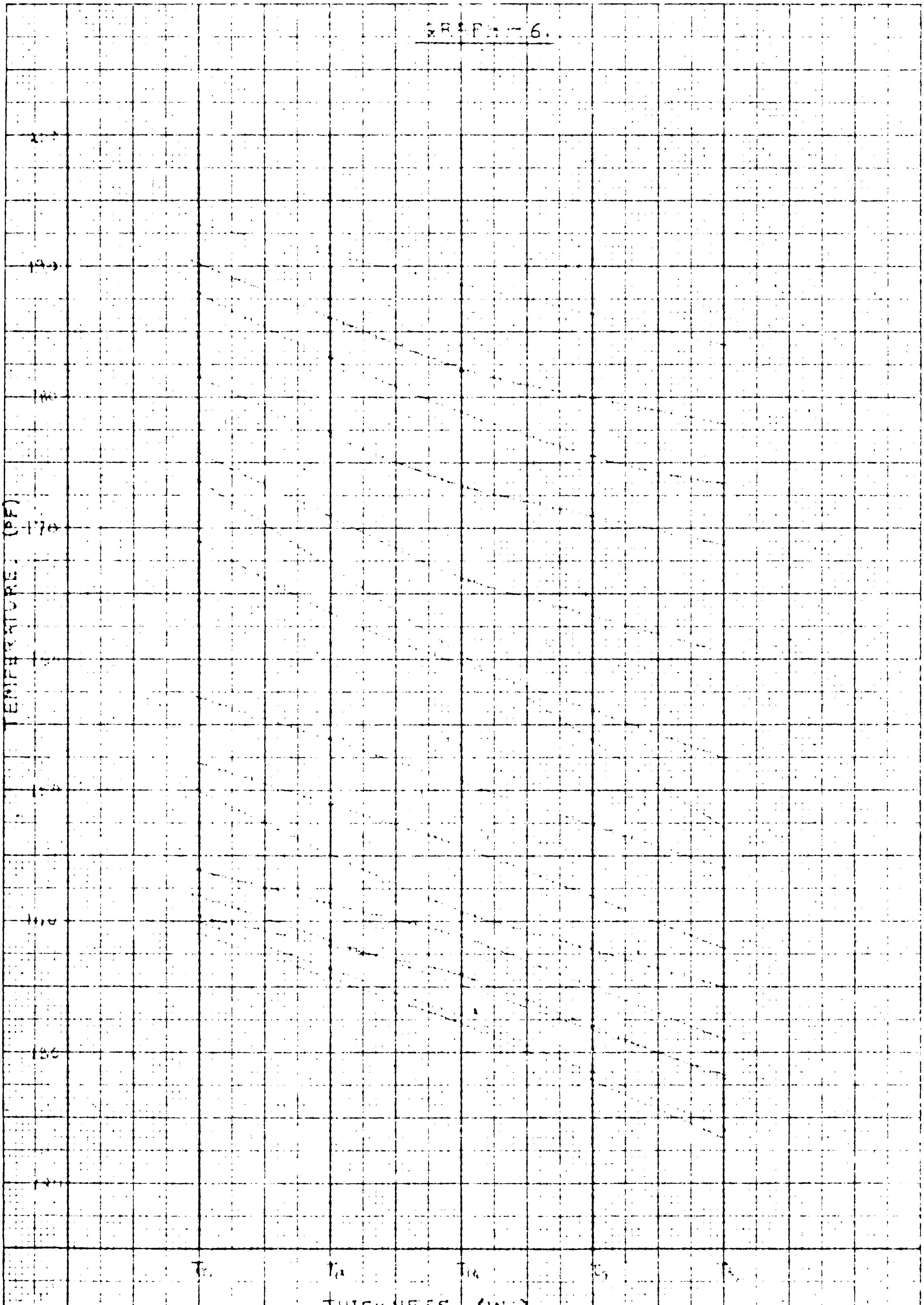

GRAPH-3.
TEMPERATURE (°C).
TIME (MIN).
90
80
70
60
5
10
15
20

GRAPH - 4.

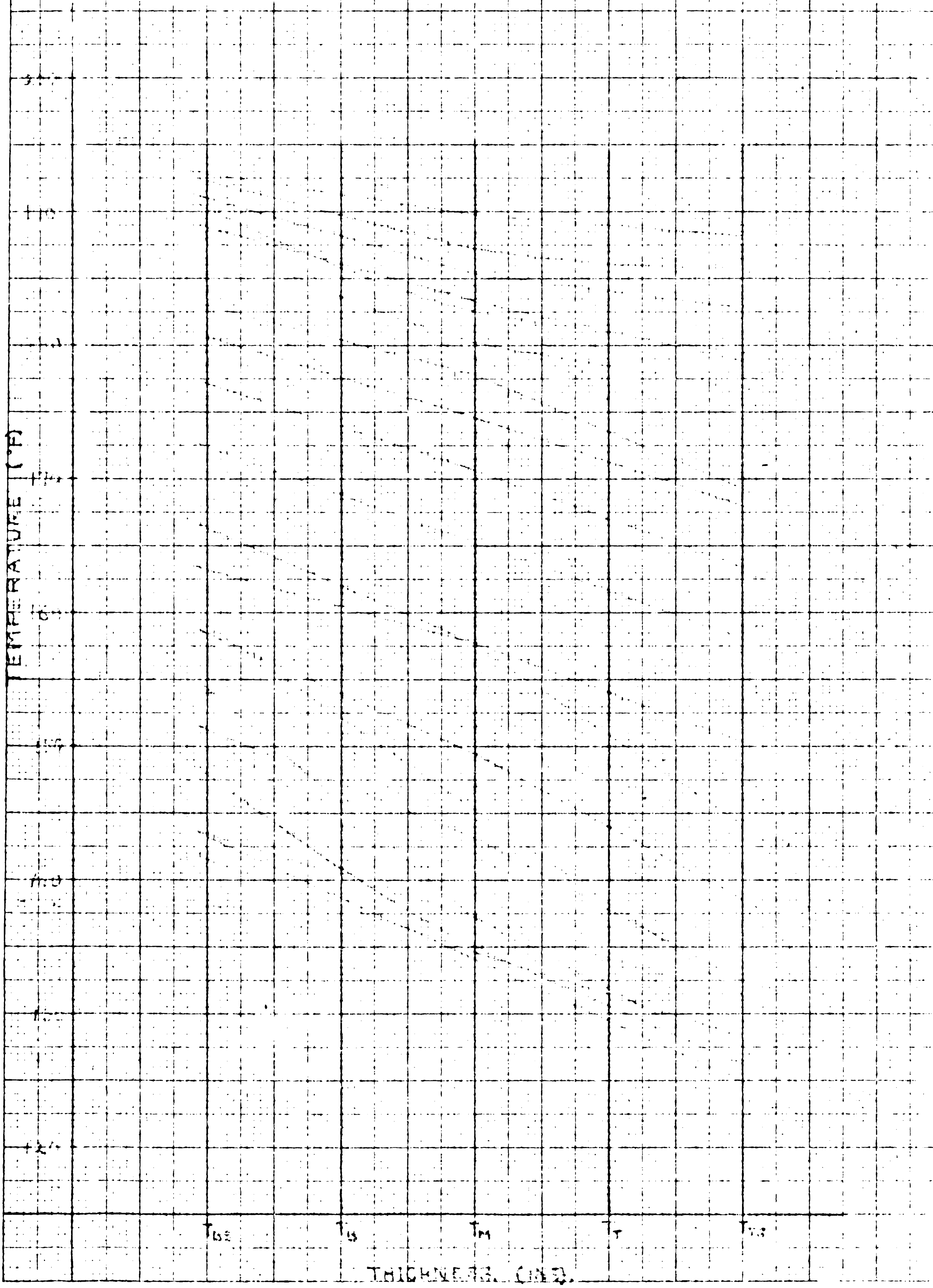


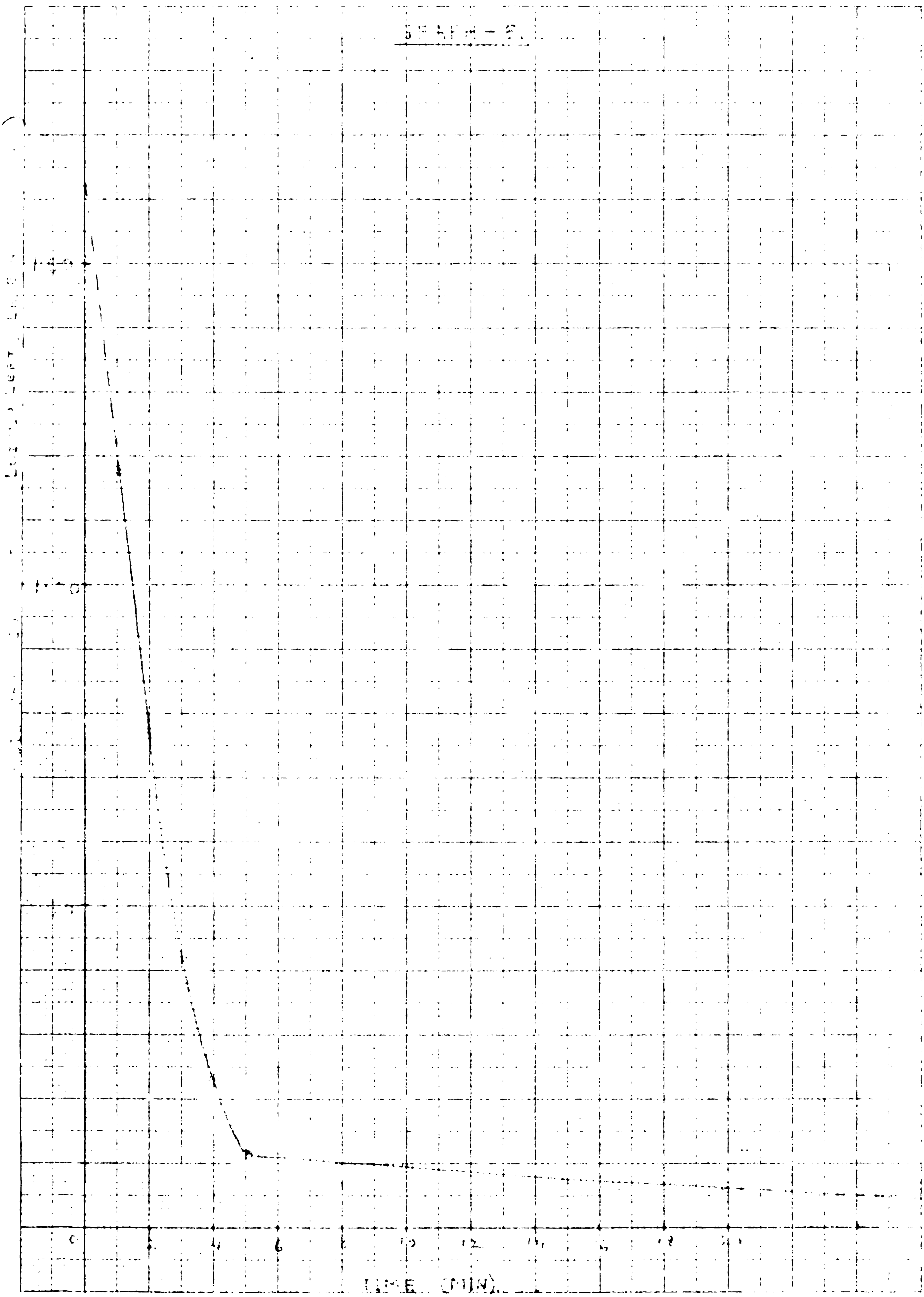


TEMPERATURE (°F)

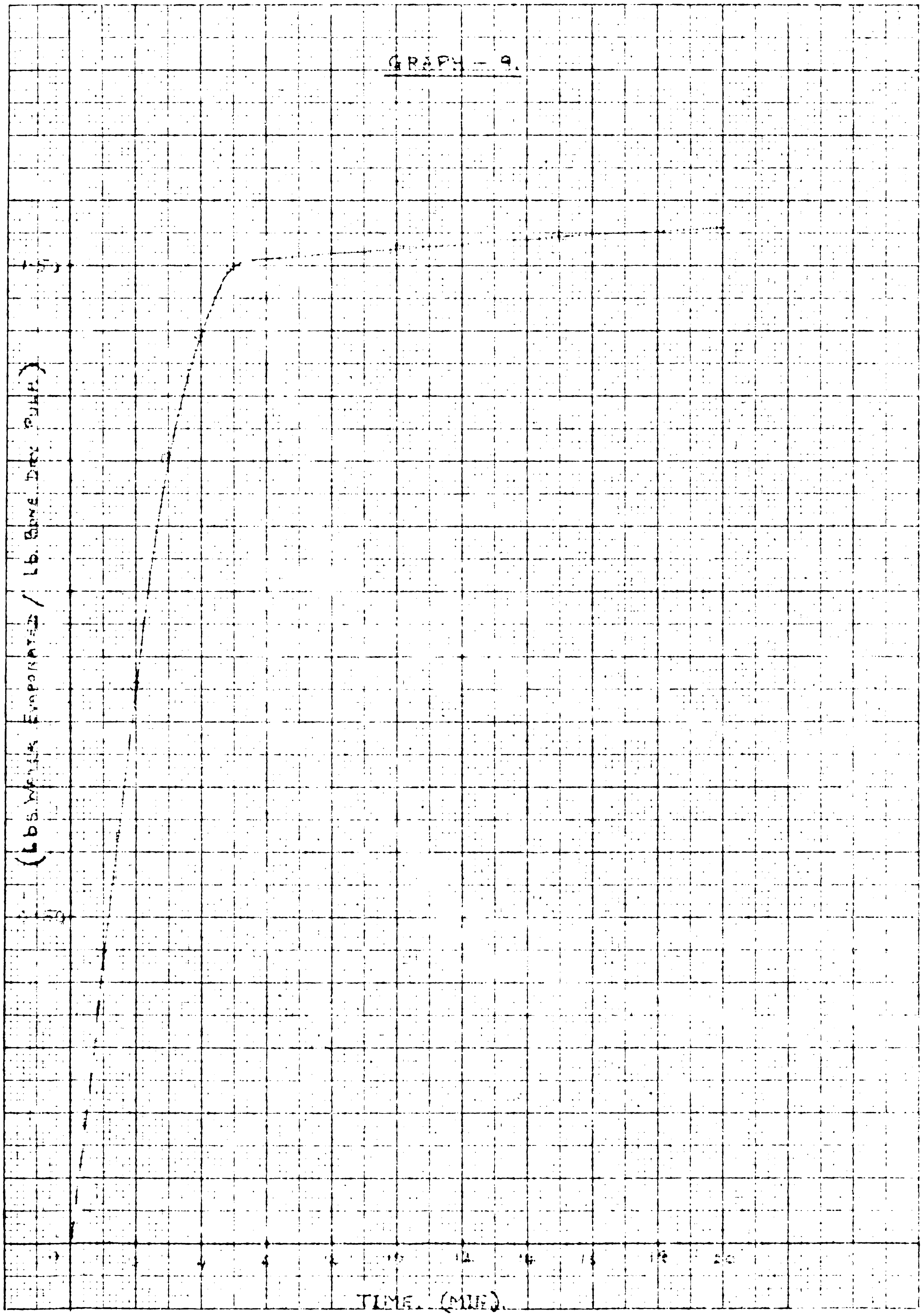

GRAPH - 6.
TEMPERATURE (°F)
170
THICKNESS (IN.)

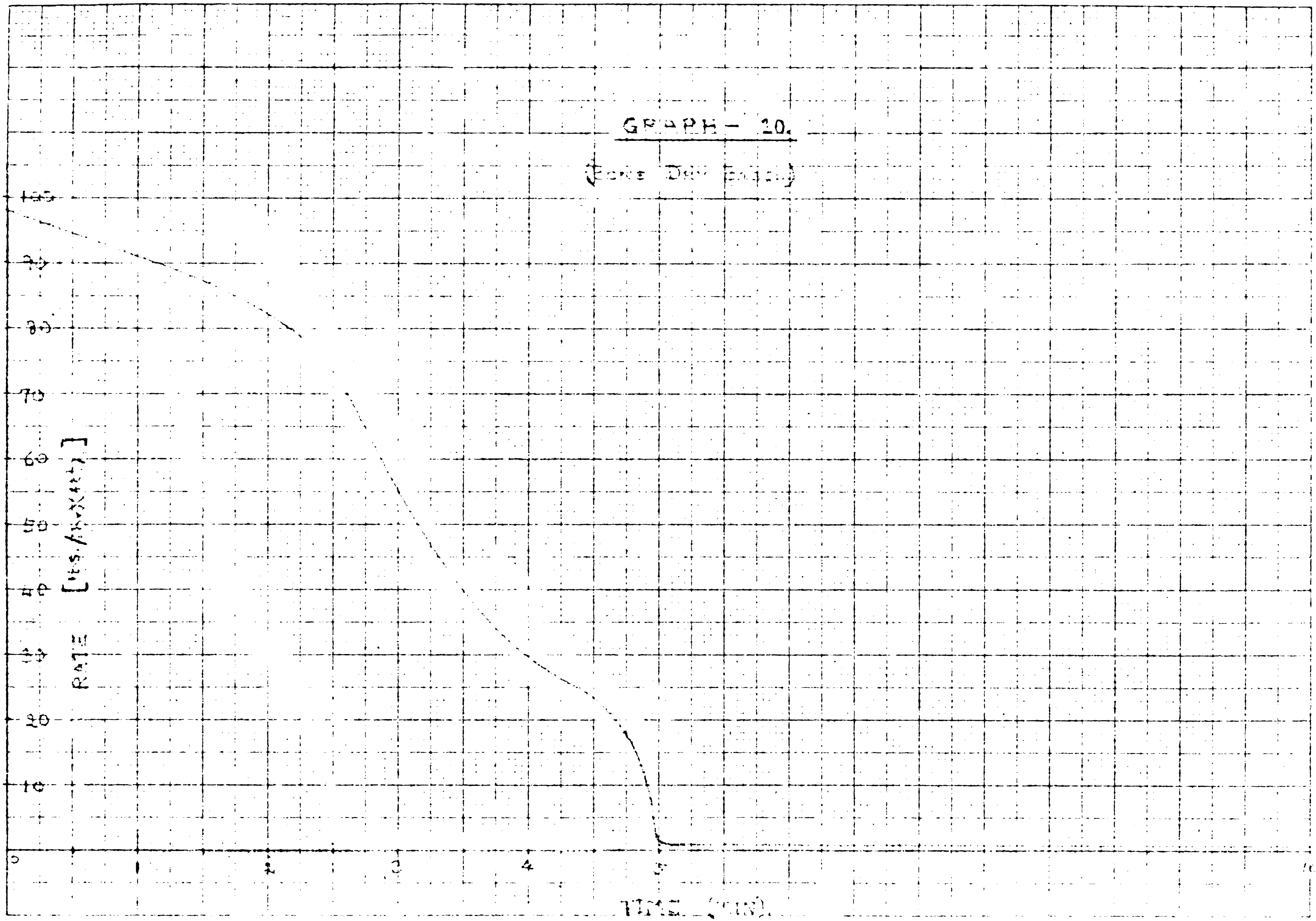
GRAPH - 7

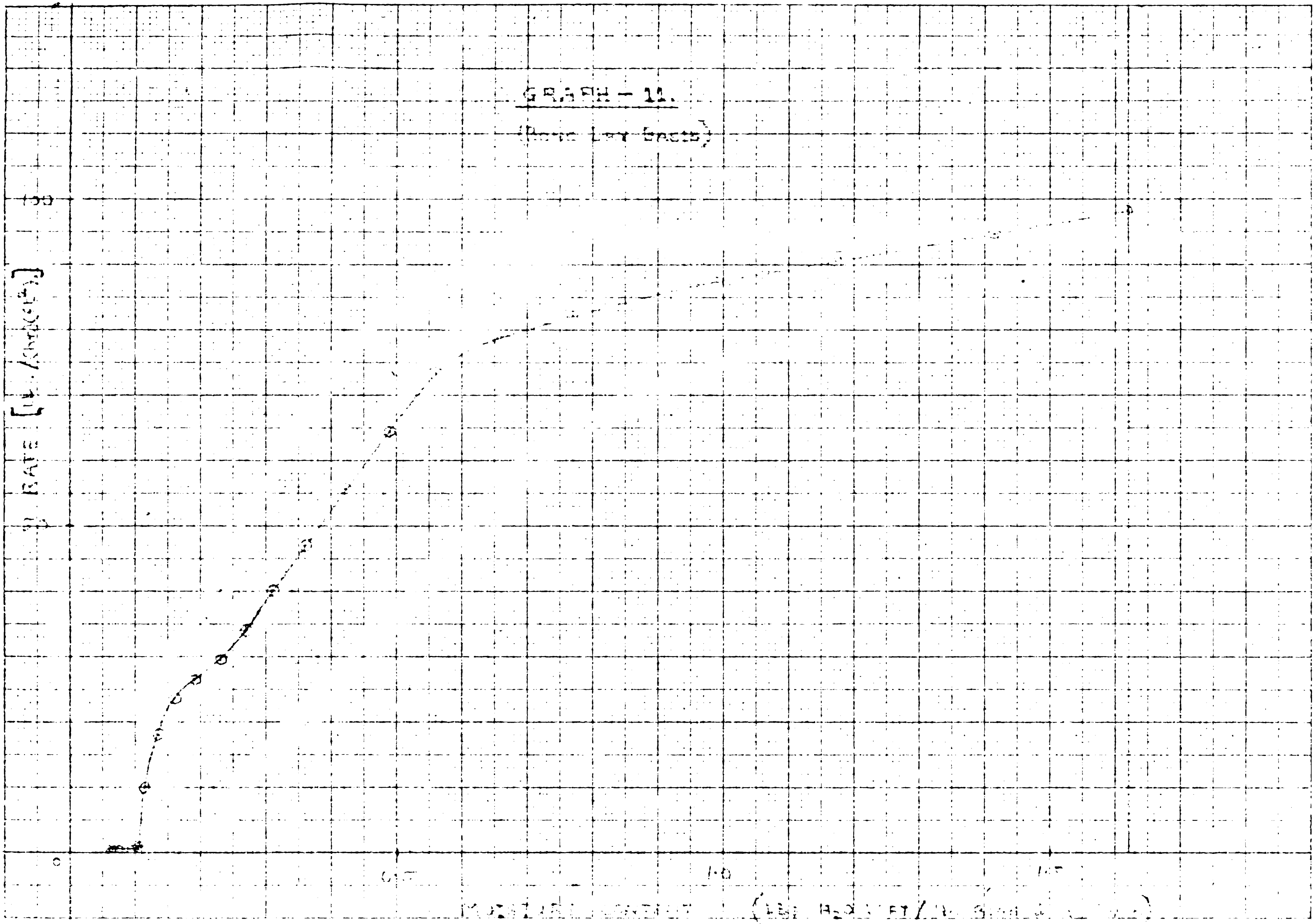


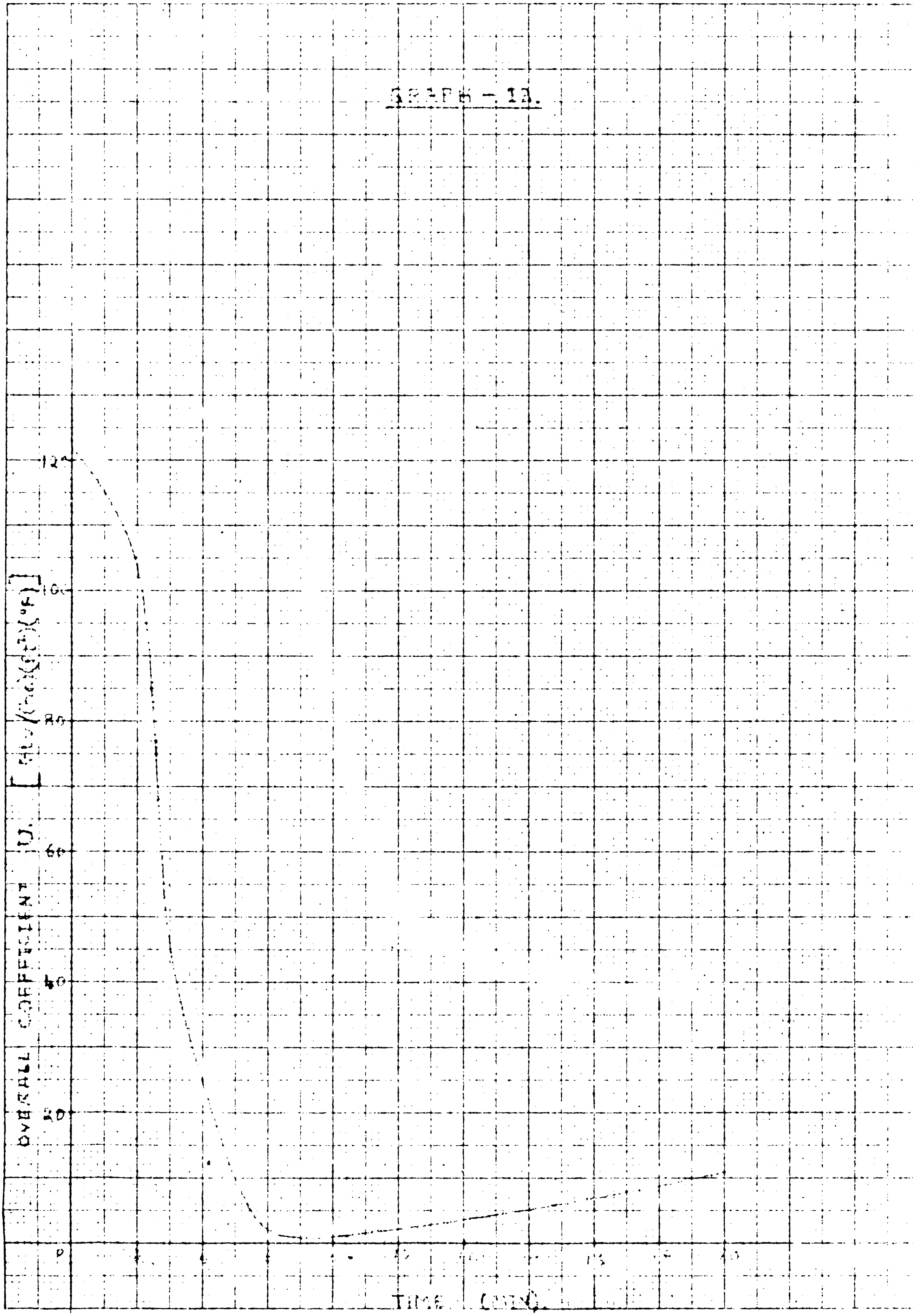

GRAPH – 5.
0
4
6
10
12
TIME (MIN).

GRAPH - 9.

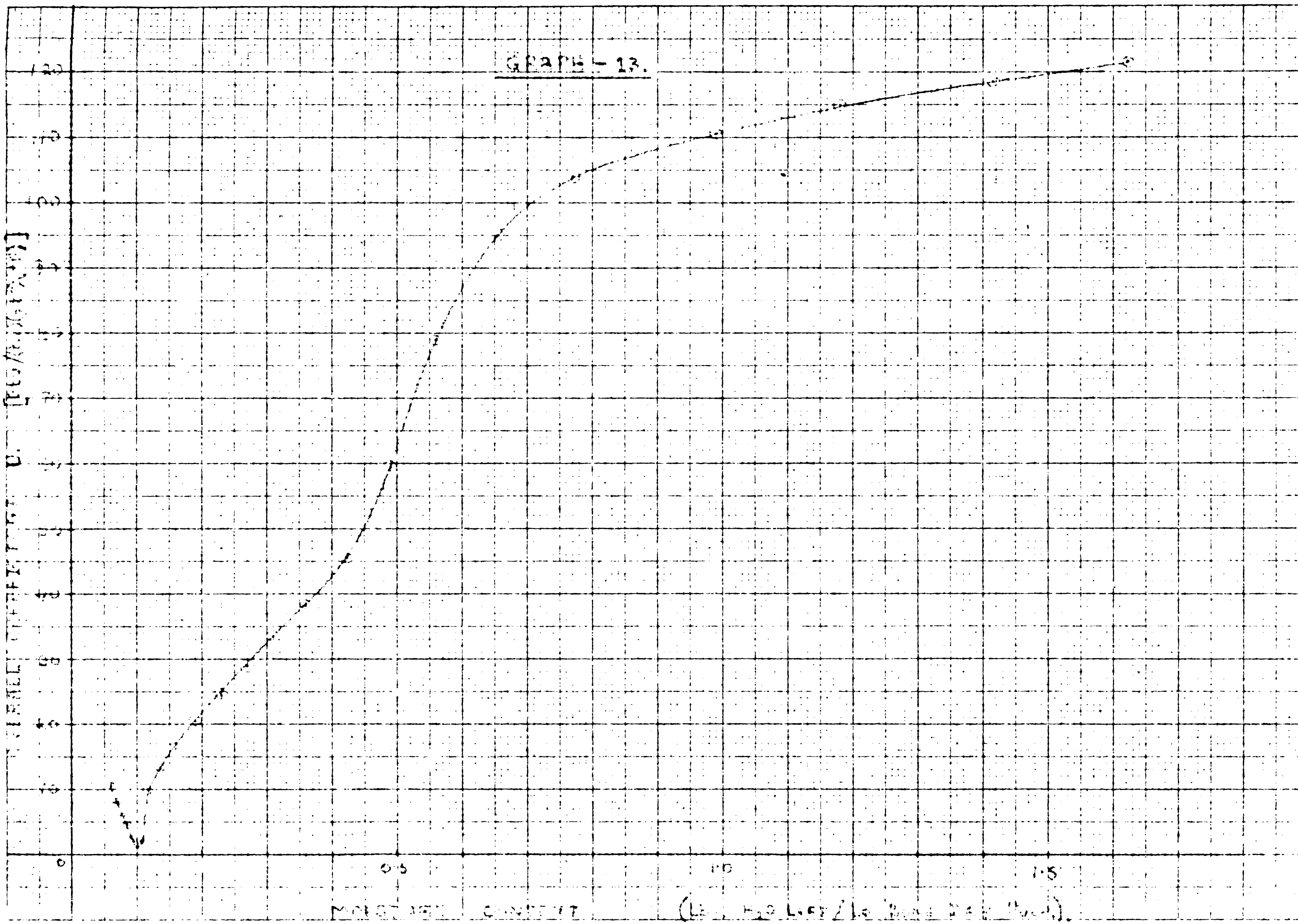


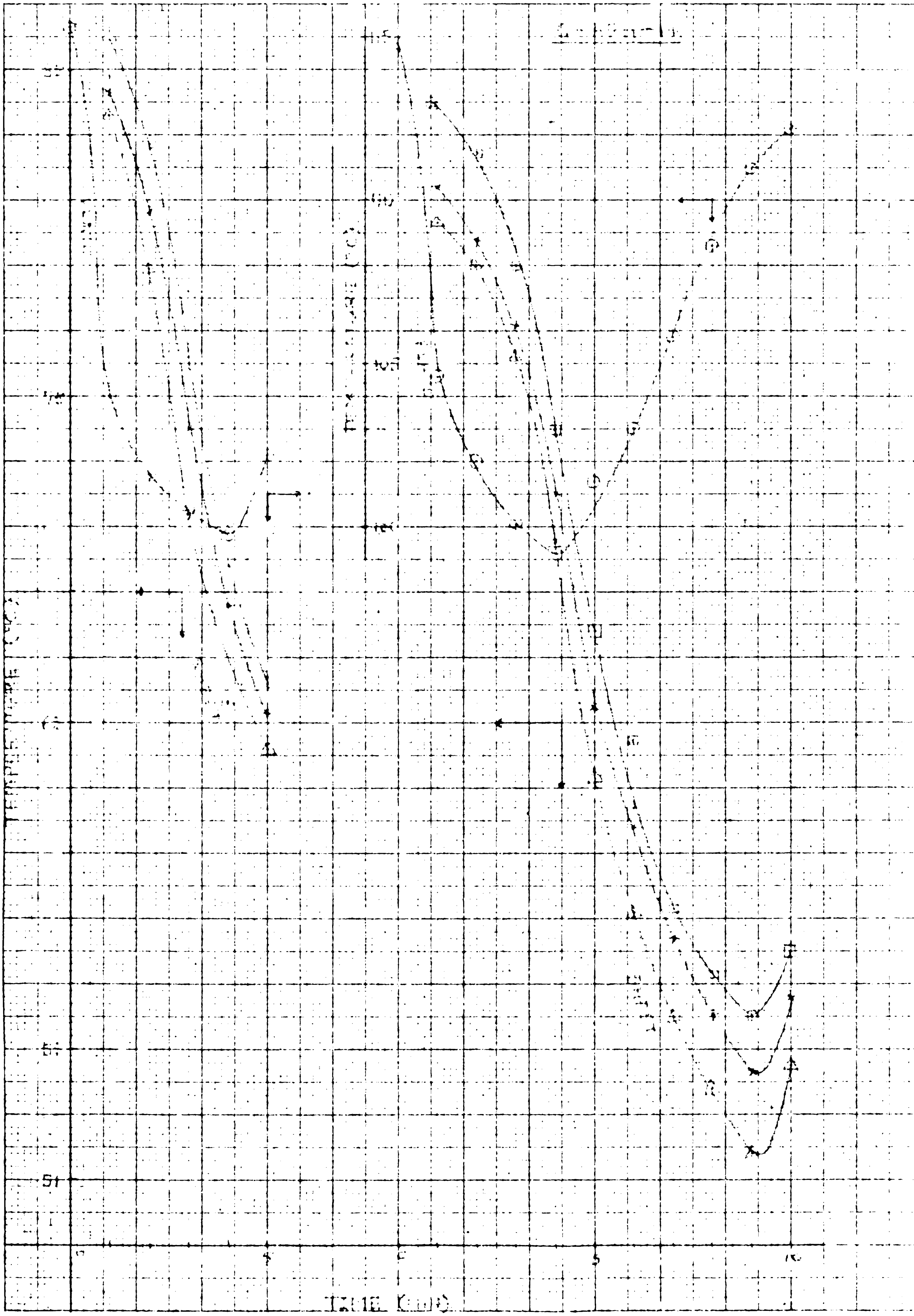

GRAPH - 10.
100
90
80
70
60
50
40
30
20
10
RATE
0
1
2
3
4
5
TIME

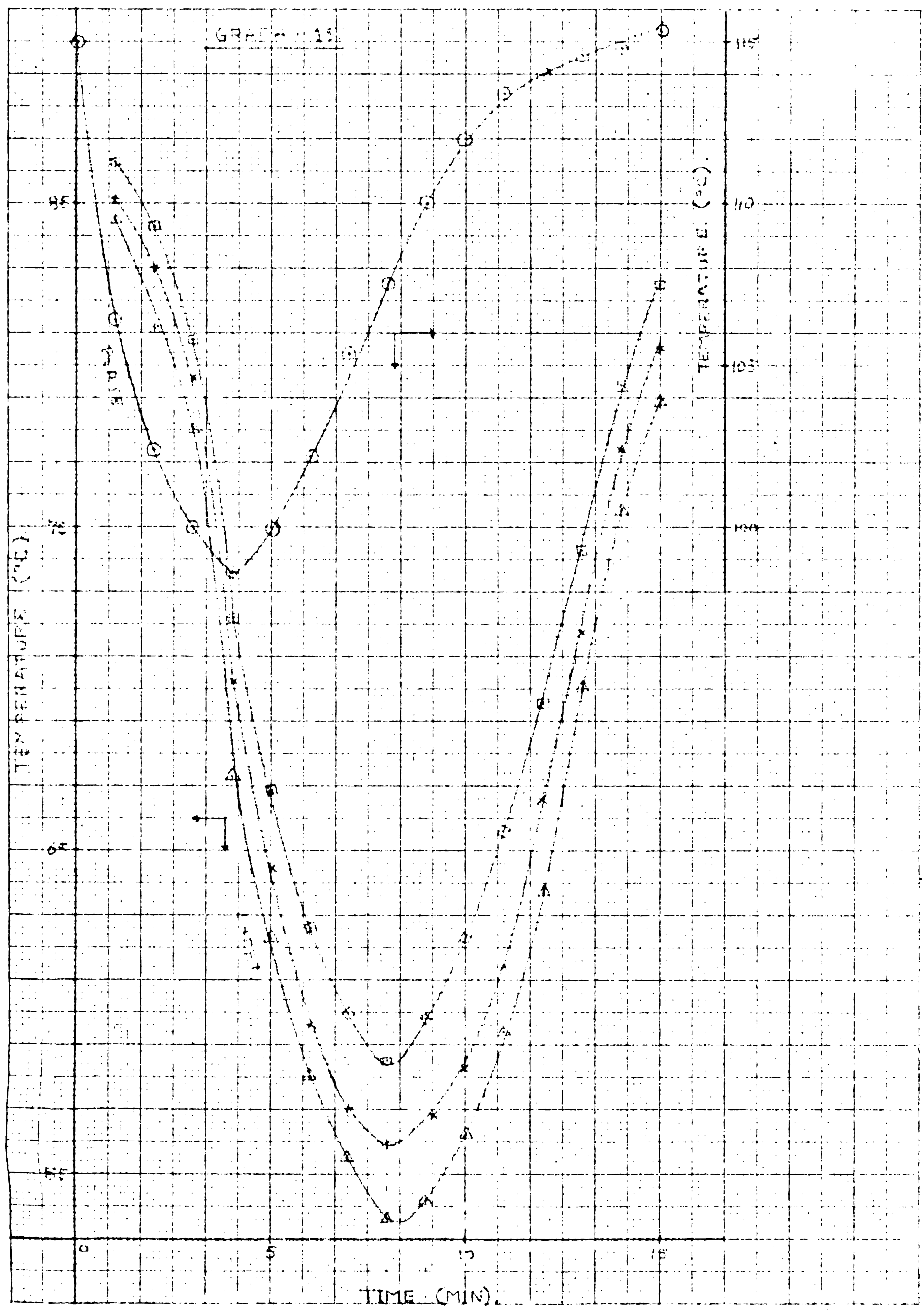

GRAPH – 11.
RATE
0
1.0

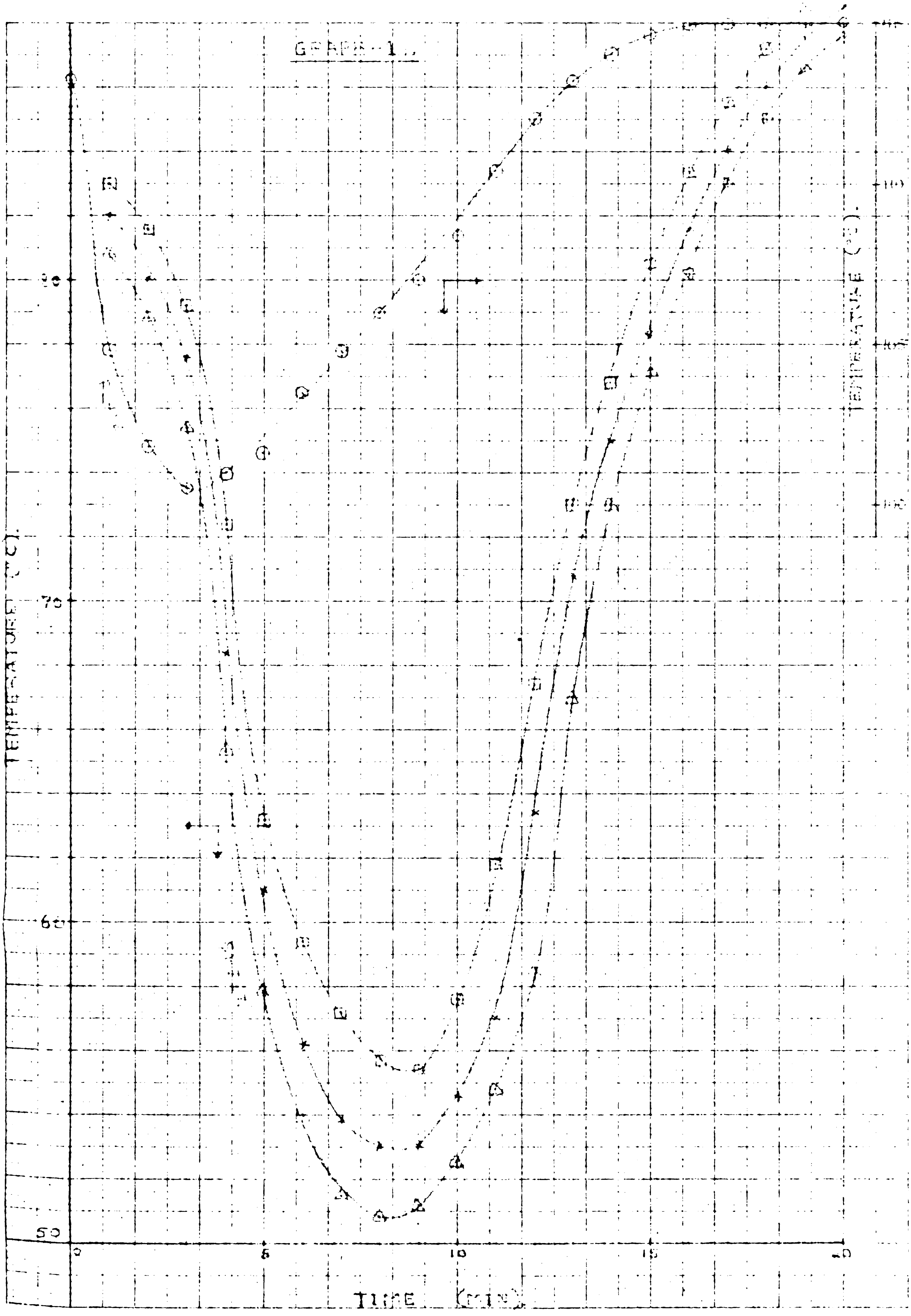


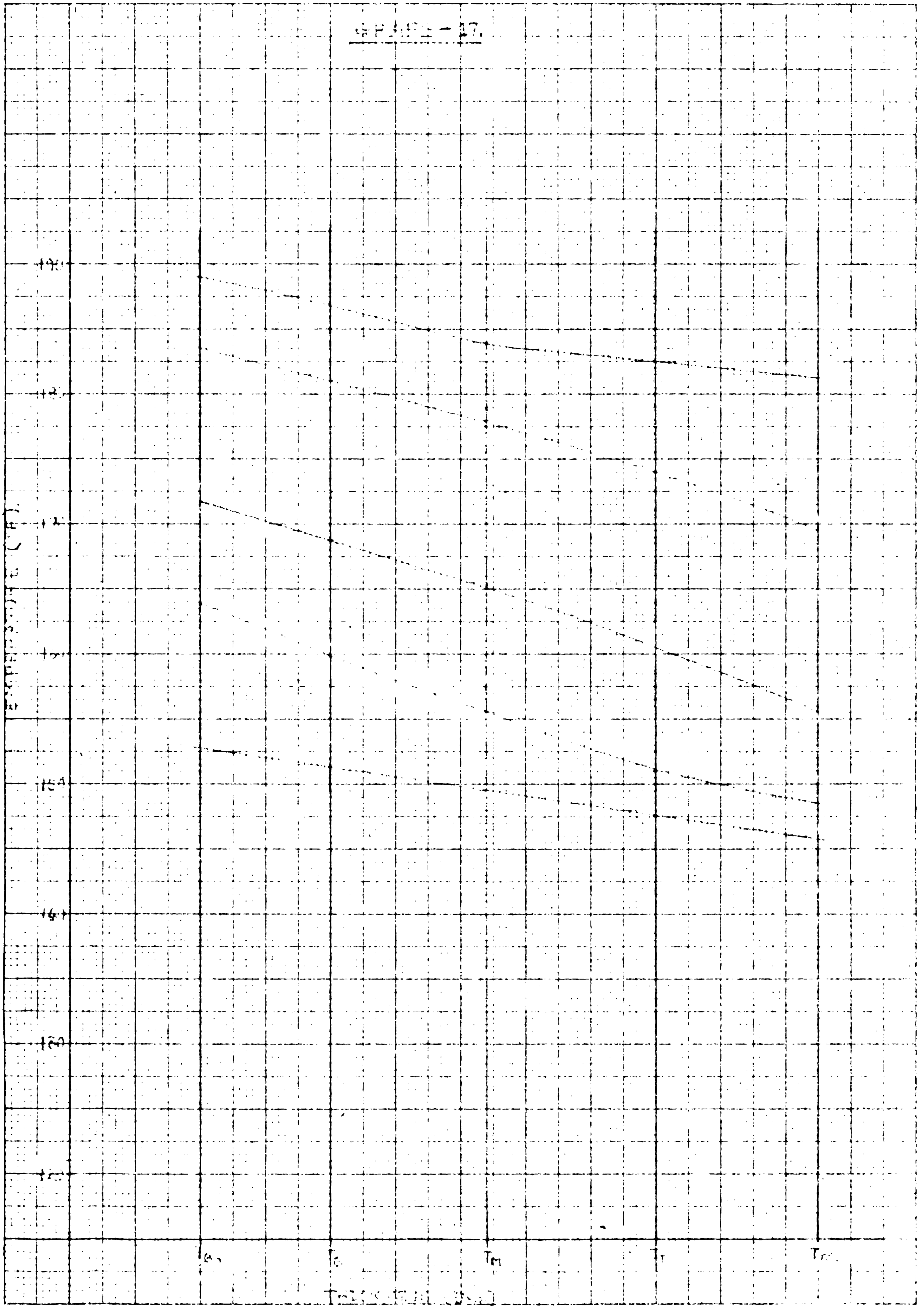
GRAPH - 11.
OVERALL COEFFICIENT U. [BTU/(hr)(ft²)(°F)]
120
100
80
60
40
20
0
TIME (MIN).


GRAPH - 13.
0
0·5
1·0
1·5

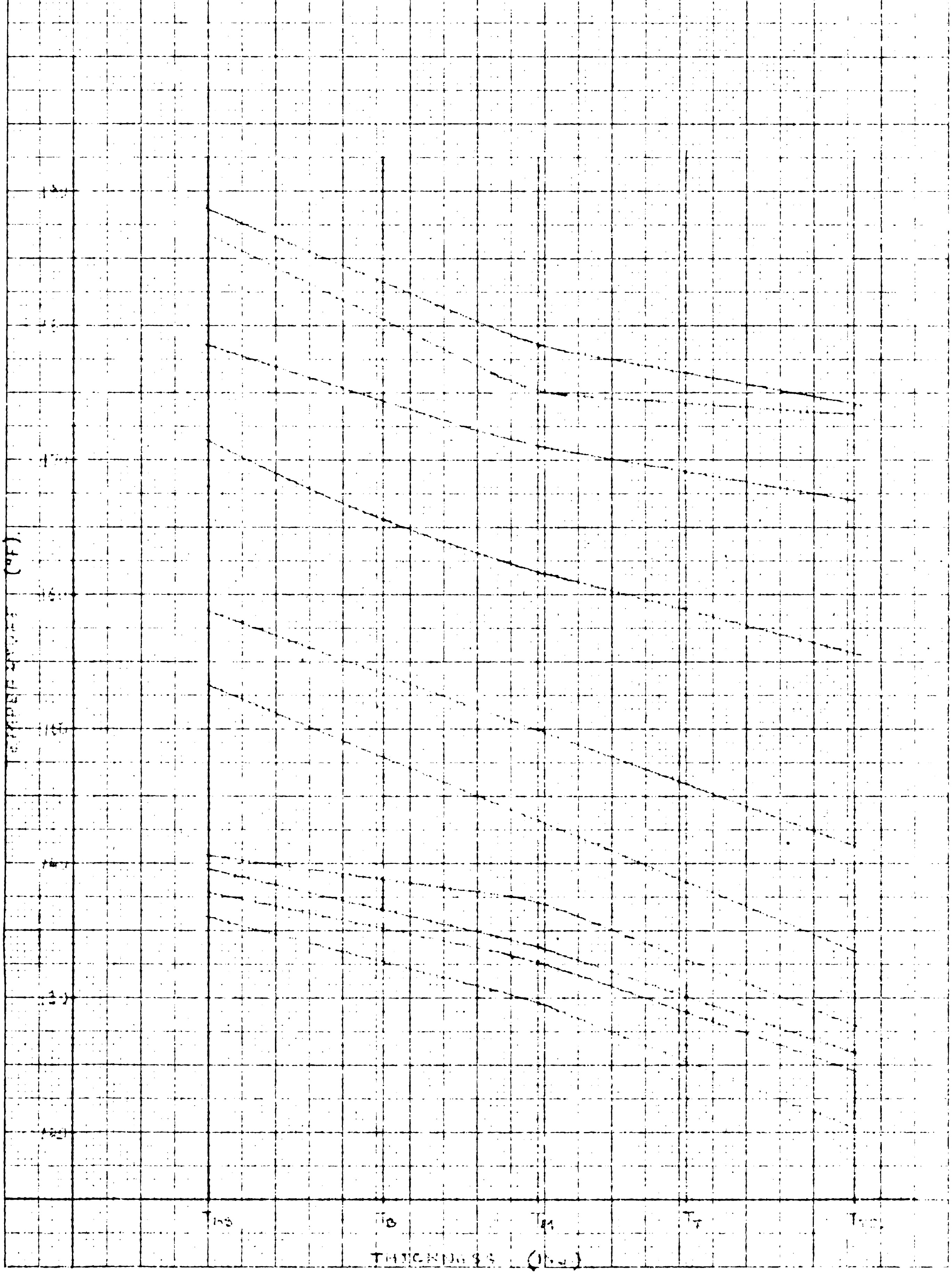

TIME (min)


GRAPH 15
TEMPERATURE (°C)
TEMPERATURE (°C)
TIME (MIN)
85
75
65
55
115
110
105
100
0
5
10
15

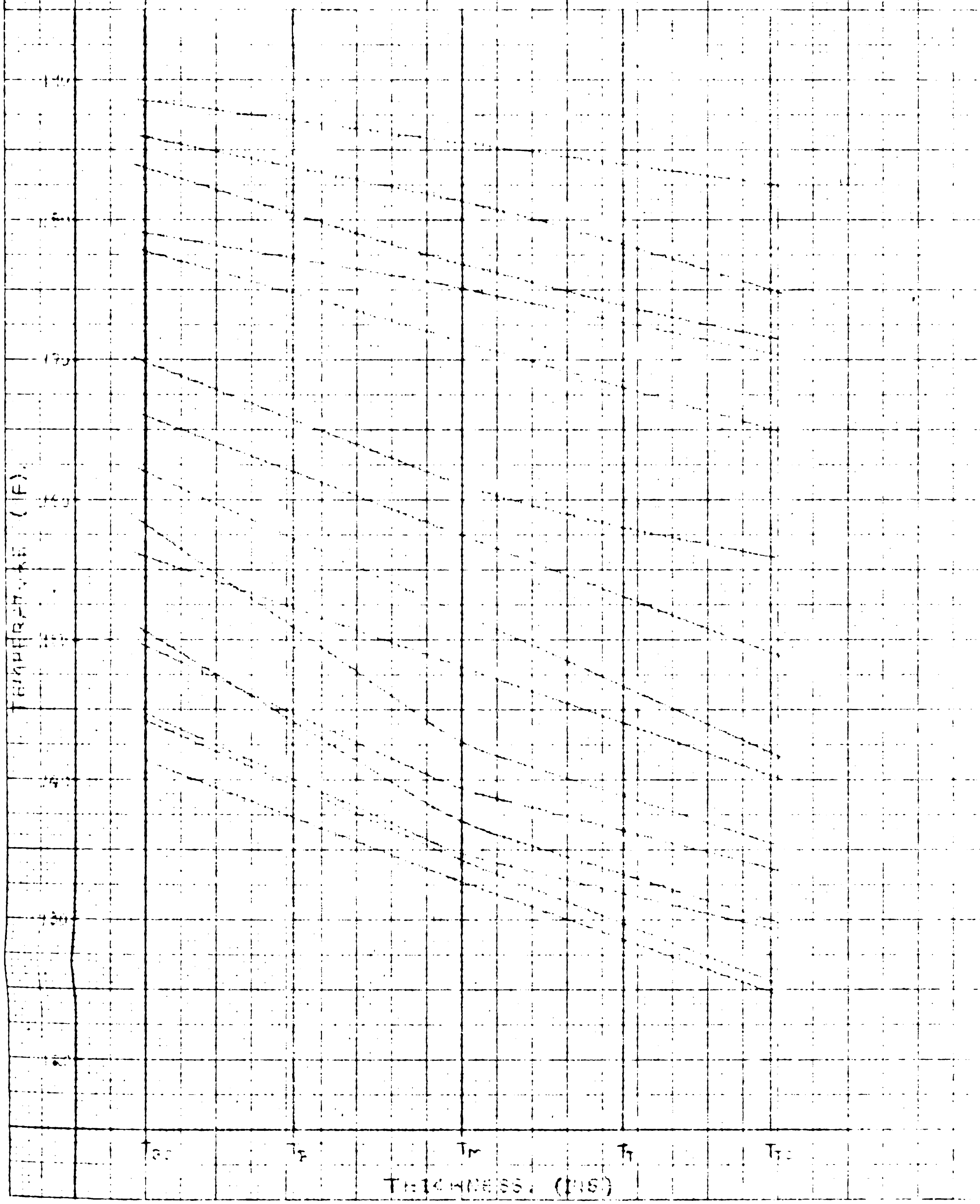

GRAPH-1.
TEMPERATURE (°C).
TEMPERATURE (°C).
TIME (MIN).
50
60
70
80
0
5
10
15
20

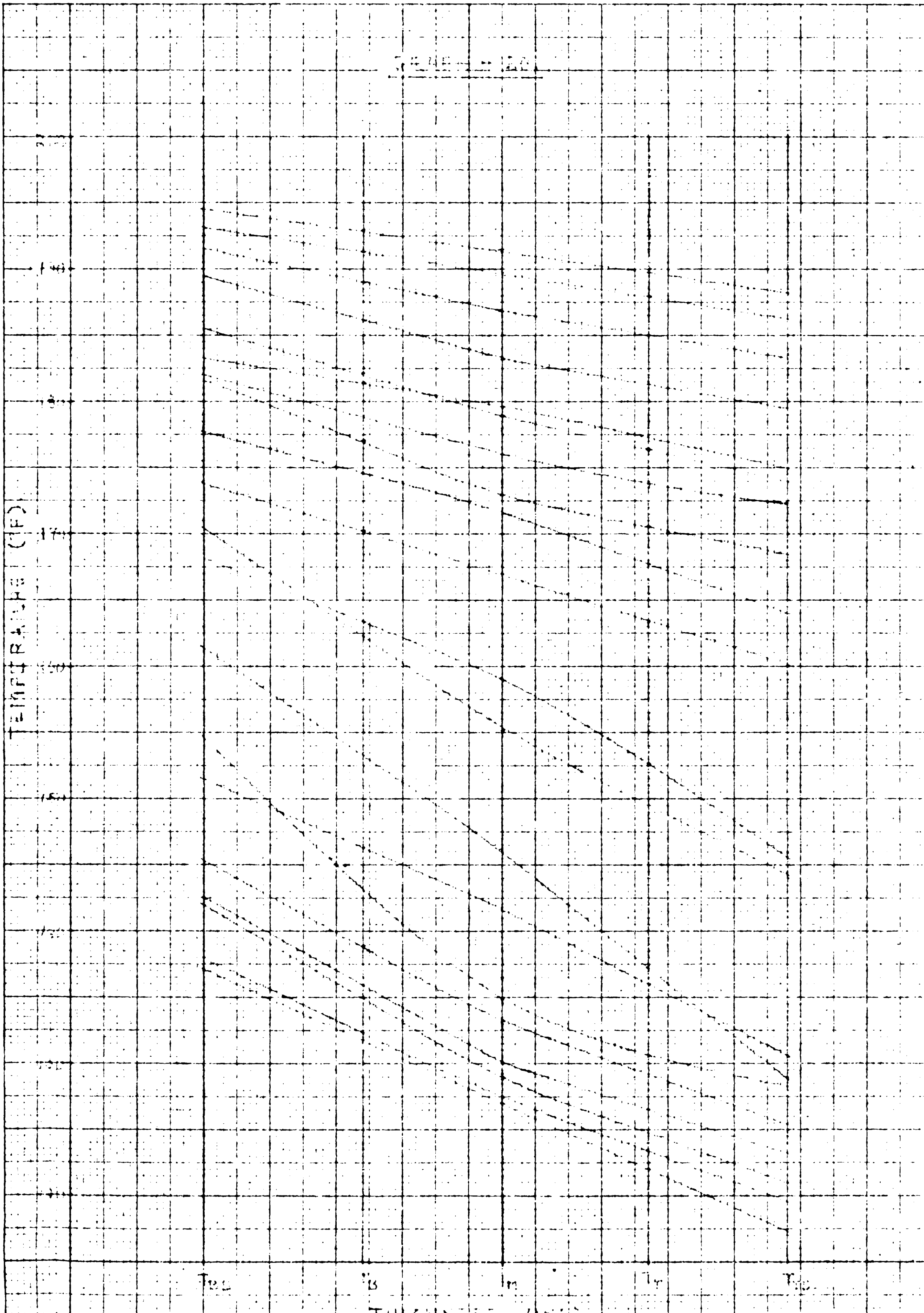


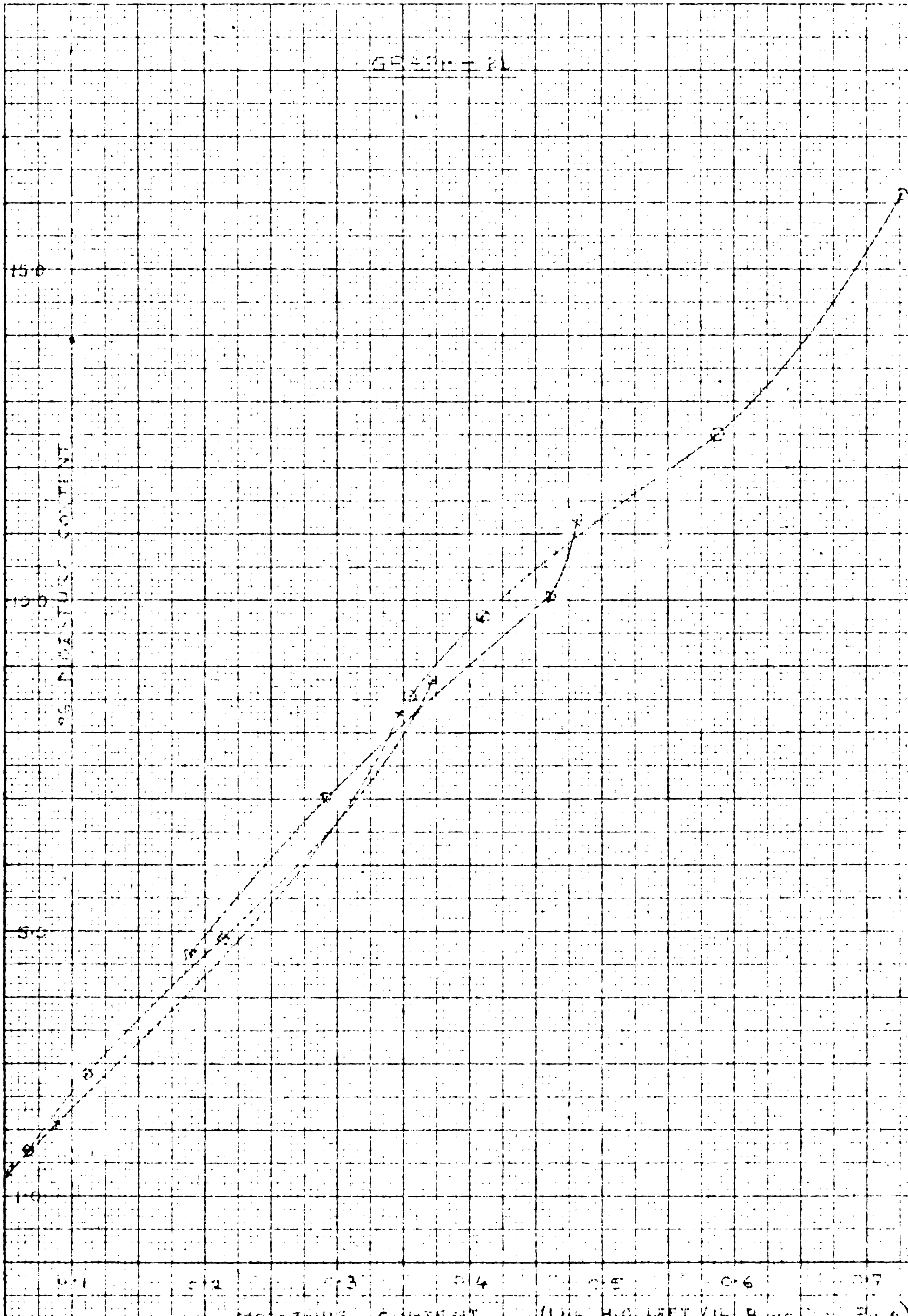
GRAPH - 18.



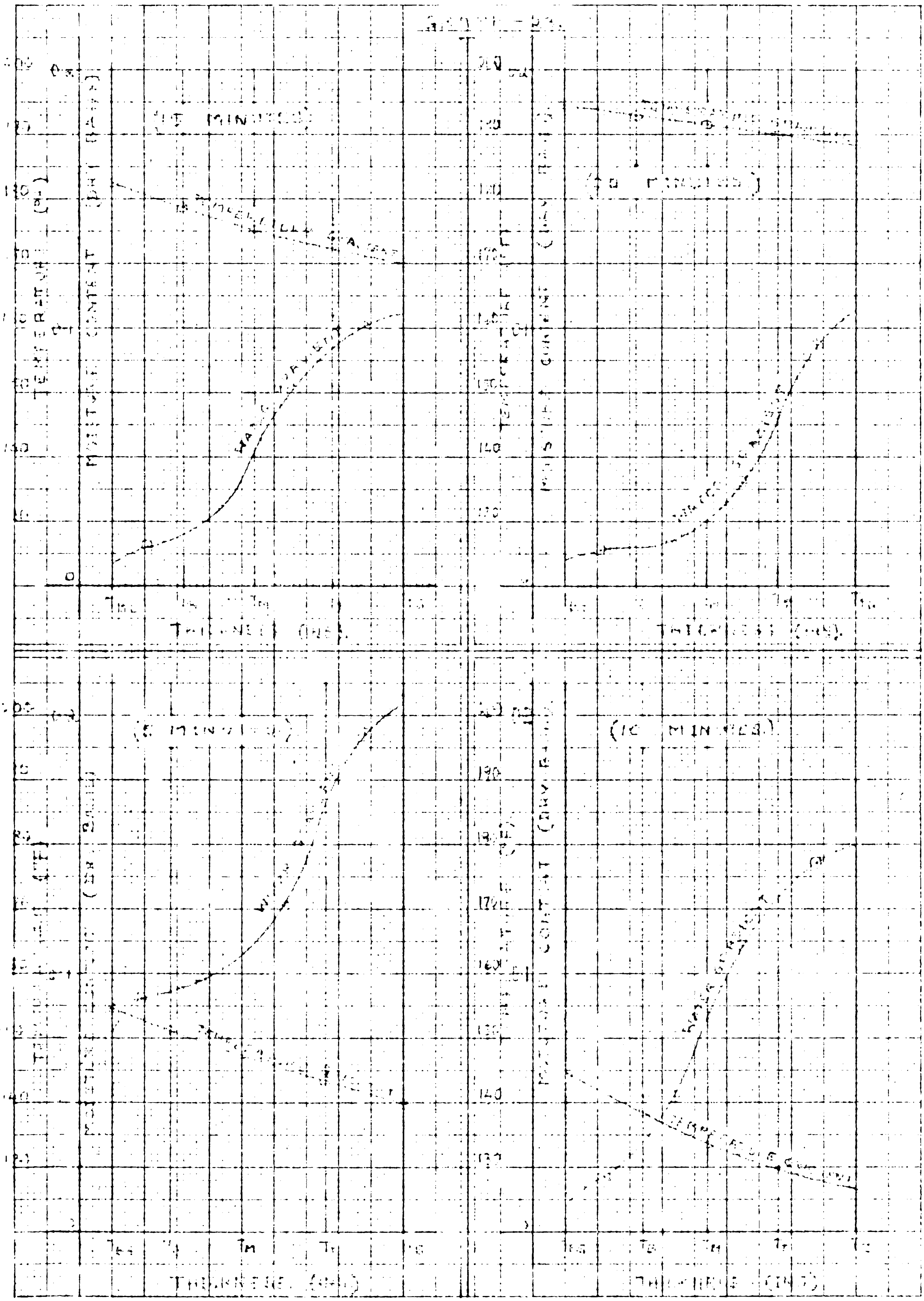
GRAPH - 14

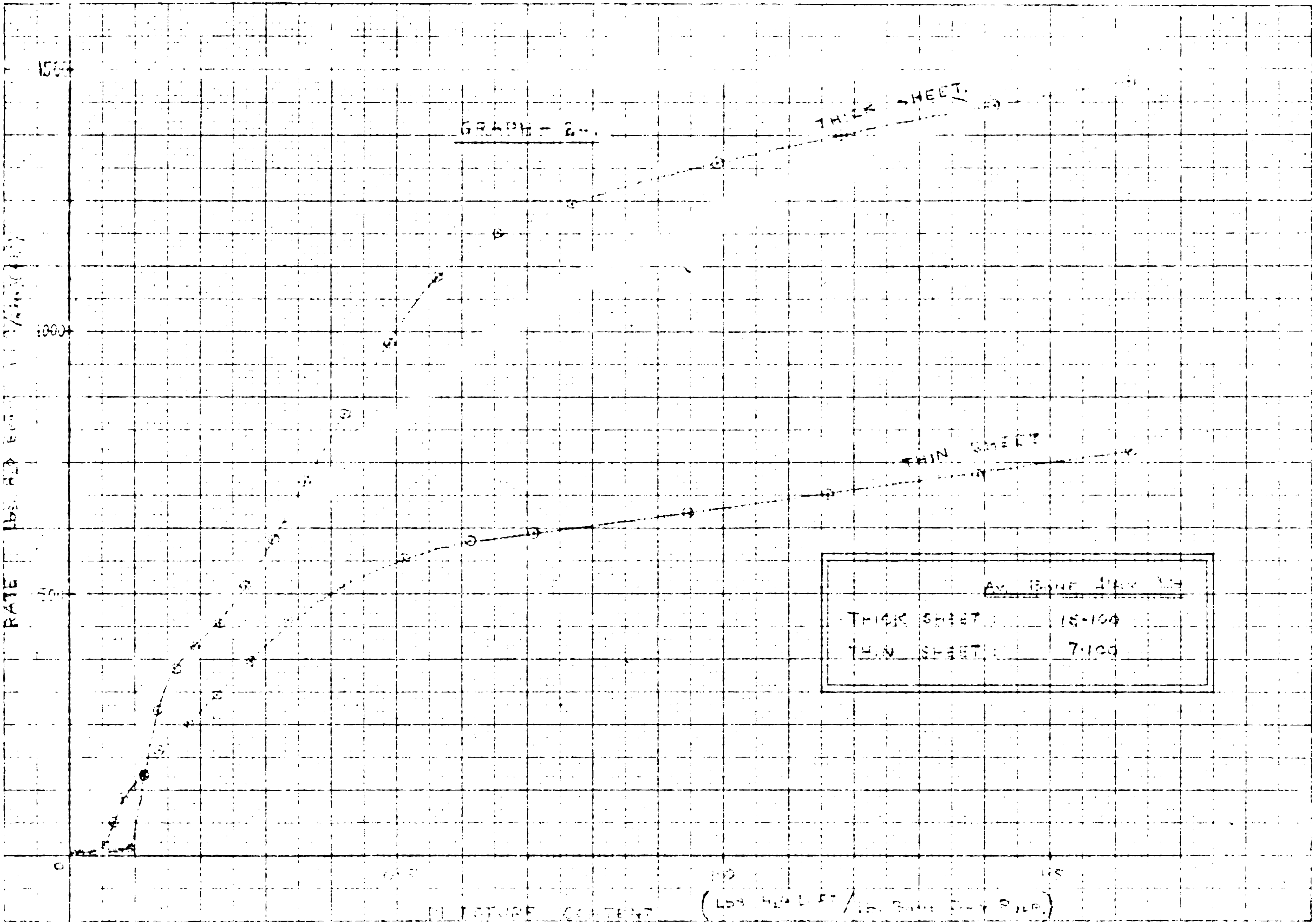



TEMPERATURE (°F)
THICKNESS (INCH)

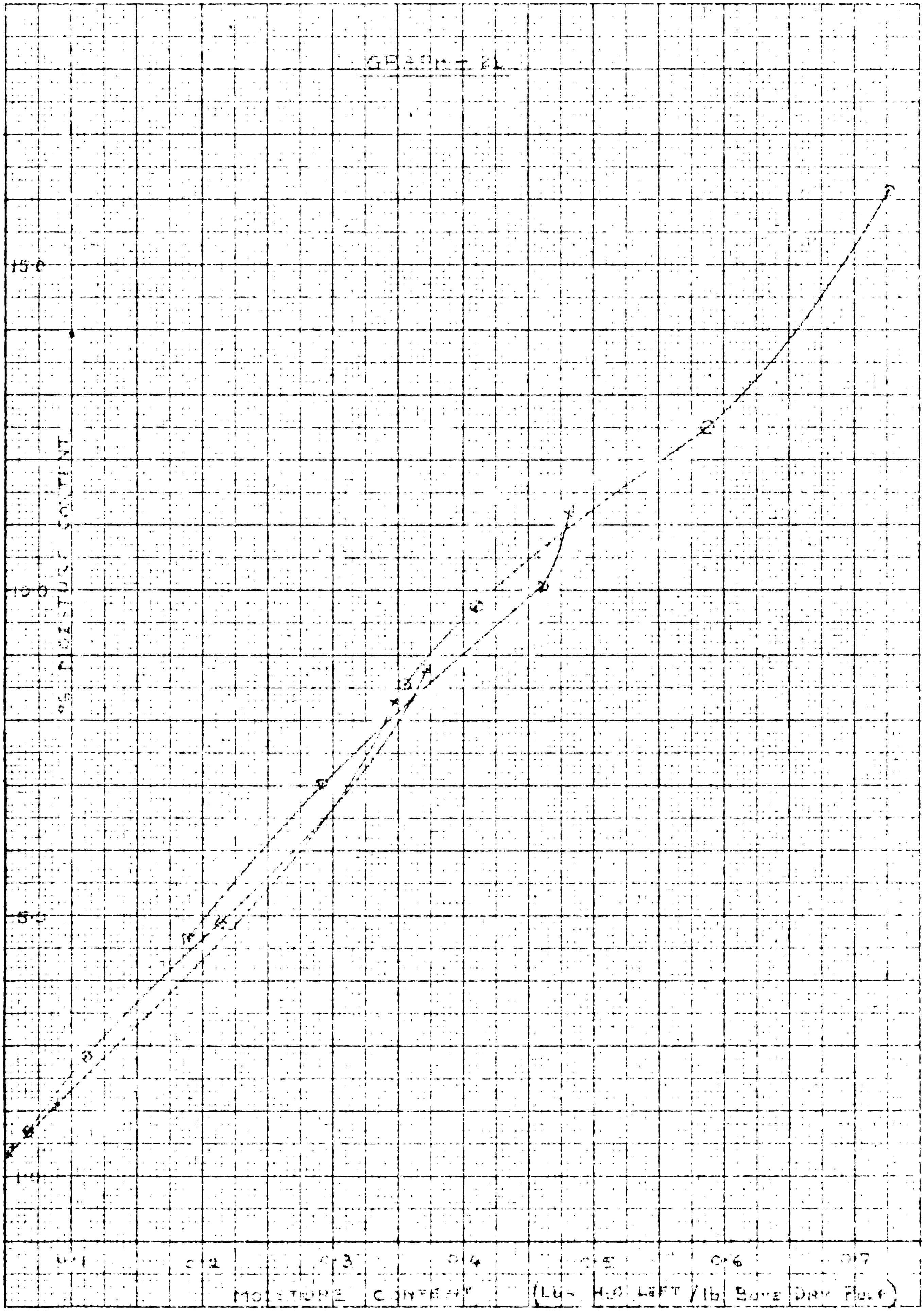

GRAPH 21
15.0
10.0
5.0
1.0
% MOISTURE CONTENT
0.1
0.2
0.3
0.4
0.5
0.6
0.7
MOISTURE CONTENT

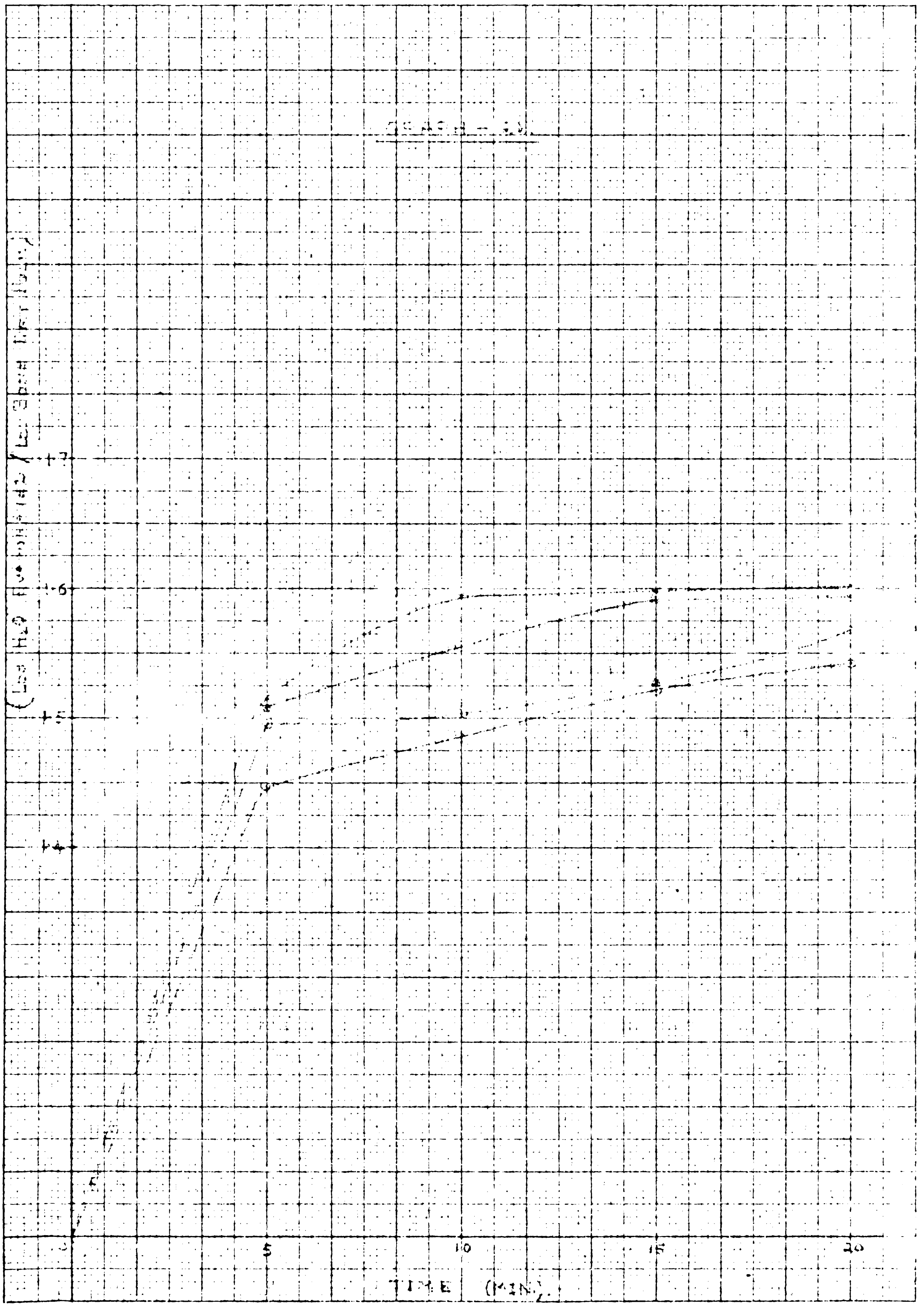
·7
·6
·5
·4
0
5
10
15
20
TIME (MIN).

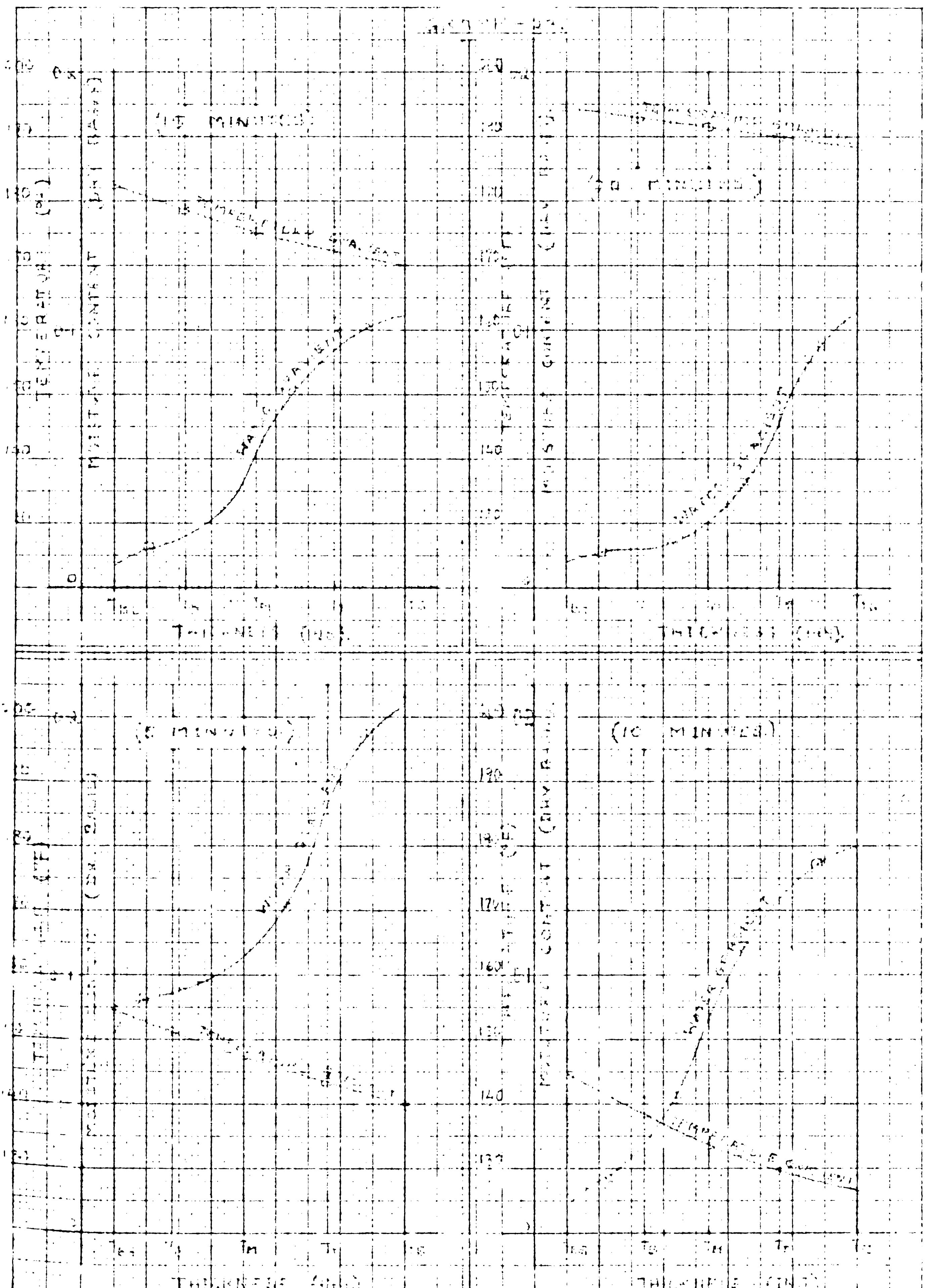


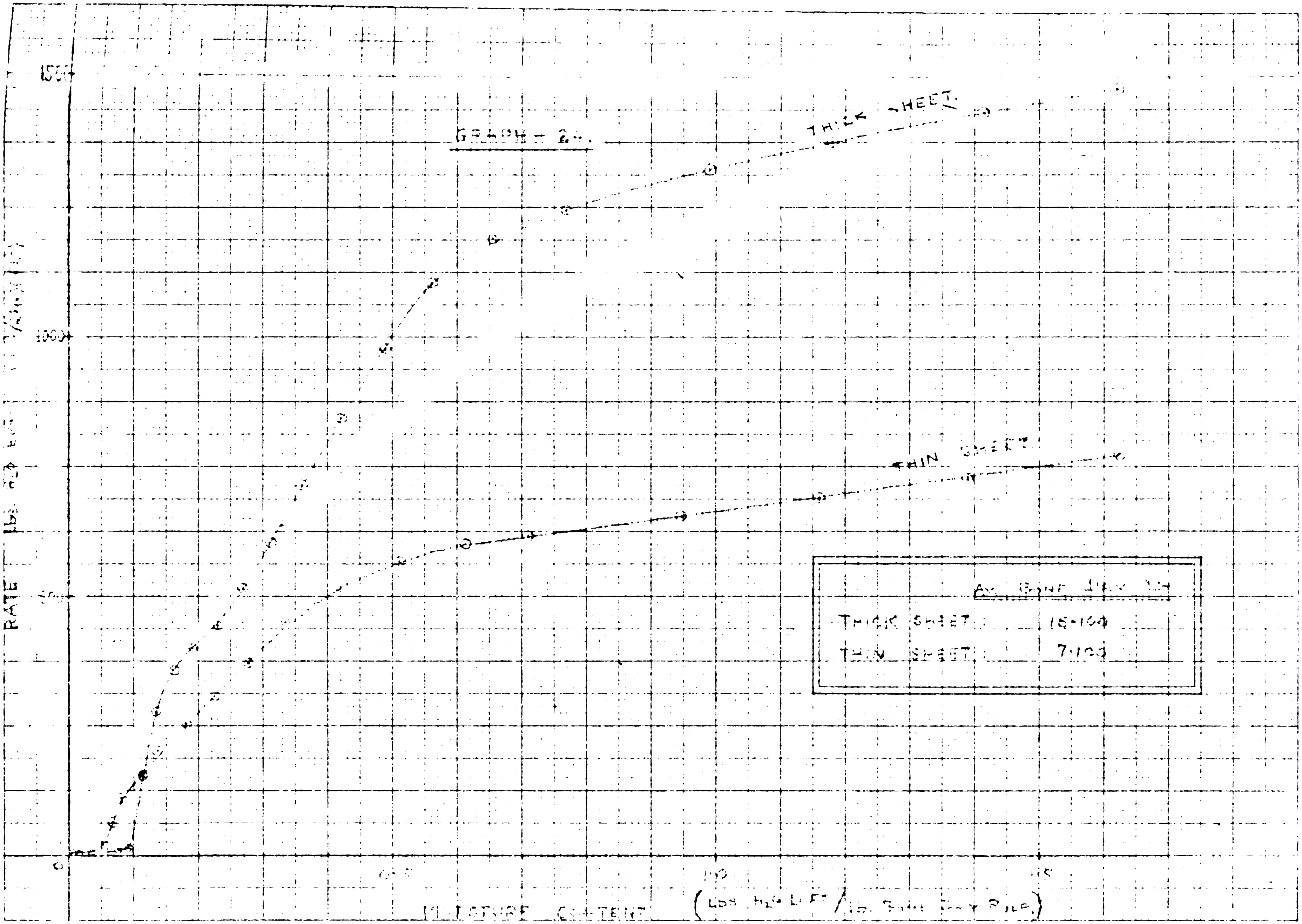


GRAPH - 2
THICK SHEET
THIN SHEET
THICK SHEET : 15.104
THIN SHEET : 7.104
RATE
1500
1000
500
0
1.0
1.5


GRAPH 21
15·0
10·0
5·0
1·0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
MOISTURE CONTENT (Lbs H₂O LEFT / lb BONE DRY PULP)

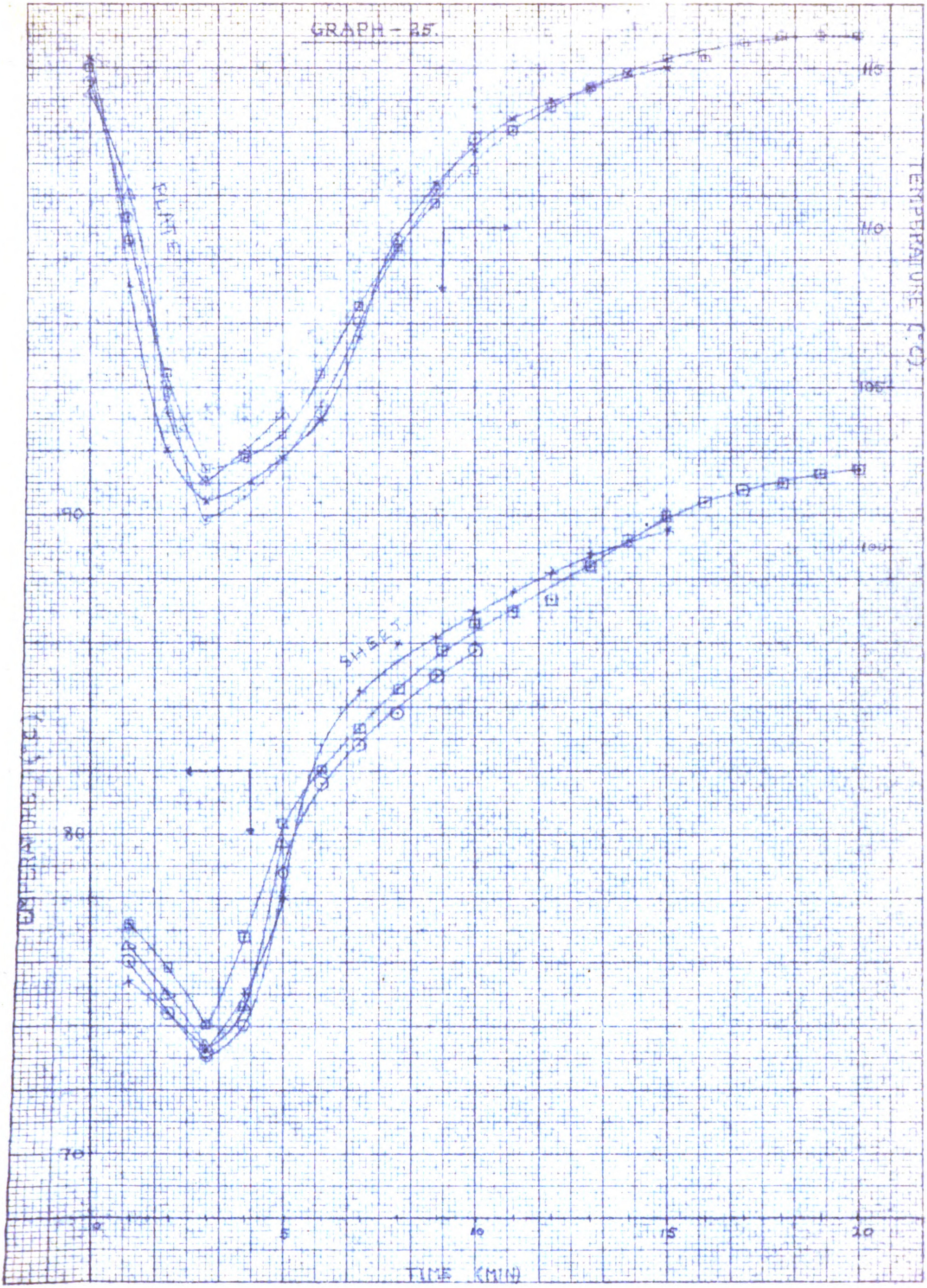

·7
·6
·5
·4
0
5
10
15
20
TIME (MIN)

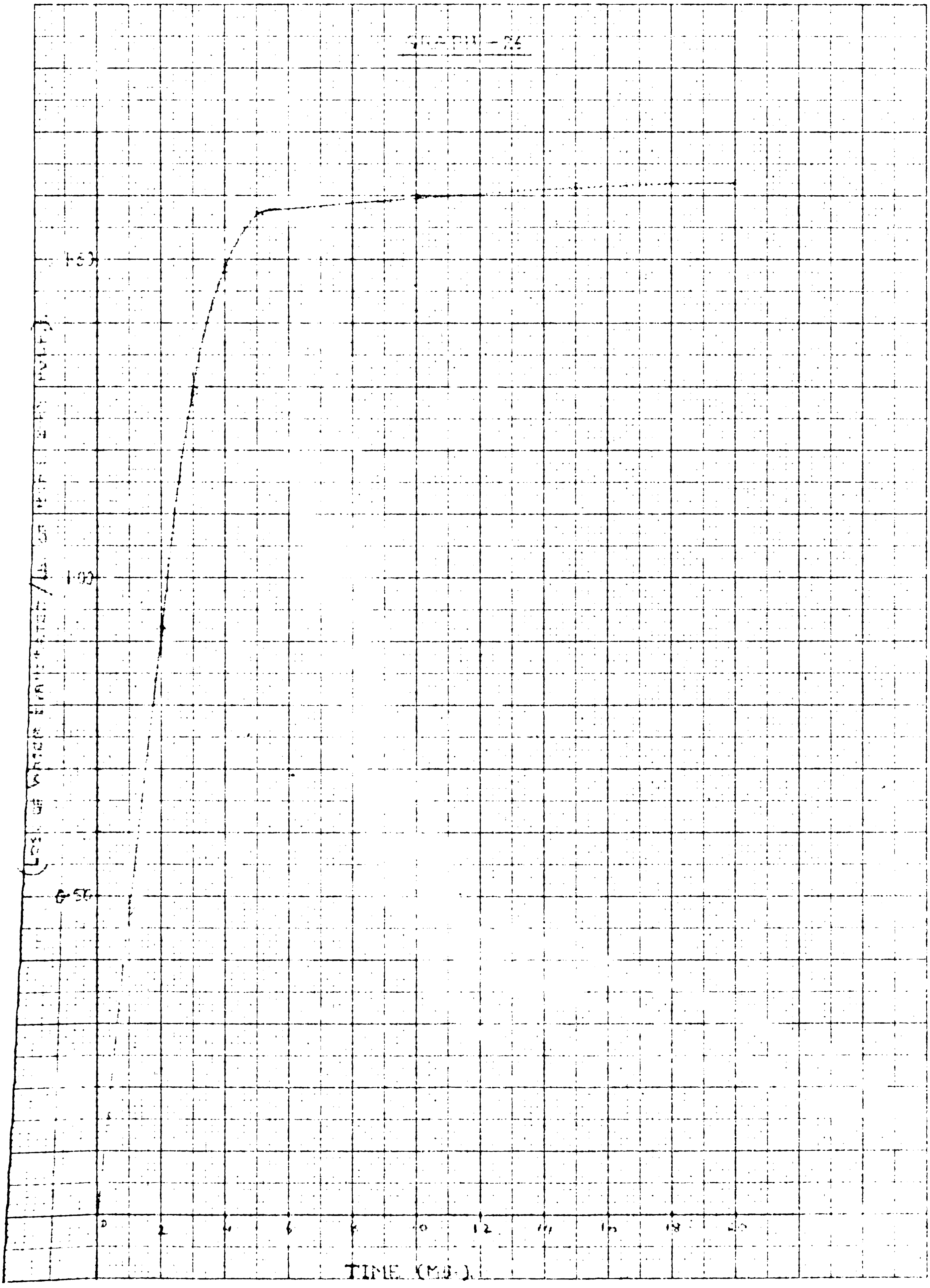

(15 MINUTES)
(30 MINUTES)
(5 MINUTES)
(10 MINUTES)
THICKNESS (INS).
THICKNESS (INS)



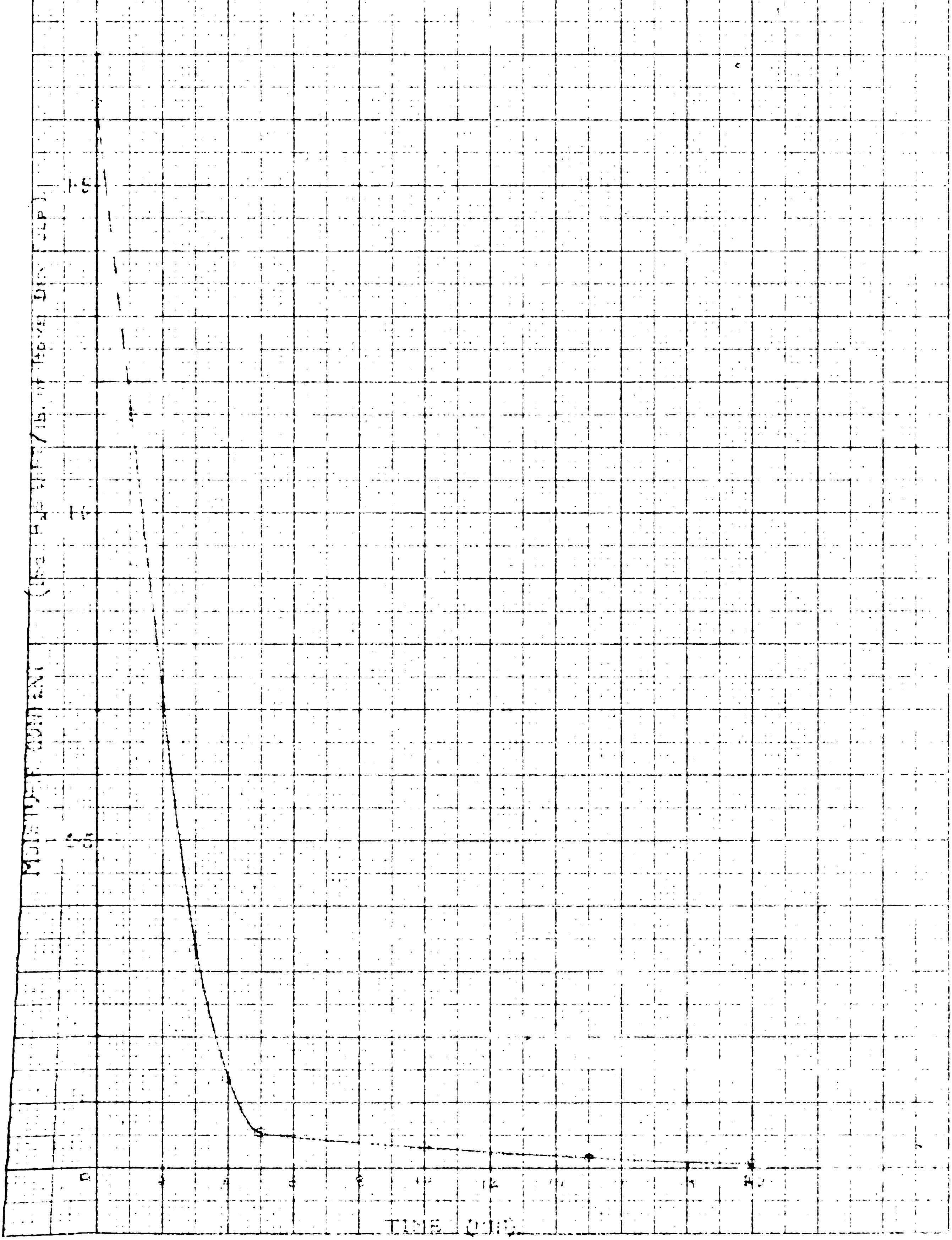
GRAPH
THICK SHEET
THIN SHEET
THICK SHEET 15·104
THIN SHEET 7·103
RATE
MOISTURE CONTENT
1500
1000
0
1.0
1.5

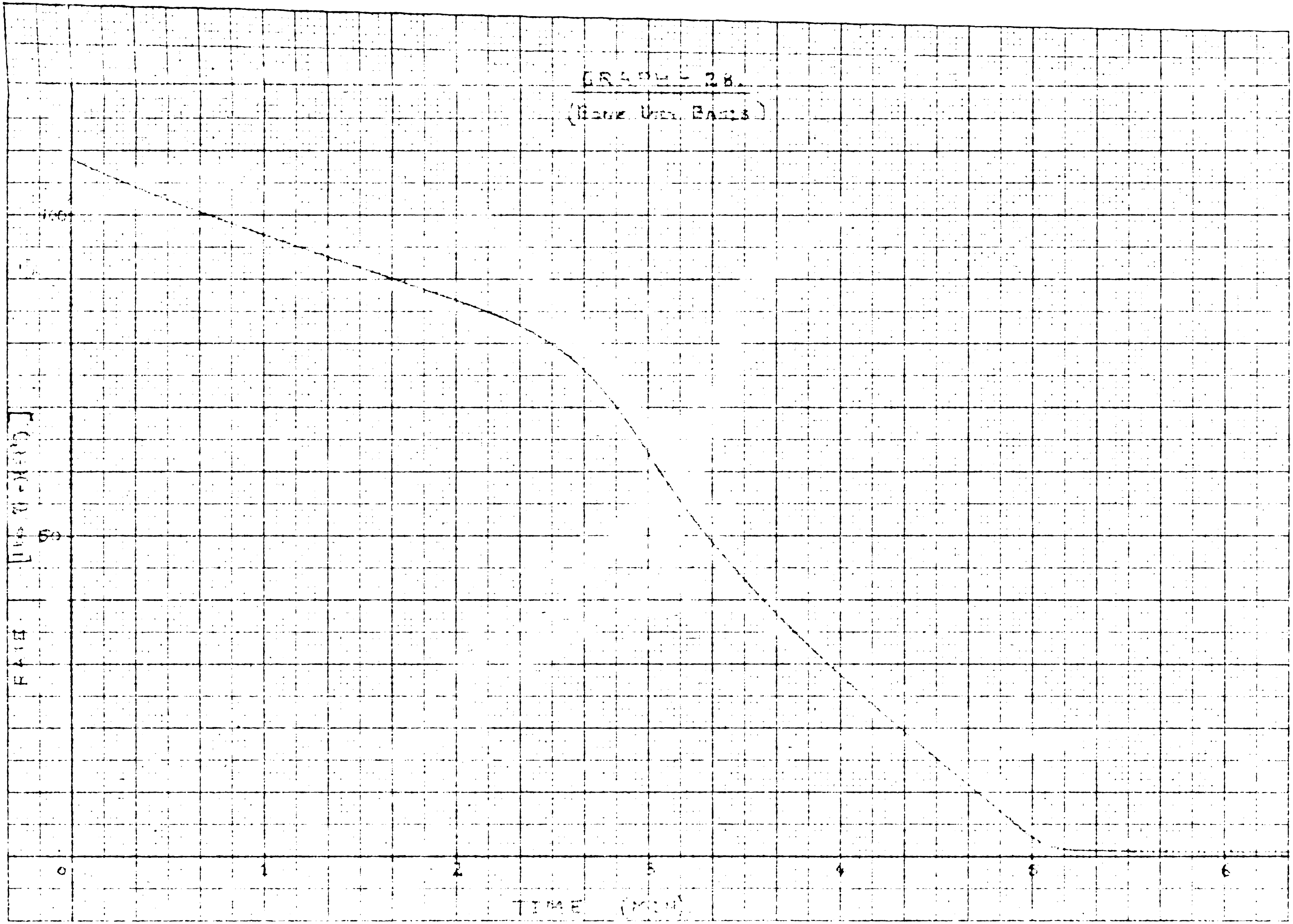
THIN SHEETS

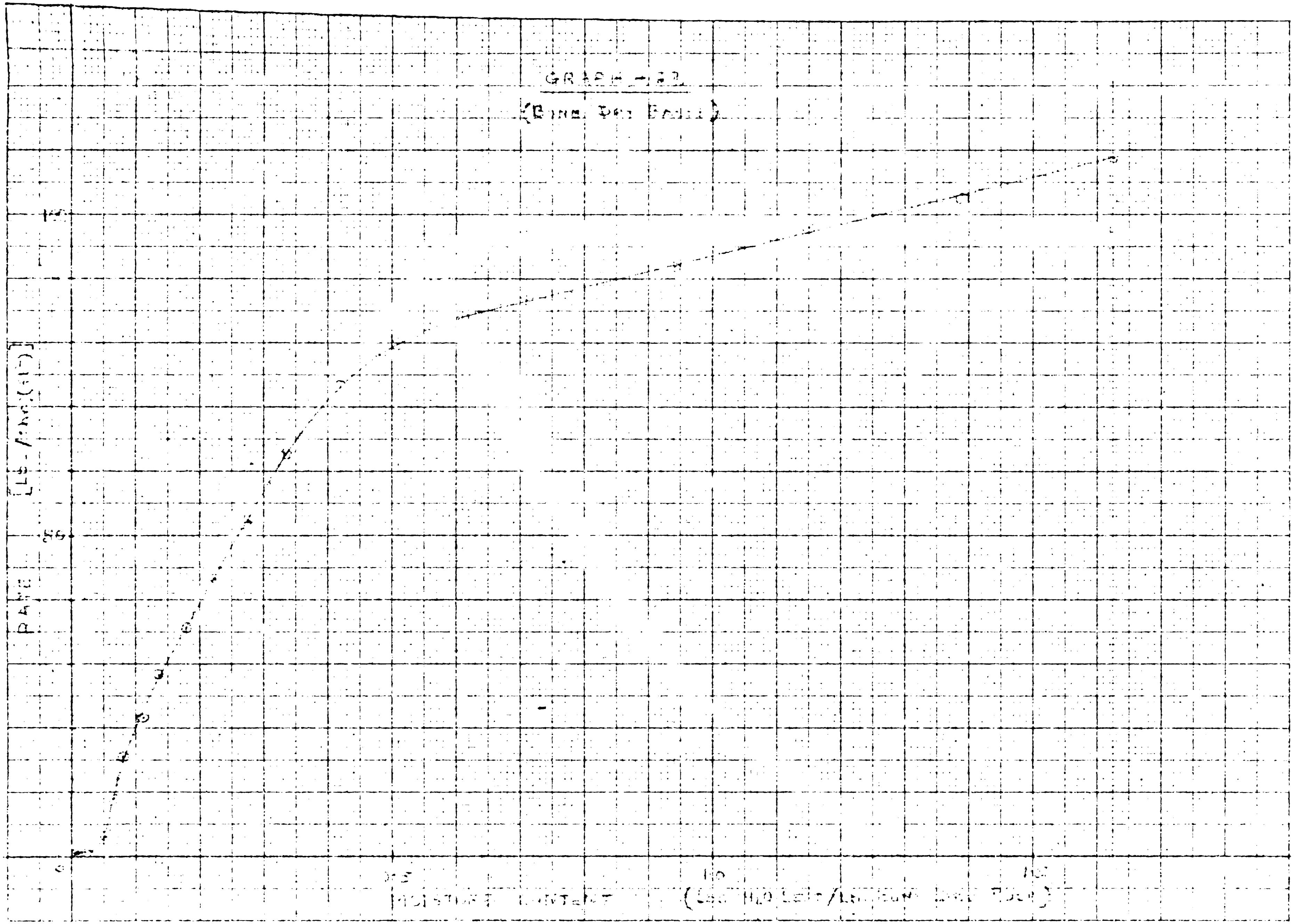

GRAPH - 25.
SLATS
SHEET
TEMPERATURE (°C)
TIME (MIN)
115
110
105
100
90
80
70
0
5
10
15
20



GRAPH - 22




GRAPH 2B
100
50
RATE
0
1
2
3
4
5
6
TIME


MOISTURE CONTENT