3-1966

The Effect of Infrared Drying Rates on the Optical Properties of Starch-Clay Coatings

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THE EFFECT OF INFRARED DRYING RATES ON THE OPTICAL PROPERTIES OF STARCH-CLAY COATINGS

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A THESIS SUBMITTED TO THE DEPARTMENT OF
PAPER TECHNOLOGY AS A PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR A B. S. DEGREE.

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Spring 1966
KALAMAZOO, MICHIGAN

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ABSTRACT

Experiments were conducted to determine the effects of varying rates of infrared drying on a starch-clay coated sheet, in-so-far as optical properties are concerned. Gloss may be increased by drying the coated side of the sheet, while brightness and opacity show decreases. There is an optimum rate of drying for a starch-clay coated sheet. Metal surfaces under a coated sheet being dried with infrared radiation materially effects the optical properties.

Purpose

To investigate the optical properties of clay-starch coated sheets that have been dried at varying rates on an infra-red drying unit. The variables being, the coat weight applied, the amount of adhesive used and the drying rates.

When coating a sheet of paper with a pigment an adhesive must be added to the pigment to hold it unto the base sheet, and to bind the pigment particles together. If starch is the adhesive hydrogen bonds, formed along the chain by carboxyl groups, cause the adhering of the starch, pigment and substrate to take place. For these adhering forces to work, the starch must "wet" the surface of the pigment and the substrate, that is, there must be molecular nearness of the pigment, substrate and adhesive.

A sheet of paper has many hills and valleys between the surface fibers. The coating becomes "keyed" to the sheet by filling these recesses in the paper. For these "keys" to be effective in holding the coating to the sheet there must be a certain amount of inherent mechanical strength in the coating mixture(14). If a portion of the coating that is not keyed to the substrate separates from the sheet, a thin film of coating remains on the sheet. This type of separation is due to low mechanical strength of the coating, and not a weakness in the coating-substrate interface. According to Singleterry(14) this weak zone forms approximately one micron away from the fiber coating interface, and is

weaker than the substrate or the rest of the coating body. The mechanical strength of the coating is a function of the quantity, of adhesive, method of preparing the mixture of adhesive and color, and the pigment used. Pick strength is dependent on substrate strength and the mechanical strength of the adhesive, not the fiber coating interface strength(14).

The surface porosity of a sheet effects the adhesive characteristics of the coating. Only 3-4 percent of the adhesive itself will migrate into a sheet, but as much as 30 percent of the water present. The removal of the adhesive from the coating by a porous sheet is usually due to capillary action. The most significant loss of starch into a sheet by a coating occurs in the first fifteen seconds of contact. After fifteen seconds have passed the capillary forces drawing the adhesive into the sheet are usually: 1) blocked by mechanical action of starch particles, 2) weakened as the capillaries fill, so that evaporation forces tend to become more important(6). Thus a layer of coating, deficient in adhesive forms a short distance from the interface due to the loss of starch into the sheet.

The penetration of adhesive into the substrate decreases with increasing coating solids and an increasing percent of adhesive(6). An increase in the density of the raw stock and an increasing amount of sizing on the base sheet will decrease penetration into the base sheet(3).

Coatings that are applied to a sheet with a decreased pore size will lose more adhesive to the substrate than a larger pore size sheet.(7) This is due to the greater capillary action exerted by the small pores in comparison to the large pores.

If a coating is dried by a blast of hot air on its surface the coating layer obtains more of the adhesive, but is considerably weaker than a slowly dried sheet. This is probably due to the reduction of time for the adhesive to migrate into the sheet and less time for the physical orientation of the adhesive particles in the coating. Orientation of the adhesive particles is the action of drawing the pigment particles close together for the secondary forces to start having an effect. When a sheet is rapidly dried the adhesive tends to evaporate toward the surface of the coating before this takes place.(7)

The principle direction of adhesive migration in a coating is toward the substrate, or toward the surface of the coating. This direction of migration is dependent on the drying rate. The quantity of binder migration is inversely proportional to the total coating solids. A high solids coating has less binder migration than a low solids coating. In a rapid drying application the direction of migration is mainly toward the coating surface and slightly toward the substrate. This migration toward the surface of the coating is directly proportional to the drying rate.(9)

When coating is dried by air the adhesive content throughout the coating layer is in a very uniform state. However as soon as a blast of hot air is blown onto the coating the adhesive migrates toward the surface of the coating layer, thus giving a non-uniform dispersion of the adhesive throughout the coating.(6)

According to Casey and Libby (3) the depth of penetration of the adhesive is decreased by: increasing the sizing of the base sheet, and decreasing the sheet moisture, to a certain extent.

The depth of the adhesive penetration into the sheet is proportional to the ink receptivity of the coating. An increase in penetration will cause a decreased smoothness in the uncalendered sheet and a correspondingly lower reflectivity. Therefore a shorter drying time, giving the adhesive less time to migrate, should yield a smoother sheet.(4).

As the particles size of clay is reduced the unbonded surface area increases as may be seen by considering the amount of surface area available per unit volume.(9) The smaller a clay particle is the greater the brightness due to an increase in reflecting surfaces. Therefore by having more penetration of the starch into the sheet and out of a coating the greater the brightness.(11)

The optical properties of a coated sheet may be predicted using the Kubelka-Munk theory. This theory states that the greater the number of free(unbonded) surfaces the greater the reflectivity and opacity. Hemstock states that a good measure of the amount of penetration of adhesive into raw stock could be accomplished by calculating the theoretical values of opacity, reflectance and scattering powers of a coating and sheet and then comparing with the experimentally determined values.(11)

Clark and Ramsey have outlined a method for predicting the optical properties of a coated sheet.(5) Their method, when coupled with Hemstock's, should be a powerful tool for evaluating the amount of starch penetration, the effect of varying degrees of infrared radiation on the migration, and the effect of infrared on the subsequent optical properties.

Prodedure

Modification of the experimental procedure previously outlined was necessary. The modifications used and the final procedure are as follows.

The base stock used was the Kalamazoo Offset sheet originally proposed for the experiments. It was used throughout the experiment so that the different effects of the base stock would not influence the tests in any way, and if there was some influence it would be constant throughout the experiments. The sheets were conditioned in the humidity room at 72°F and 49% relative humidity and weighed in order to have a method of accurately determining the coat weight applied. All finished sheets were also conditioned in this same room for a period of at least 24 hours before testing.

The starch solutions used were prepared as follows: 300 milliliters of distilled water was agitated with a small electric mixer, to which 100 grams of Stayco M Starch was slowly added. The resulting suspensions were then brought to a temperature of 180°F and kept there for ten minutes with slow agitation. The exact duplication of this procedure should have given very comparable starch solutions for all three runs that were made.

The Spray Satin coating color was prepared in the following way. The clay and water were added to a Hamilton Beech mixer and agitated for 10 minutes at 70% solids. The cup containing the clay suspension was then removed from the mixer and poured into a tared beaker until the desired amount of suspension was in the beaker. The starch solution as prepared above was then added to

the mixture, very slowly with agitation with a wooden stirring rod, until enough had been added to make a 55% solids coating color. Any necessary makeup water was also added at this time.

A check was run on the percent solids of the prepared color and it was found to contain approximately, to the nearest 1%, 56.5% solids. The increase in solids is due to evaporation of the water from the starch and clay suspensions during mixing and preparation.

The base for a Martinson laboratory coater was used to transport the coating with minimum clay to a position under the heat source. This consisted of only the track for the coater and the steel tray which rides upon the track. All drawdowns were made on the tray using numbers 3, 14, 24 Meyer rods. The drawdowns could then be immediately slipped under the Doyle Infrared Dryer used for drying the sheets.

The drying apparatus was mounted on a movable steel pipe so that it could be both raised and lowered at will. The dryer was constantly turned to the "high" position and allowed to warm up for fifteen minutes before operation. This was done so that the heat source would be emitting a constant wavelength of radiation throughout the experiment and to give the surroundings a chance to come to equilibrium with the heat being delivered by the dryer. The drying rates were varied by changing the distance of the source of radiation from the sheet. This was done by marking the pipe at twelve inch intervals and numbering the intervals, 1, 2, 3, with number 1 interval being only twelve inches from the sheet. All sheets were dried only until the surface of the coating "appeared" dry. It was assumed that by the time the sheet appeared dry there could be little, if any, transport of material in the coating sub-

strate. Indeed, any drying in excess of this at the number one setting caused severe scorching of the sheet on the side of the sheet laying on the steel tray.

The sheets were tested, after conditioning, on the G.E. brightness meter, the Bausch and Lomb Glossimeter, and the Bausch and Lomb Opacimeter. The sheets were also tested for Dennison wax pick just as a rough comparison of the relative strengths.

Graphs have been prepared of drying rates versus the optical properties of the coatings and also versus the wax pick. Graphs have also been drawn of coat weight applied versus the optical properties of the coatings.

The data acquired has been averaged, and is presented in the following tables.

(Table 1) COAT WEIGHT (#'s/3300 ft^2) VERSUS MEYER RODS

MEYER RODS	DRYING RATE	6% STARCH	12% STARCH	16% STARCH
	0	7.105	8.81	9.64
3	1	7.670	7.51	8.75
	2	7.28	10.18	10.82
	3	6.58	9.93	10.65
	0	14.28	14.67	18.21
14	1	16.07	18.35	18.14
	2	16.94	19.84	19.51
	3	18.41	14.44	17.24
	0	29.64	29.08	29.60
24	1	26.58	32.51	28.26
	2	30.01	26.79	29.60
	3	29.79	28.66	30.45

(Table 2)

G.E. BRIGHTNESS VERSUS MEYER RODS

MEYER RODS	DRYING RATE	6% STARCH	12% STARCH	16% STARCH
3	0	79.9	78.0	78.0
	1	80.2	78.8	79.1
	2	79.9	79.6	78.3
	3	80.6	78.3	78.4
14	0	80.8	76.3	78.0
	1	81.6	80.8	79.0
	2	80.9	80.0	78.7
	3	81.0	78.0	78.3
24	0	80.9	76.4	78.0
	1	81.6	81.3	79.2
	2	81.2	81.3	79.2
	3	80.9	78.2	78.6

(Table 3)

BAUSCH AND LOMB OPACITY VERSUS MEYER RODS

MEYER RODS	DRYING RATE	6% STARCH	12% STARCH	16% STARCH
3	0	90.7	89.8	90.0
	1	90.6	91.9	91.2
	2	90.2	91.4	91.5
	3	90.8	90.5	90.0
14	0	96.0	92.2	93.9
	1	94.7	96.1	94.5
	2	94.7	95.6	94.1
	3	94.9	90.9	94.4
24	0	97.0	92.6	95.9
	1	96.4	96.9	95.9
	2	96.5	97.1	96.4
	3	96.2	94.4	95.5

(Table 4)

BAUSCH AND LOMB GLOSS VERSUS MEYER RODS

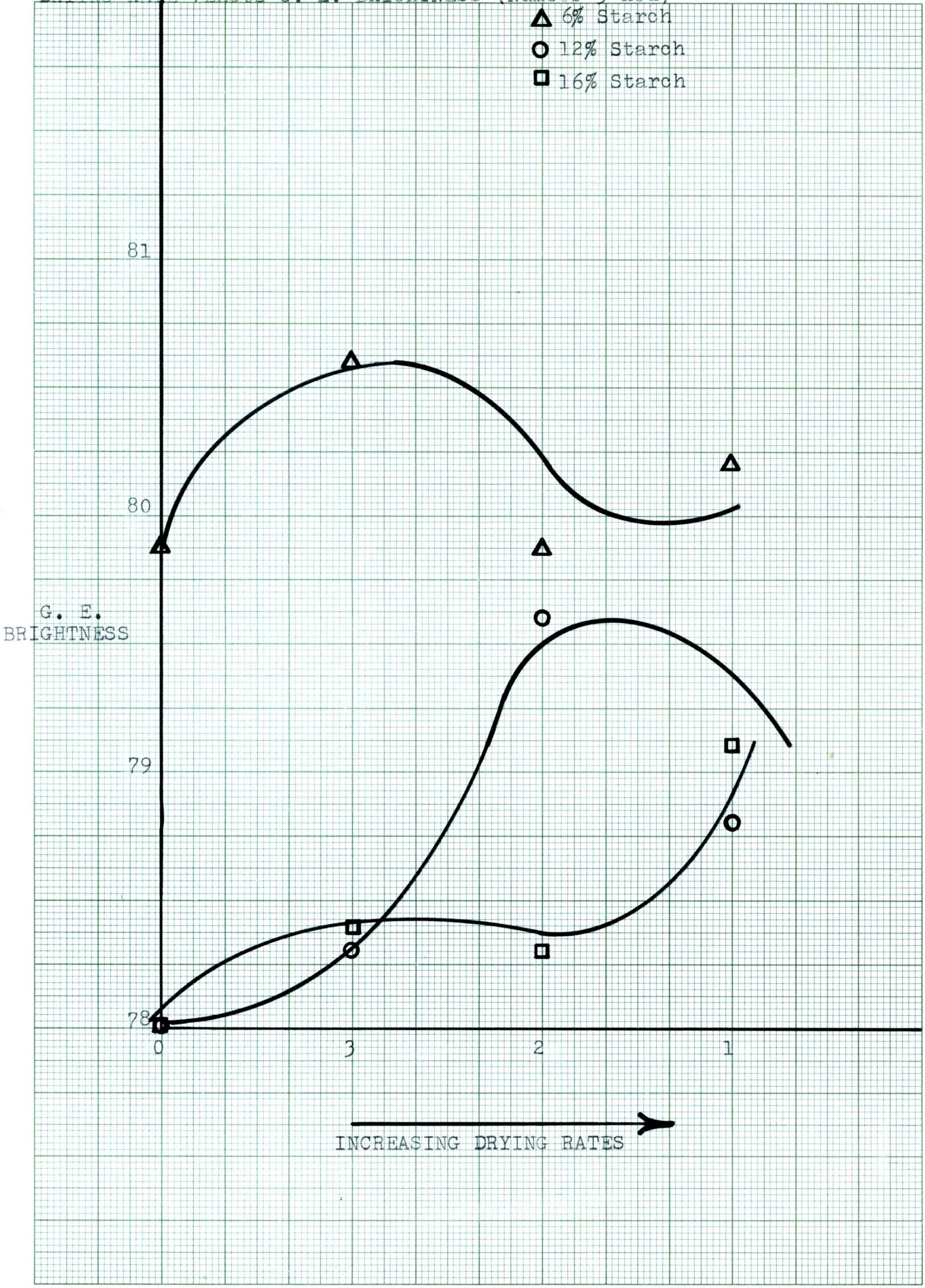
MEYER RODS	DRYING RATE	6% STARCH	12% STARCH	16% STARCH
3	0	48.7	25.0	33.9
	1	52.4	43.7	29.2
	2	49.7	44.1	33.6
	3	52.7	27.3	34.1
14	0	52.1	30.8	35.1
	1	59.7	48.8	29.7
	2	58.1	48.1	34.2
	3	52.1	30.3	34.4
24	0	54.4	29.6	34.9
	1	62.2	49.6	32.5
	2	62.1	48.0	34.9
	3	52.4	35.5	36.3

(Table 5)

DENNISON WAX PICKS VERSUS MEYER RODS

MEYER RODS	DRYING RATE	6% STARCH	12% STARCH	16% STARCH
3	0	1	8	6
	1	5	4	7
	2	5	4	6
	3	3	9	6
14	0	1	9	7
	1	1	6	7
	2	1	5	7
	3	1	9	7
24	0	1	9	6
	1	1	5	7
	2	1	6	7
	3	1	8	7.5

DRYING RATE VERSUS G. E. BRIGHTNESS (Number 3 Rod)



DRYING RATE VERSUS BRIGHTNESS (Number 14 Rod)

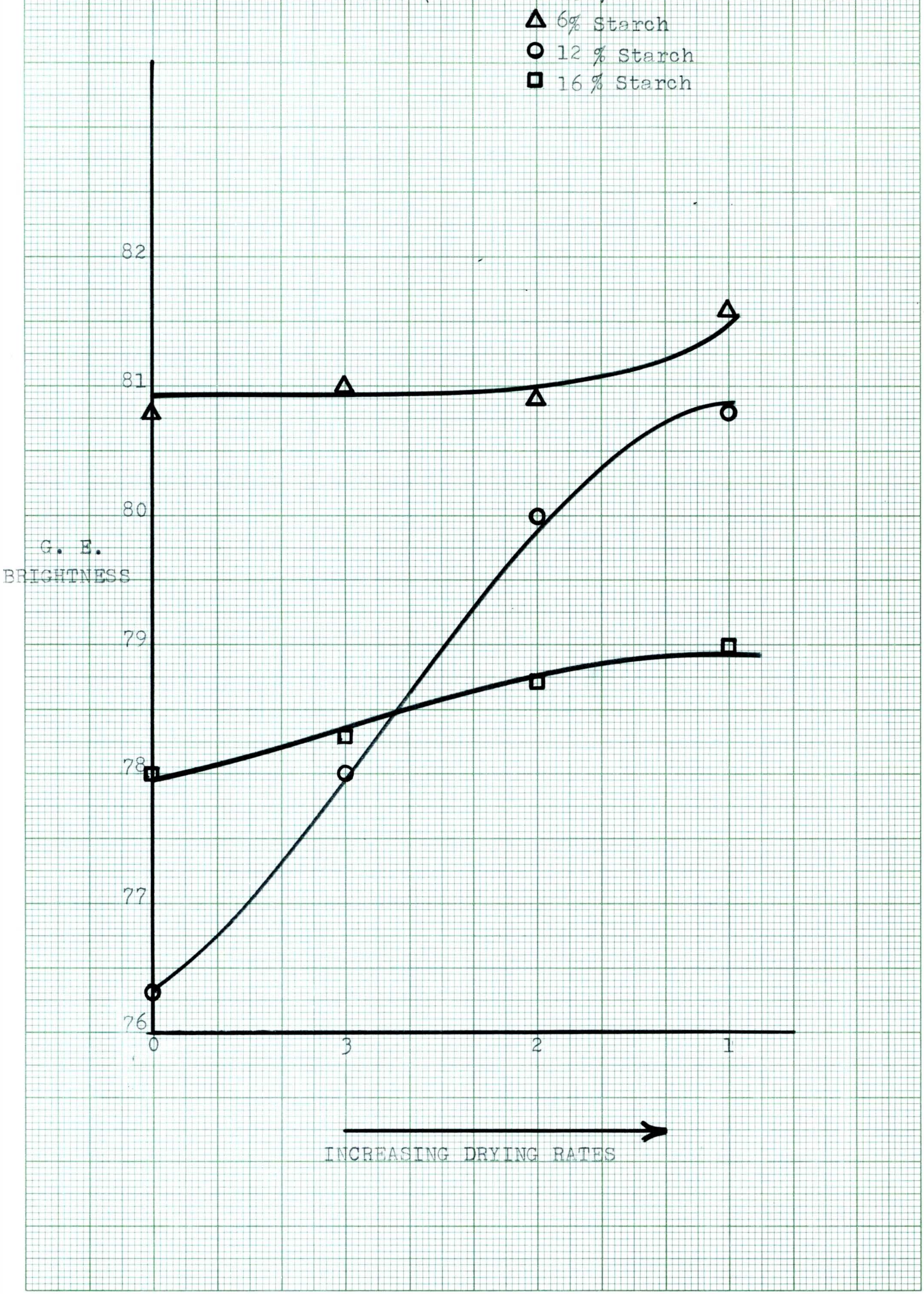


Figure (3)

DRYING RATE VERSUS G.E. BRIGHTNESS (Number 24 Rod)

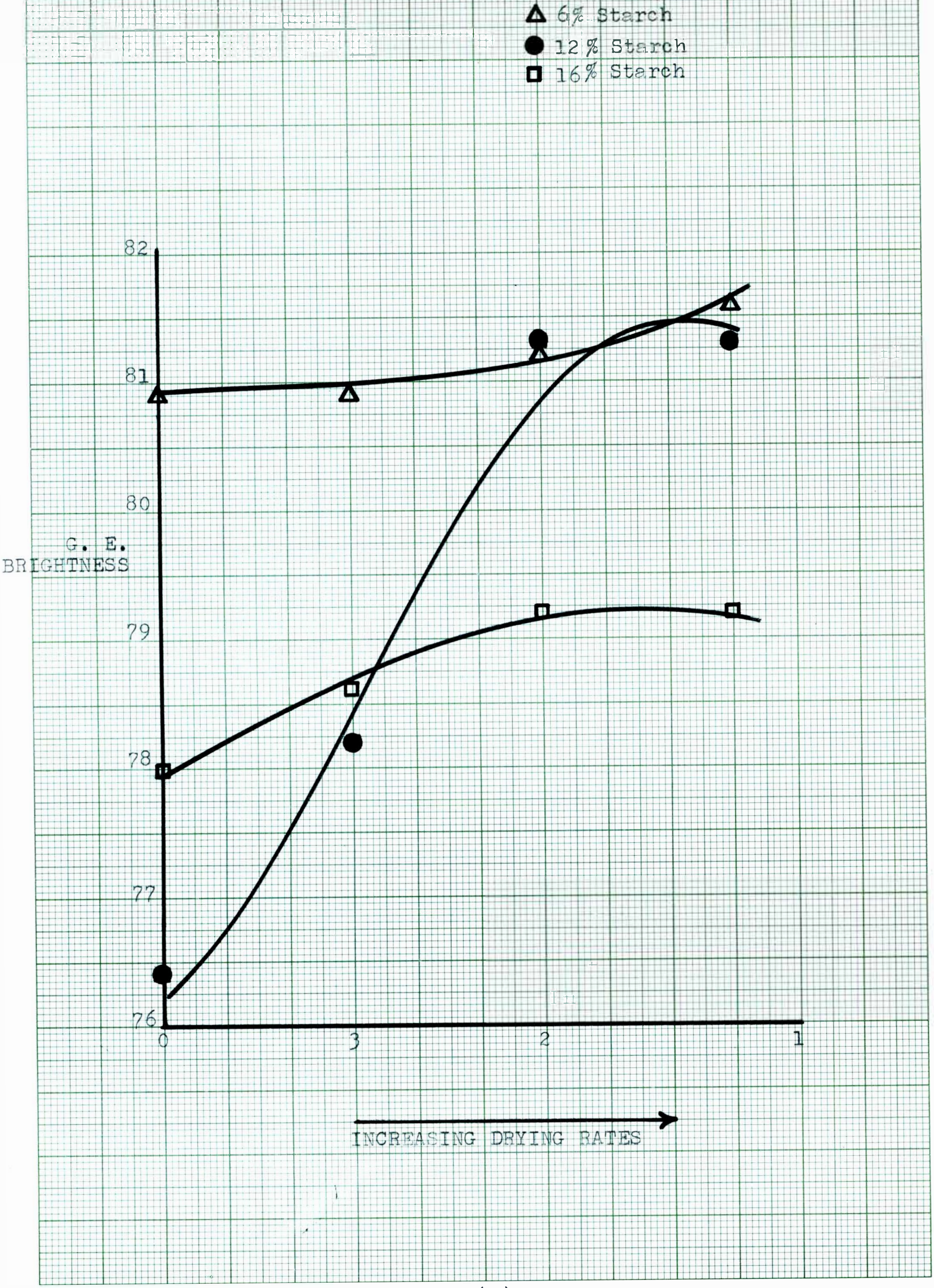
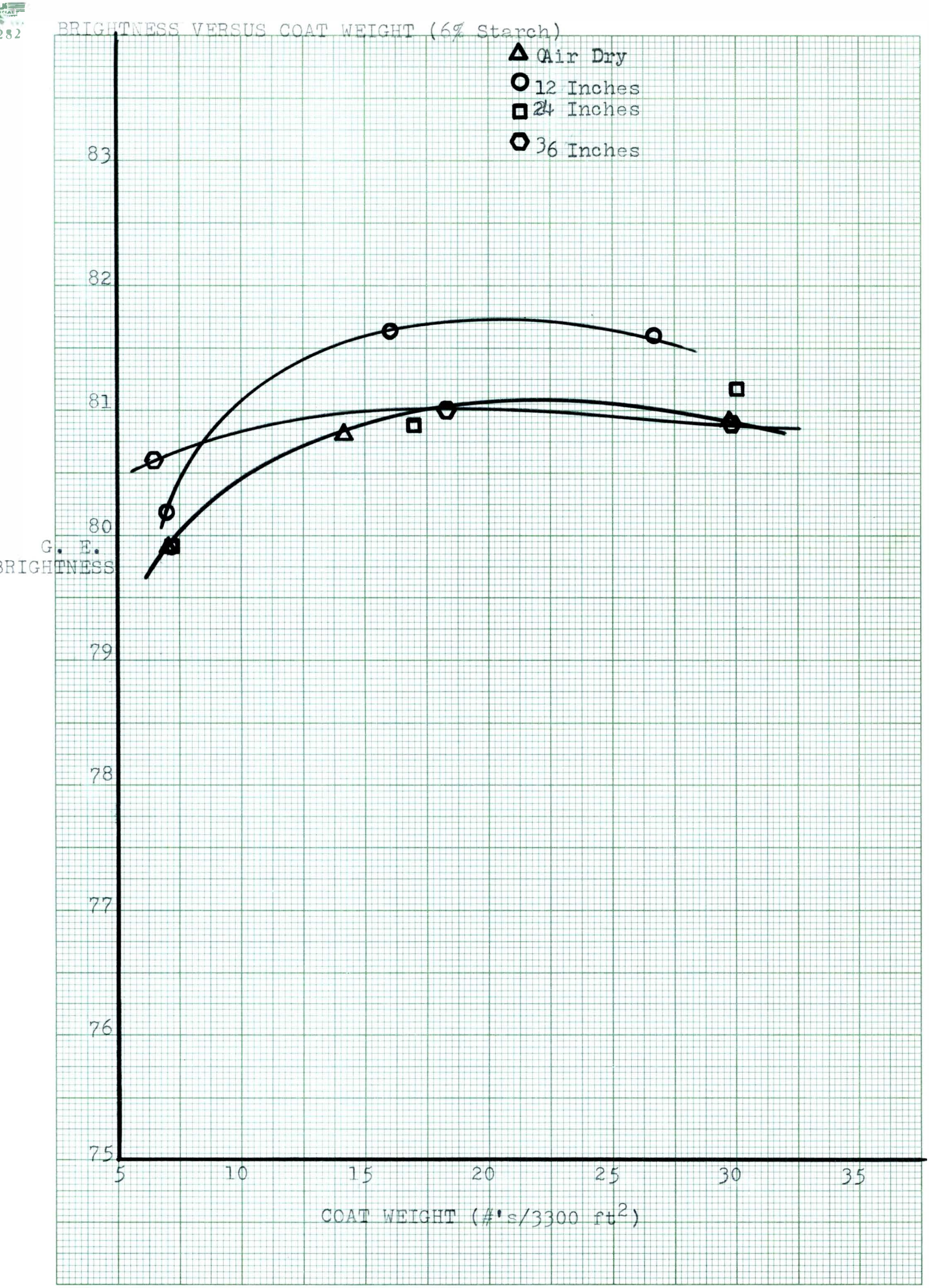


Figure (3)



BRIGHTNESS VERSUS COAT WEIGHT (6% Starch)
Air Dry
12 Inches
24 Inches
36 Inches
83
82
81
80
79
78
77
76
75
G. E.
BRIGHTNESS
5
10
15
20
25
30
35
COAT WEIGHT (#'s/3300 ft²)

Figure (4)

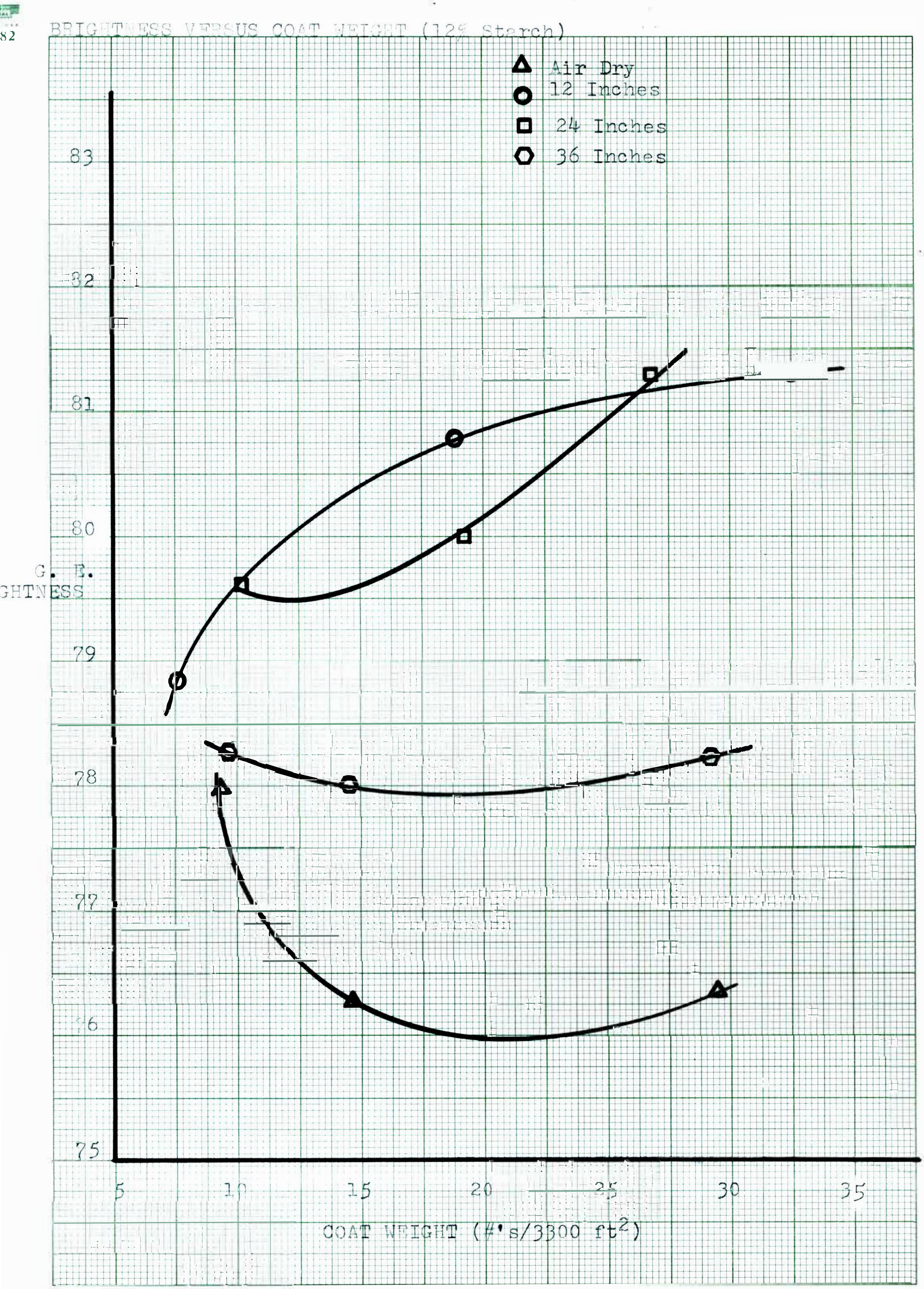
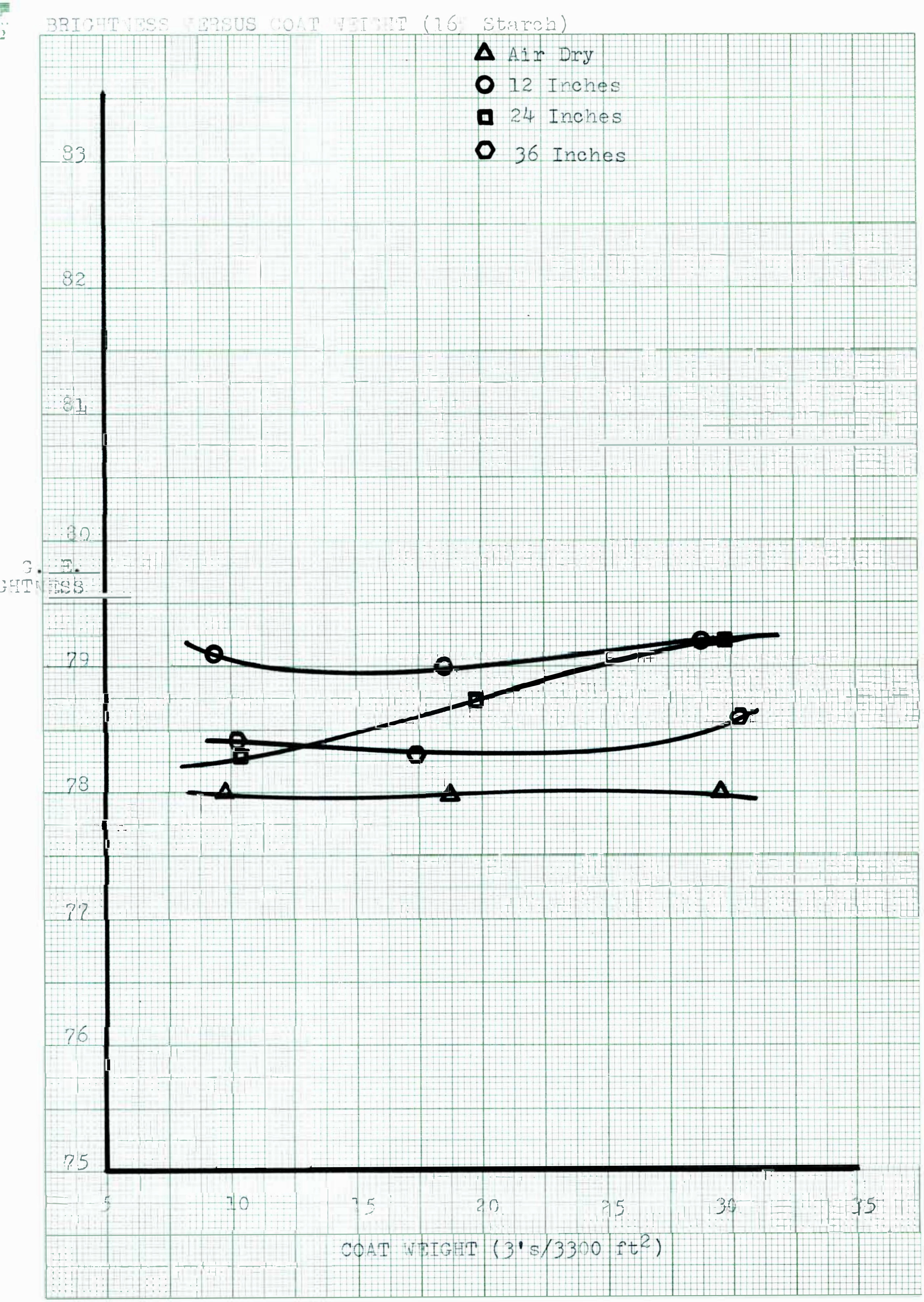

BRIGHTNESS VERSUS COAT WEIGHT (12% Starch)
Air Dry
12 Inches
24 Inches
36 Inches
83
82
81
80
79
78
77
76
75
G. E.
BRIGHTNESS
5
10
15
20
25
30
35
COAT WEIGHT (#'s/3300 ft²)

Figure (5)



BRIGHTNESS VERSUS COAT WEIGHT (16% Starch)
Air Dry
12 Inches
24 Inches
36 Inches
83
82
81
80
G. E.
BRIGHTNESS
79
78
77
76
75
5
10
15
20
25
30
35
COAT WEIGHT (3's/3300 ft2)

Figure (6)

DRYING RATE VERSUS OPACITY (Number 3 Rod)

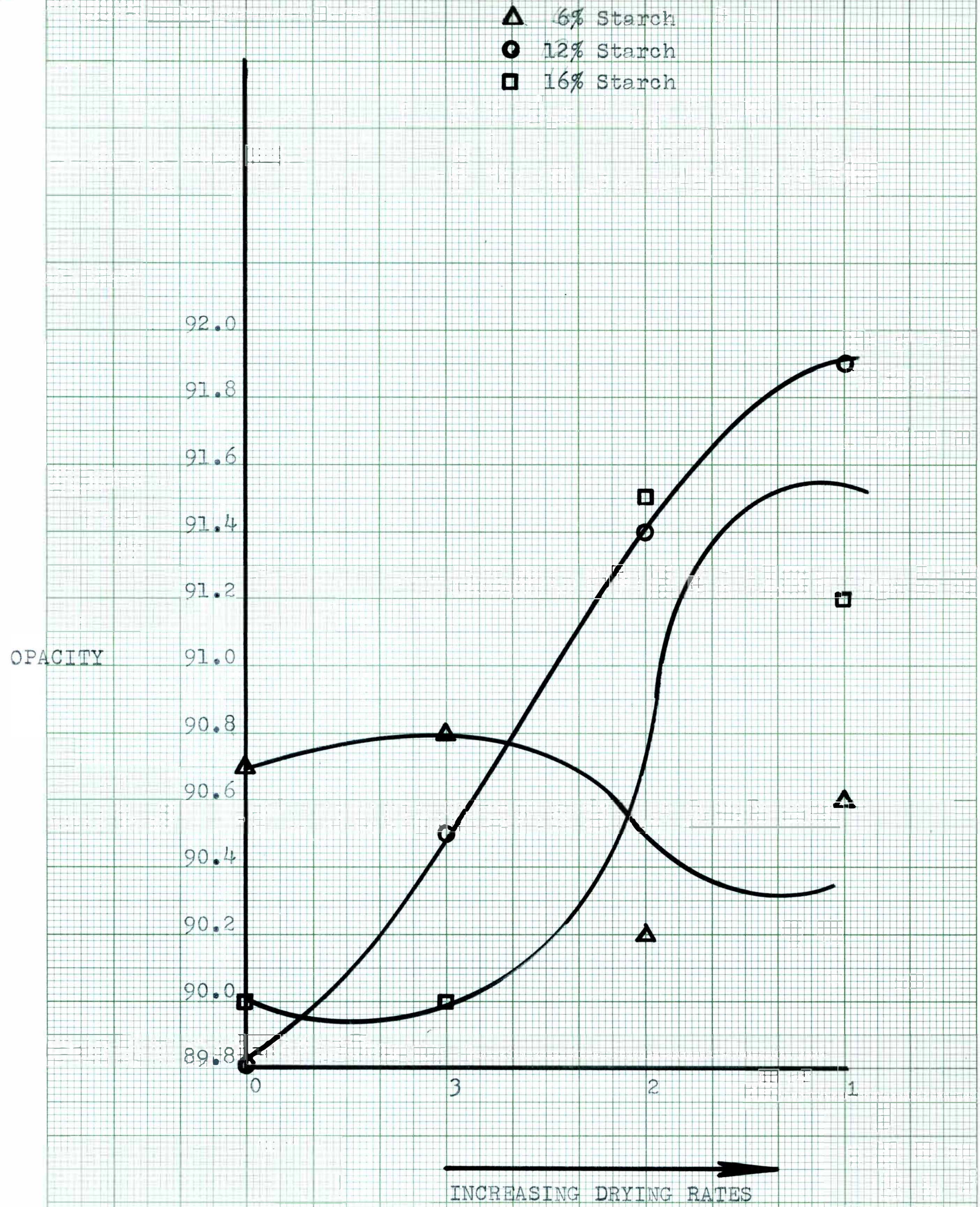


Figure (7)

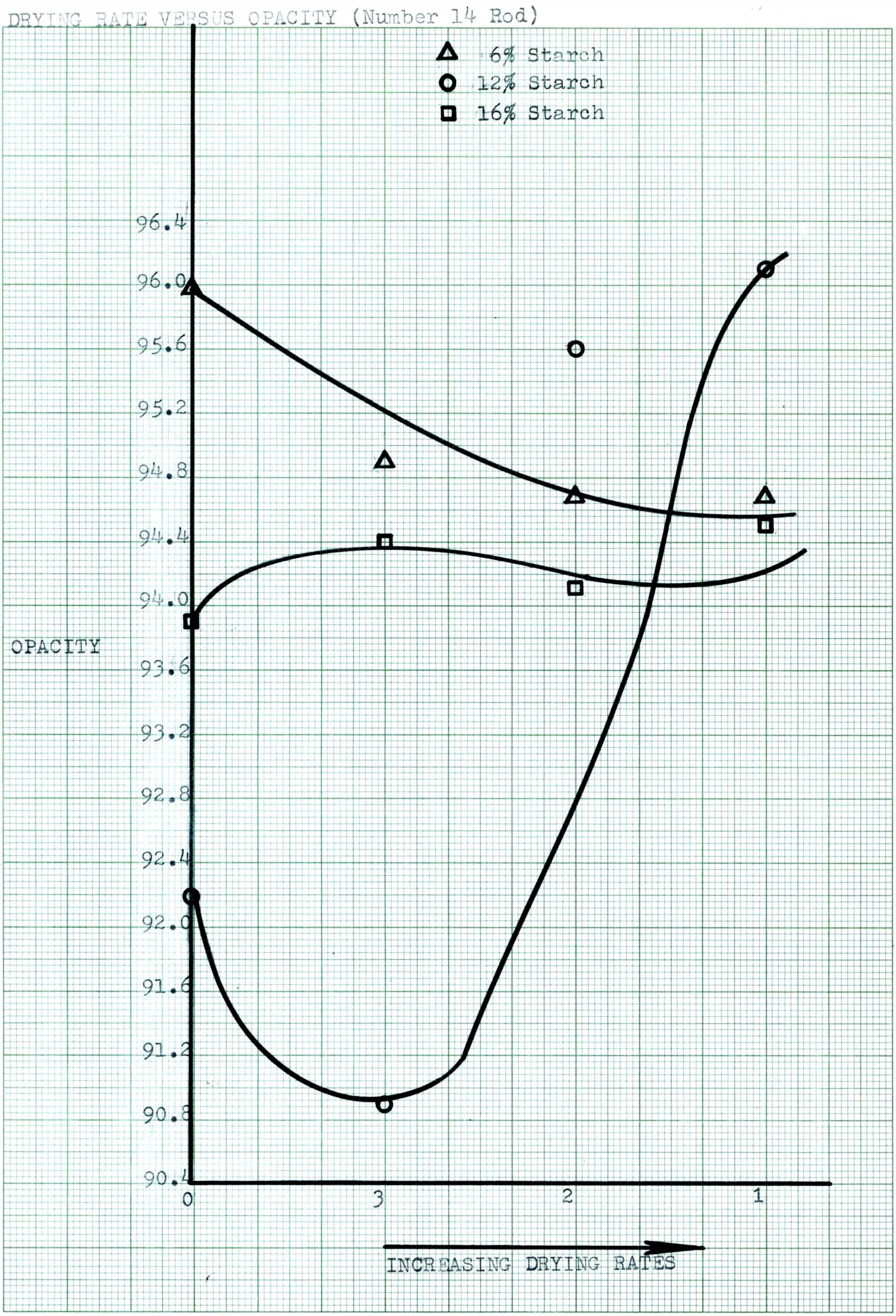

DRYING RATE VERSUS OPACITY (Number 14 Rod)
6% Starch
12% Starch
16% Starch
OPACITY
96.4
96.0
95.6
95.2
94.8
94.4
94.0
93.6
93.2
92.8
92.4
92.0
91.6
91.2
90.8
90.4
0
3
2
1
INCREASING DRYING RATES

Figure (8)

DRYING RATE VERSUS OPACITY (Number 24 Rod)

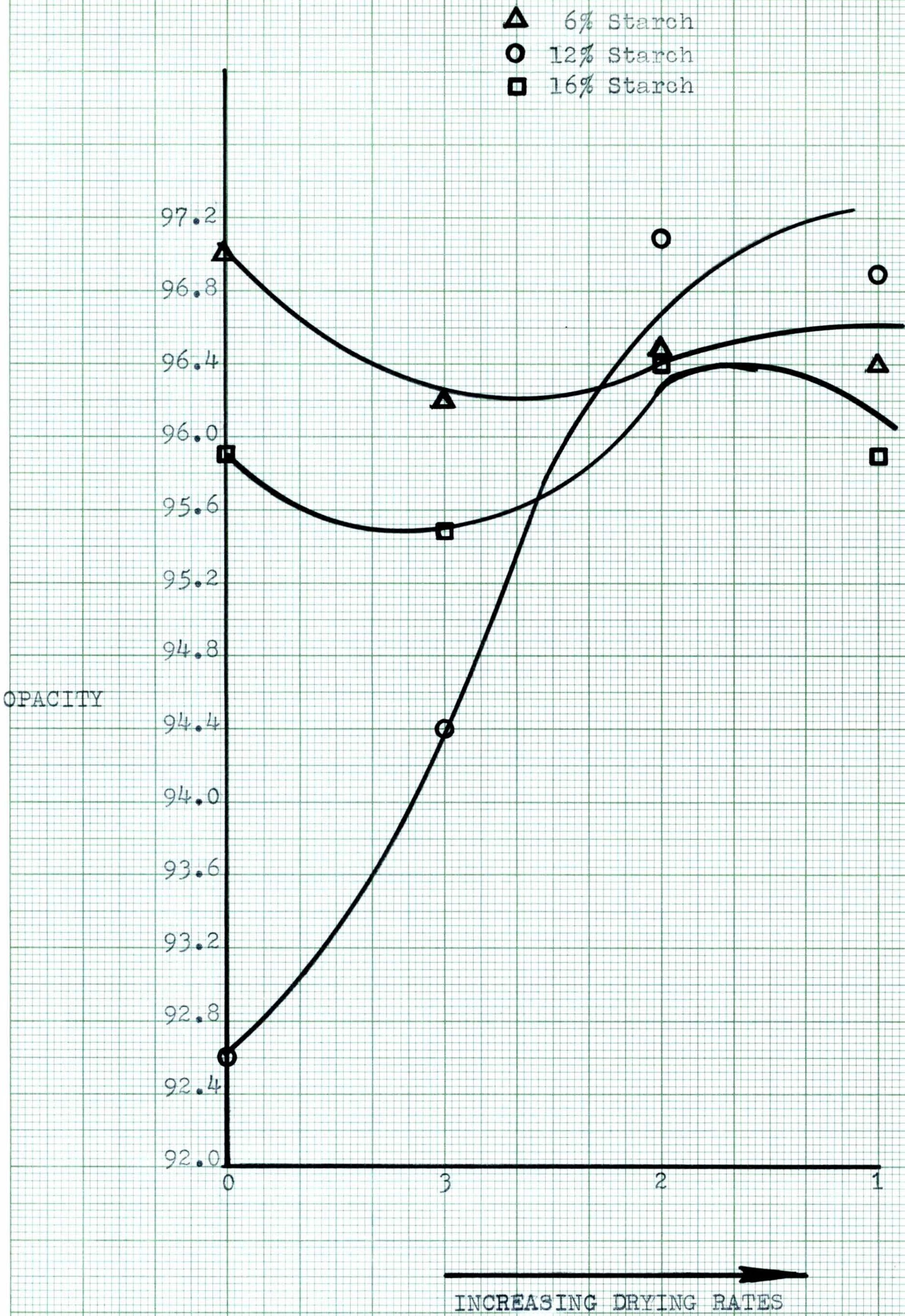


Figure (9)

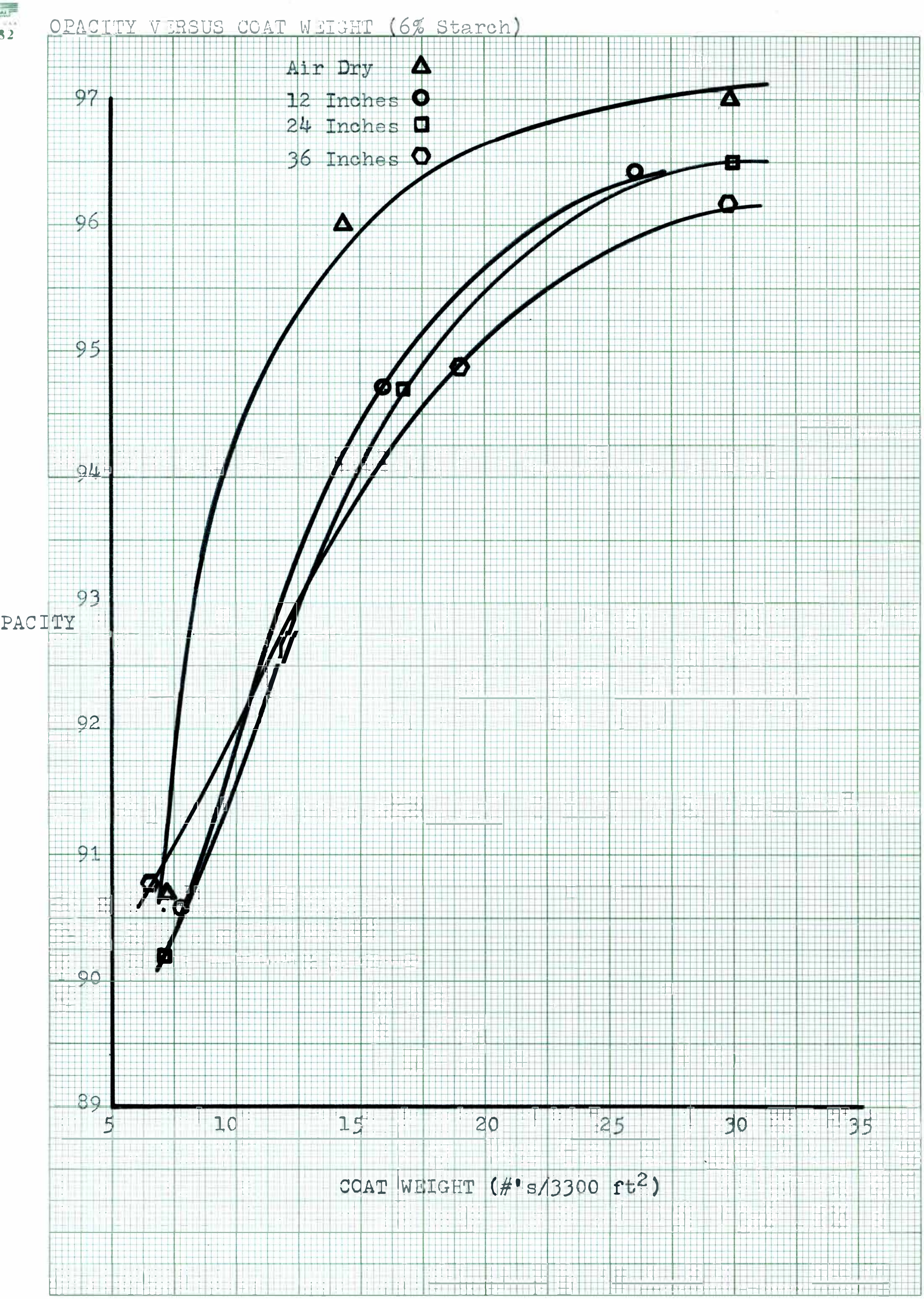

OPACITY VERSUS COAT WEIGHT (6% Starch)
Air Dry
12 Inches
24 Inches
36 Inches
97
96
95
94
93
92
91
90
89
PACITY
5
10
15
20
25
30
35
COAT WEIGHT (#'s/3300 ft2)

Figure (10)

OPACITY VERSUS COAT WEIGHT (12% Starch)

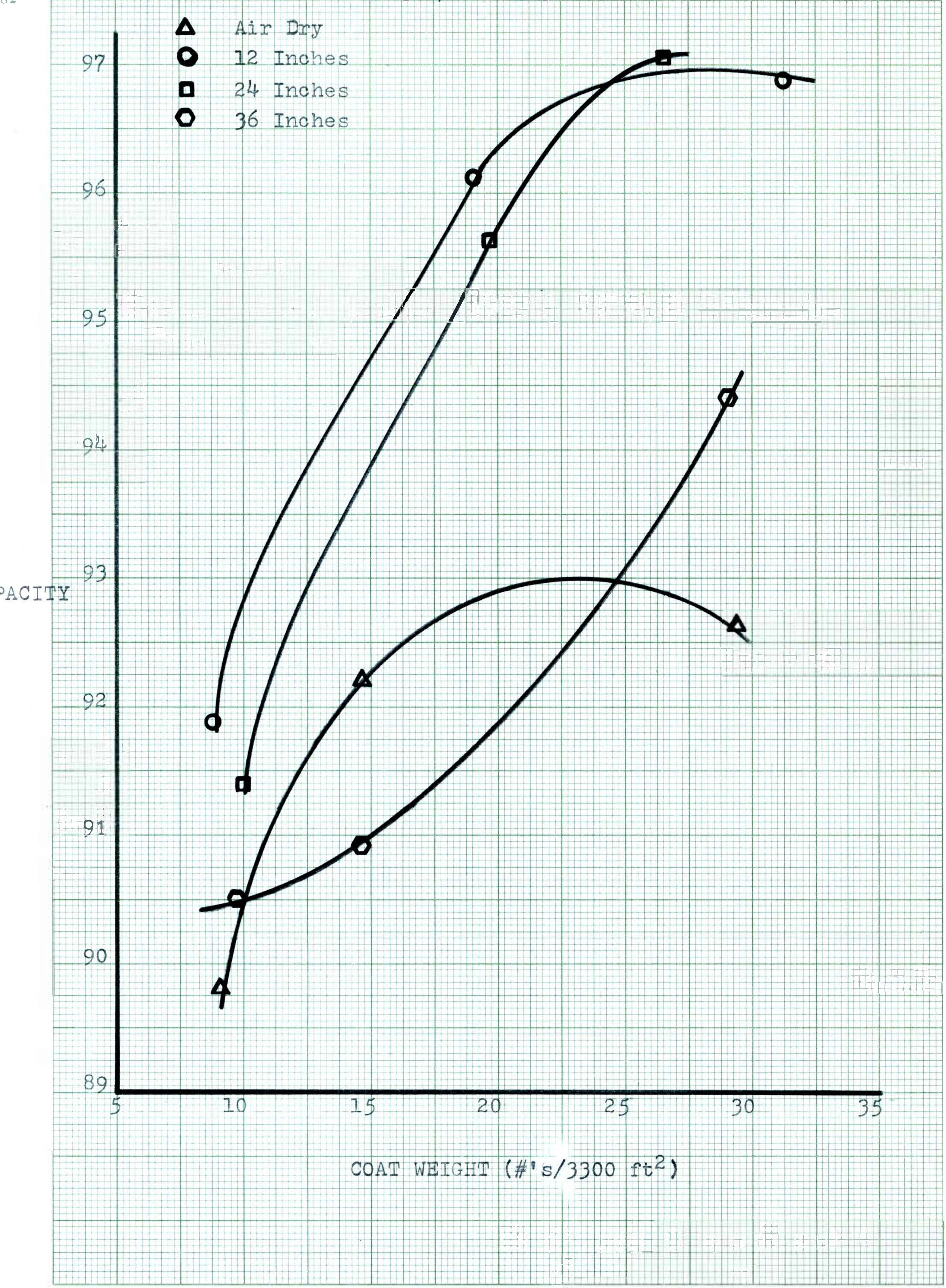


Figure (11)

OPACITY VERSUS COAT WEIGHT (16% Starch)

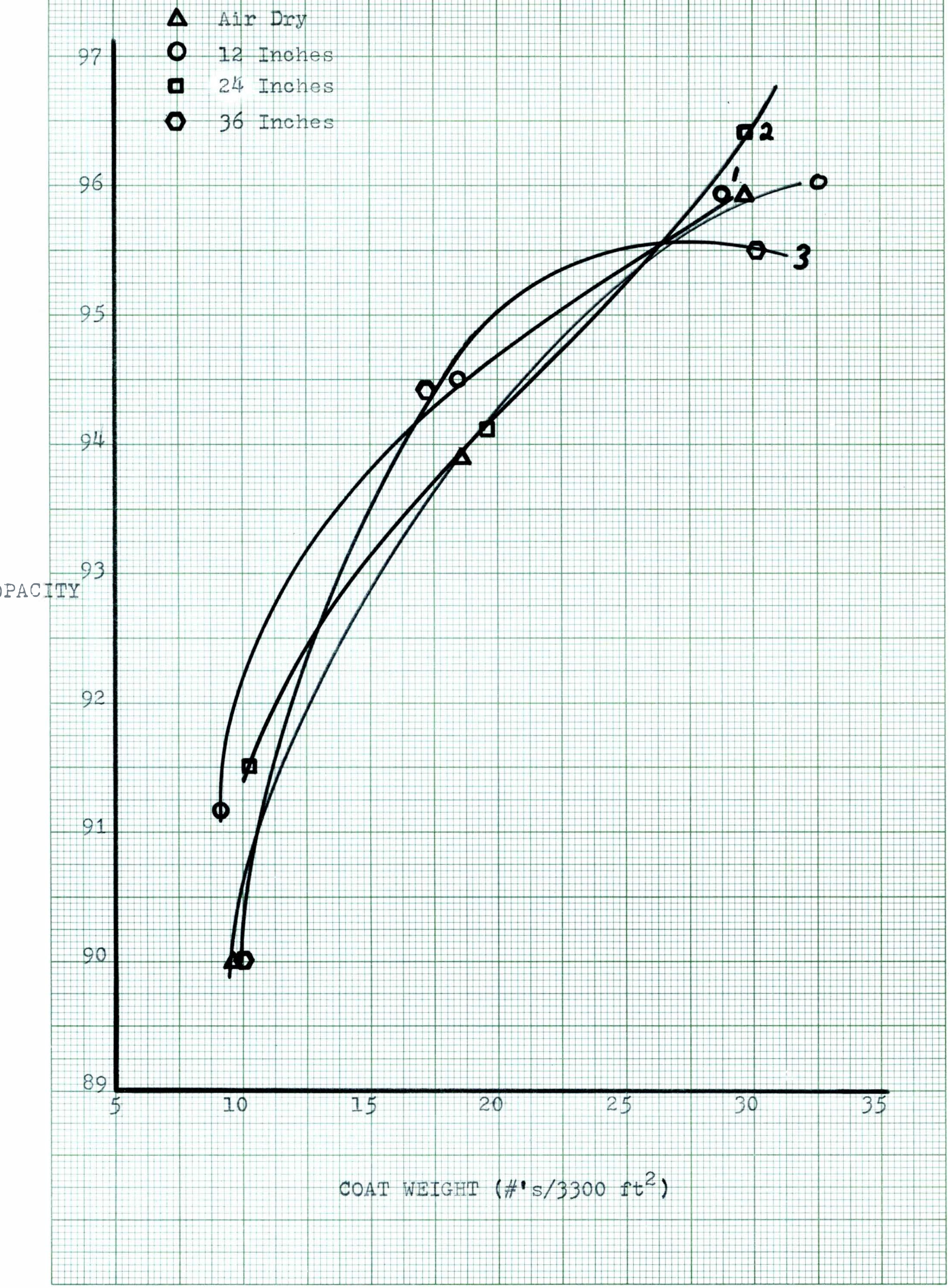


Figure (12)

DRYING RATE VERSUS GLOSS (Number 3 Rod)

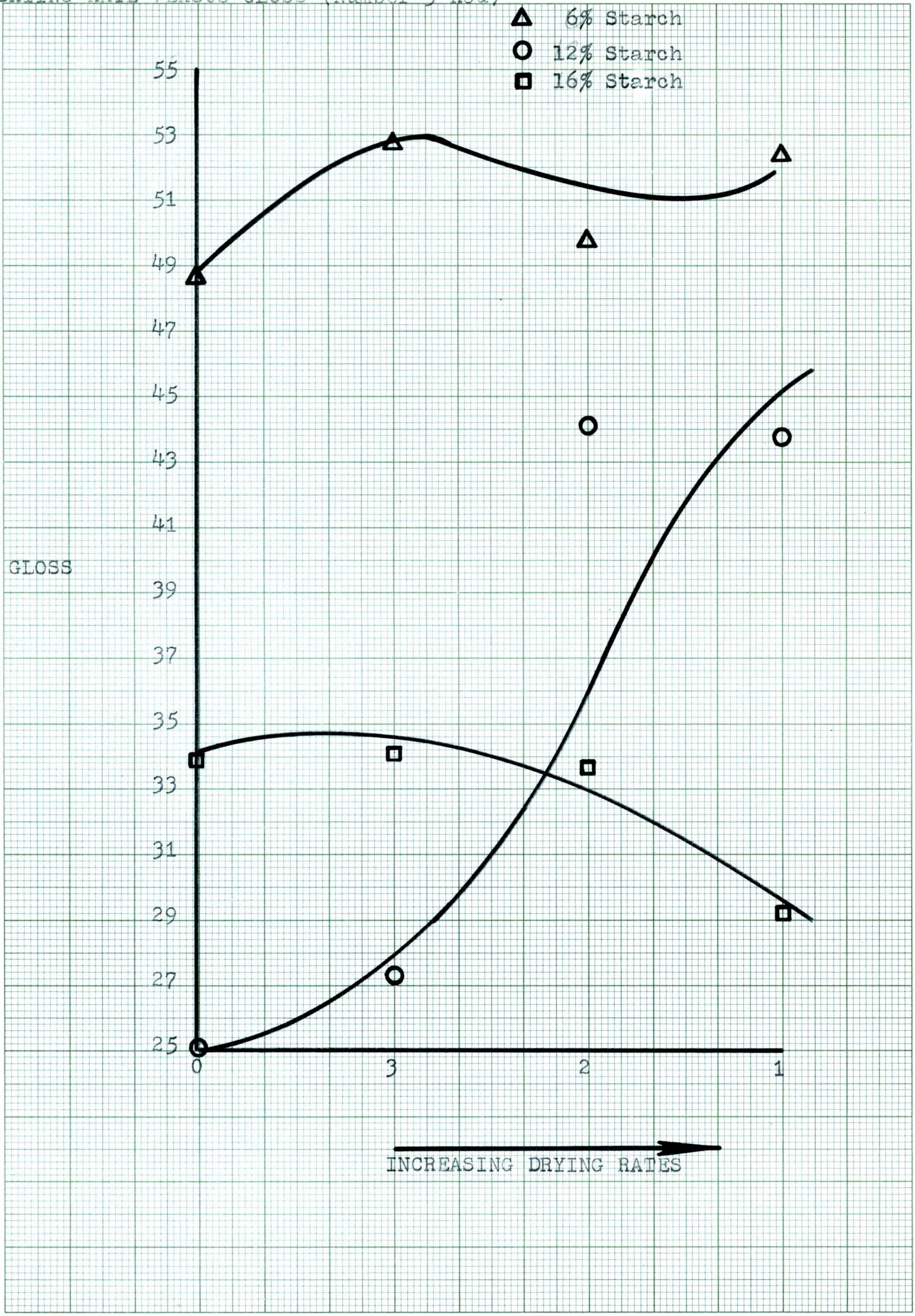


Figure (13)

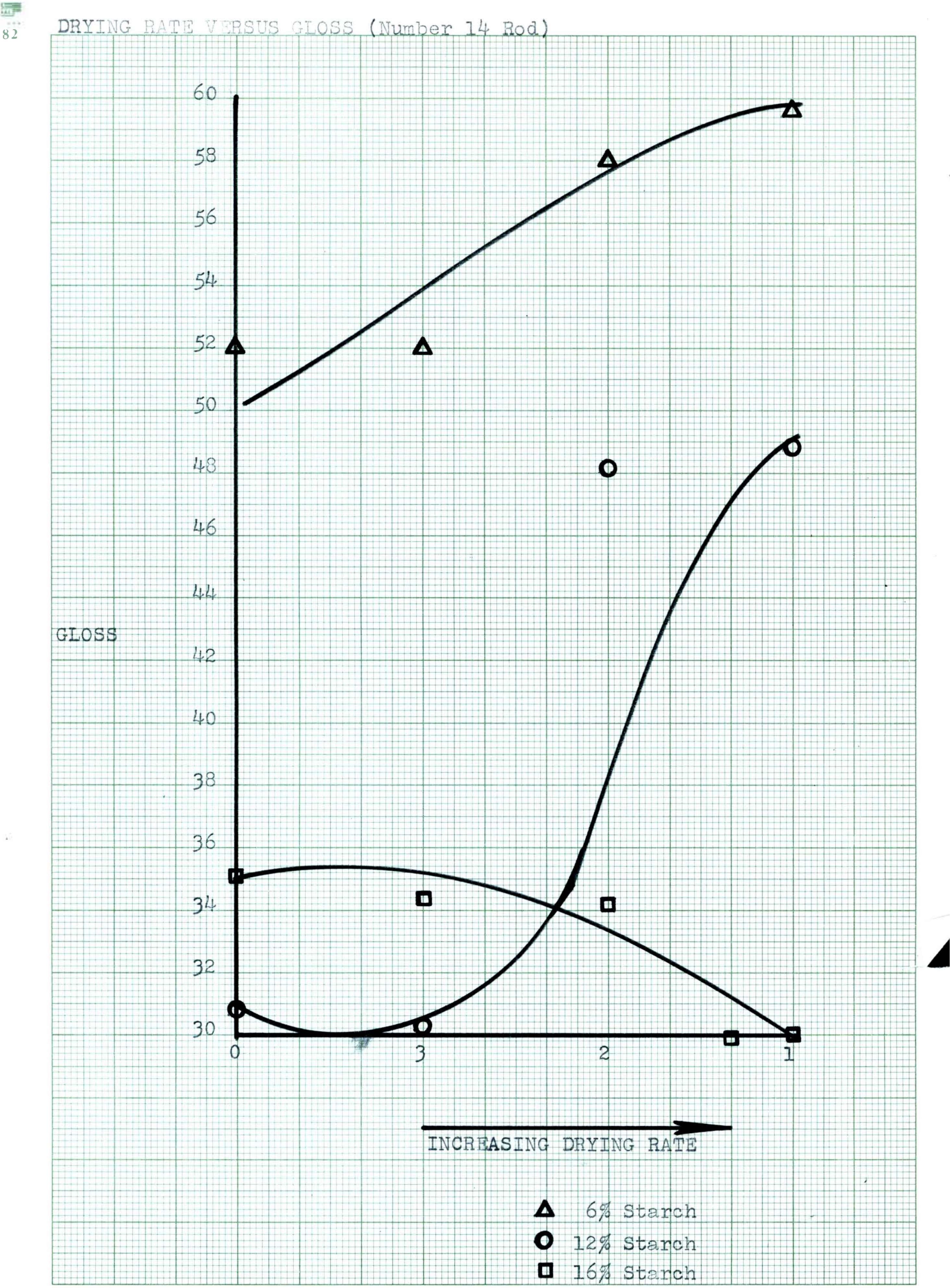

DRYING RATE VERSUS GLOSS (Number 14 Rod)
GLOSS
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
0
3
2
1
INCREASING DRYING RATE
6% Starch
12% Starch
16% Starch

Figure (14)

DRYING RATE VERSUS GLOSS (Number 24 Rod)

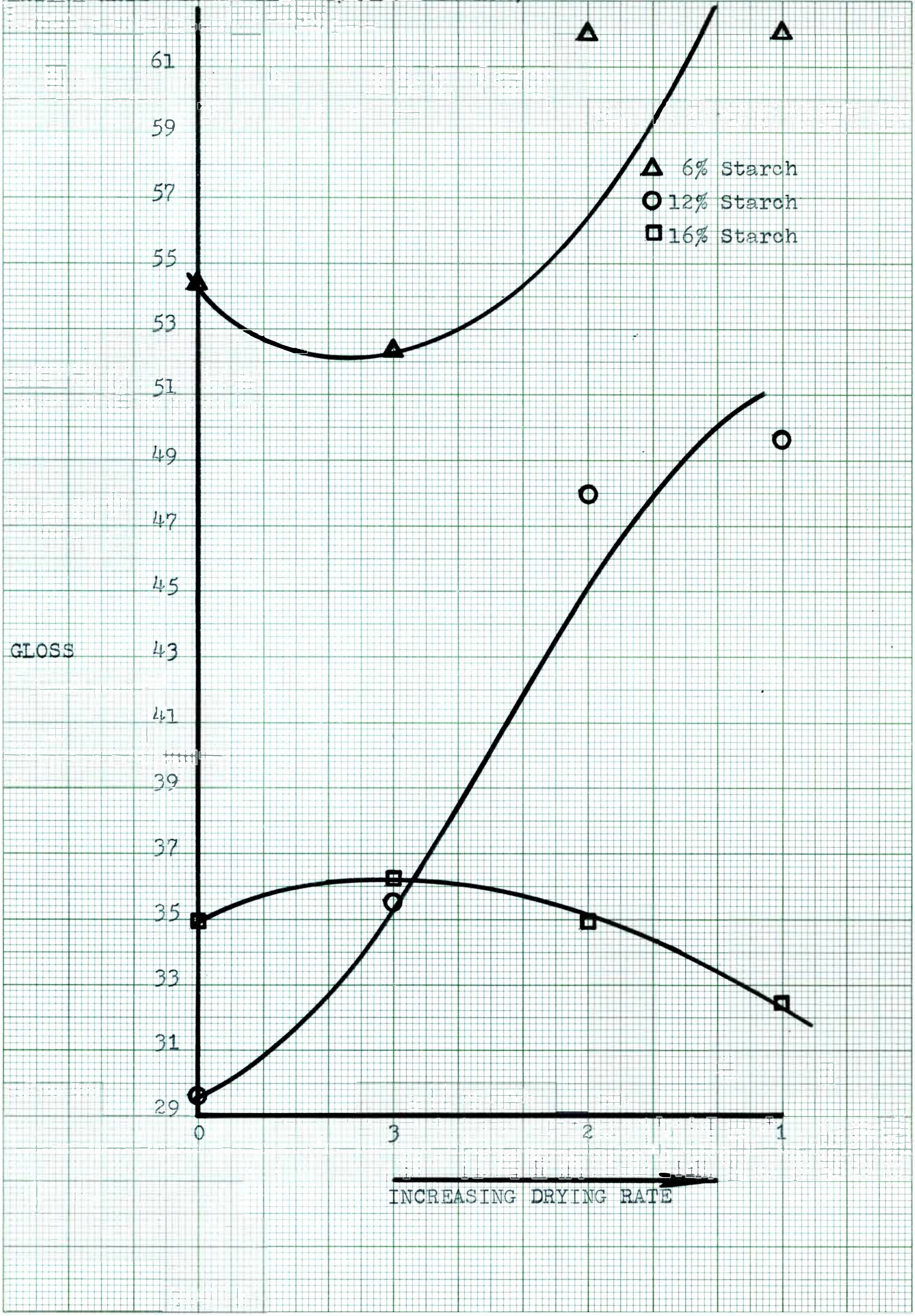


Figure (15)

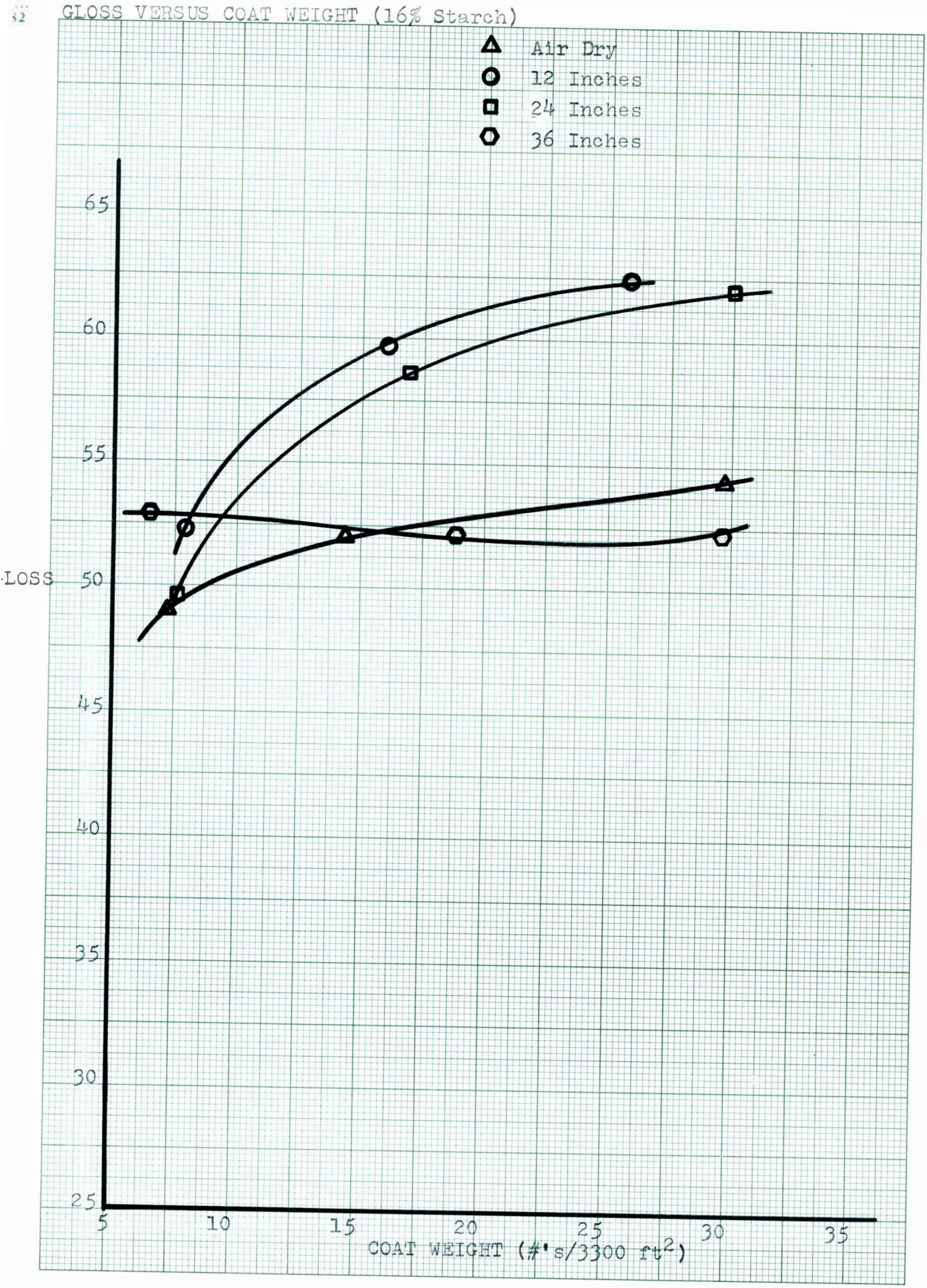

GLOSS VERSUS COAT WEIGHT (16% Starch)
Air Dry
12 Inches
24 Inches
36 Inches
GLOSS
65
60
55
50
45
40
35
30
25
5
10
15
20
25
30
35
COAT WEIGHT (#'s/3300 ft²)

Figure (16)

GLOSS VERSUS COAT WEIGHT (12% Starch)

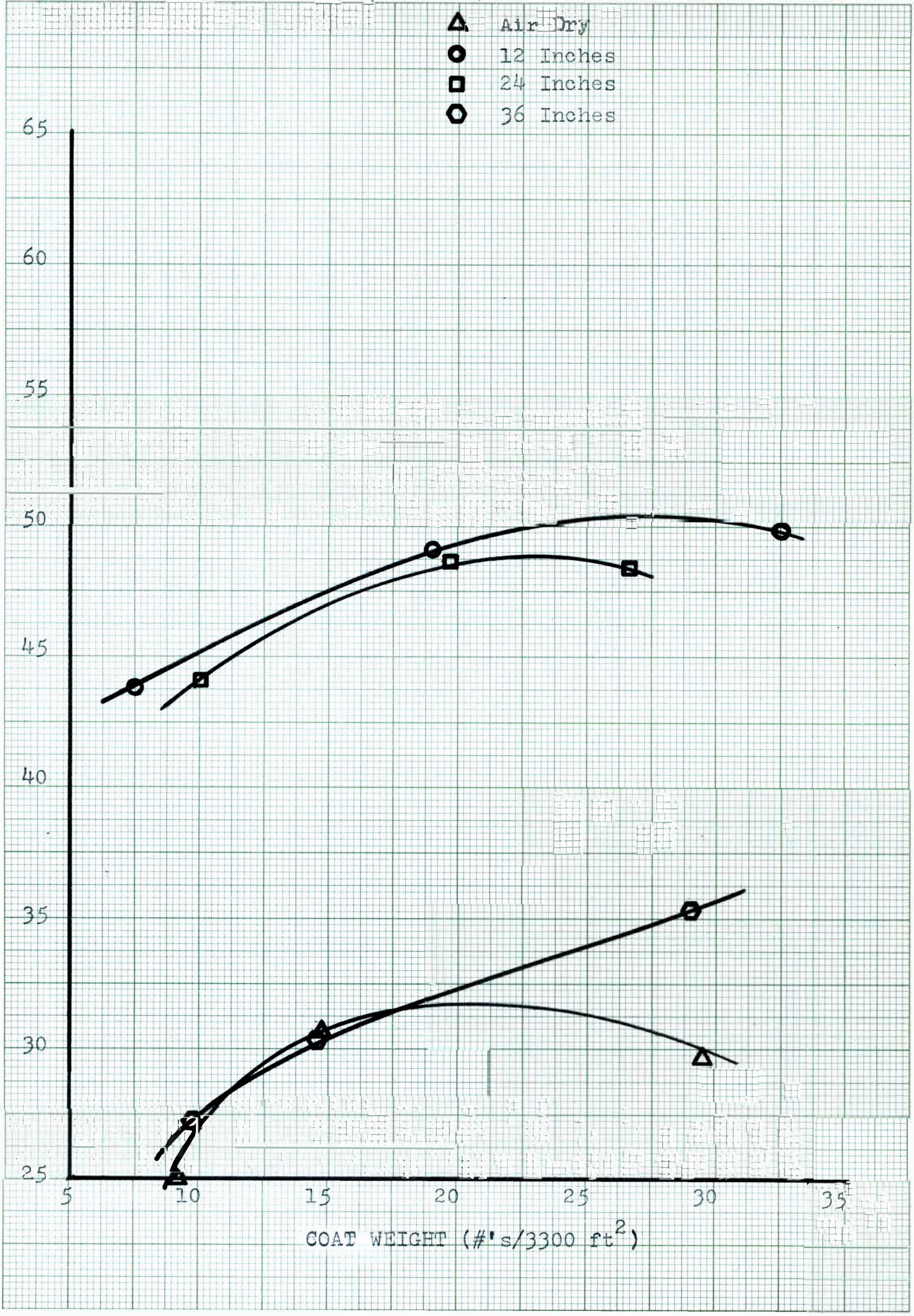


Figure (17)

GLOSS VERSUS COAT WEIGHT (16% Starch)

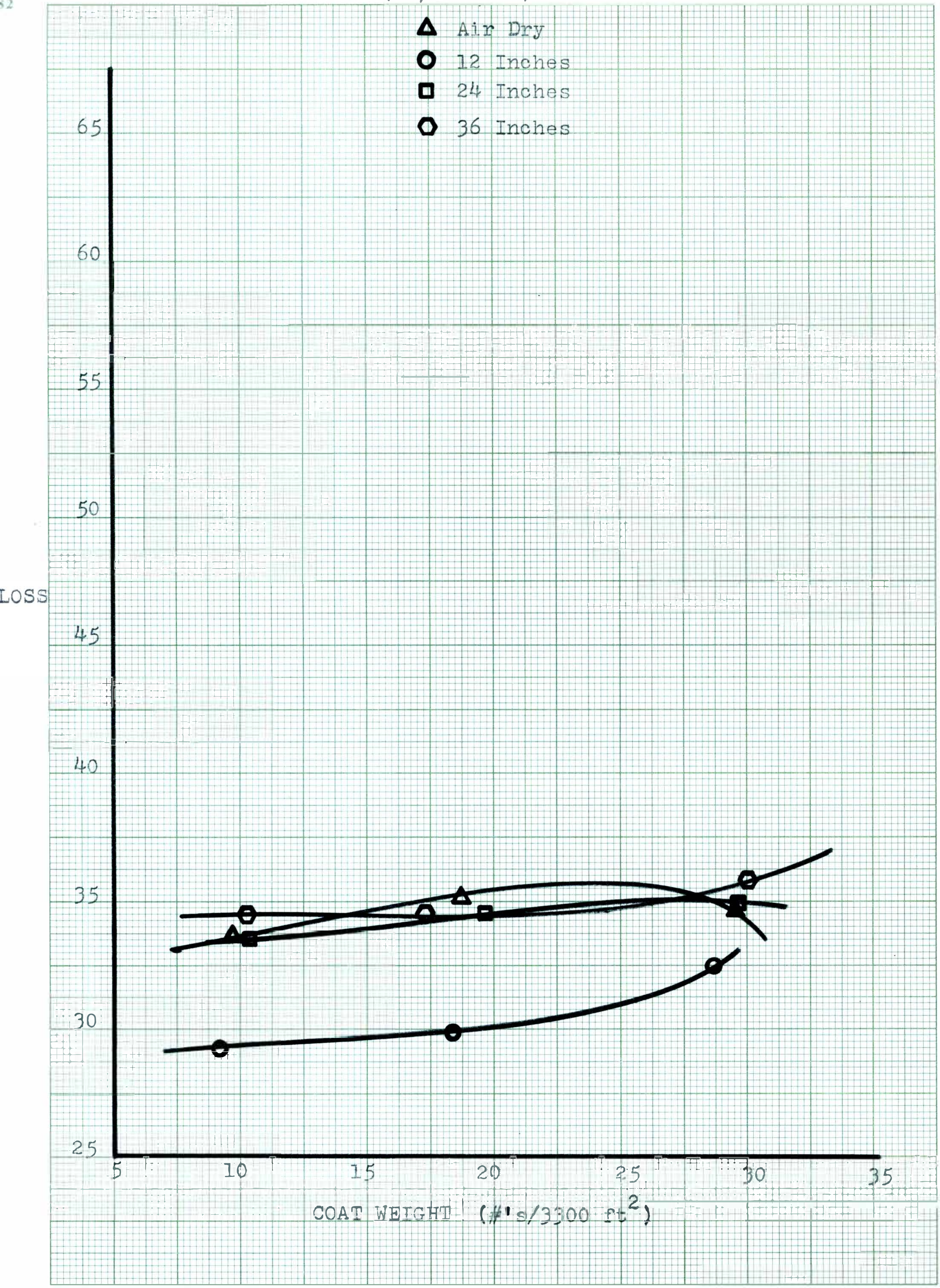


Figure (18)

DRYING RATE VERSUS WAX PICK (Number 3 Rod)

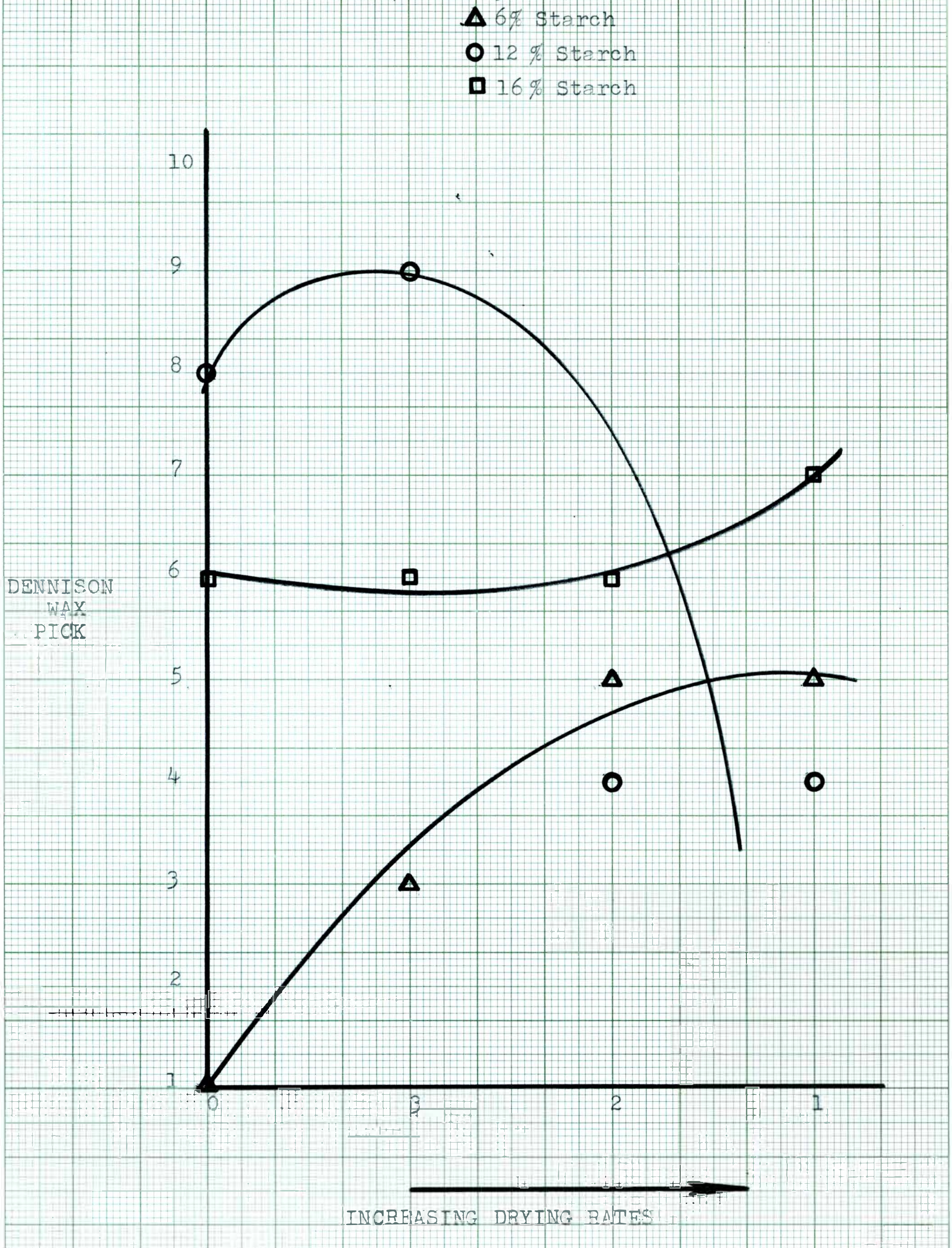
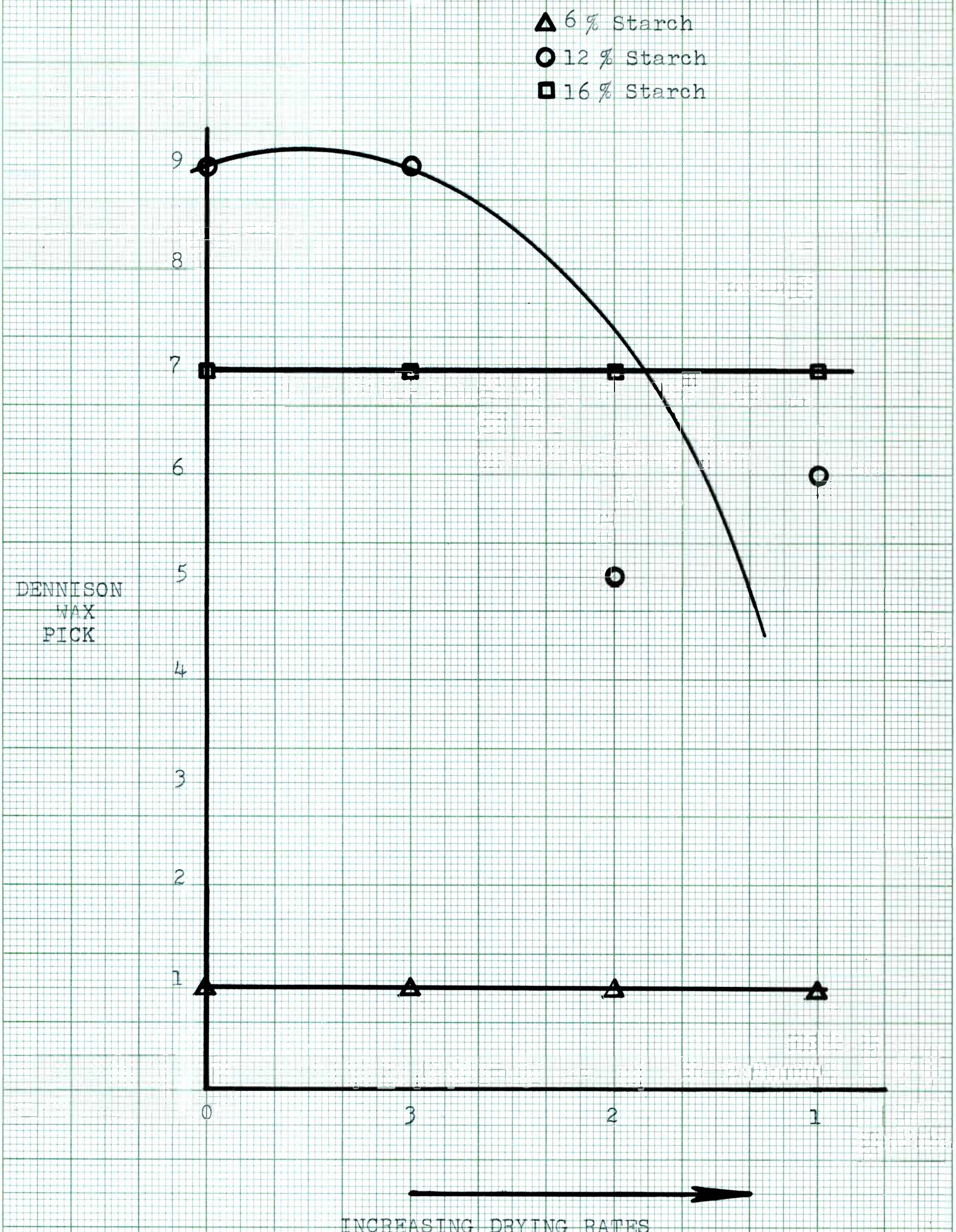


Figure (19)

uares to the Inch

DRYING RATE VERSUS WAX PICK (Number 14 Rod)



ares to the Inch

Figure (20)

DRYING RATE VERSUS DENNISON WAX PICKS (Number 24 Meyer Rod)

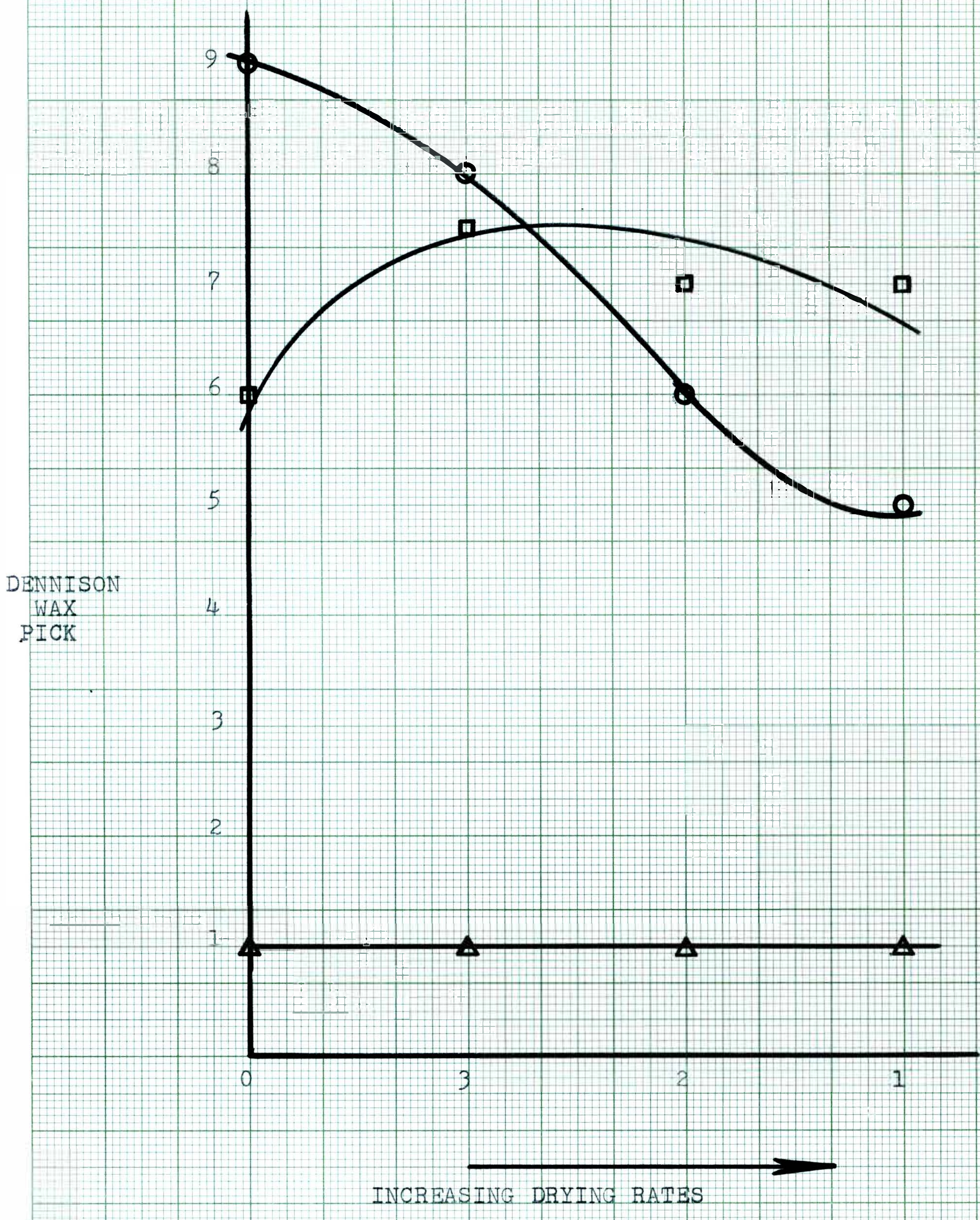


Figure (21)

INTERPRETATIONS

The air dried sheet at each of the different starch concentrations and coat weights used will be considered the control in this paper; i.e., all results and other figures will be related to this "norm".

Brightness

The brightness of the sheets increases with an increase in coat weight. This is due to the fact that the pigment is somewhat brighter than the base sheet, thus the more pigment added the more of an increase in brightness. The more starch that is in the coating, graph 6 with 16% starch, the greater brightness can be achieved by drying at an increased rate. This is probably due to a migration of the moisture in the substrate into the sheet, which would, by the mechanism, of bulk transport, also move the starch in the slurry to the base of the sheet.

This prediction is also born out on the basis of the observation during the experiment that a moisture vapor was collecting, under the sheet. This removal of the starch to the paper surface would cause an increased brightness due to the fact that the coating would not have as many surfaces in contact with the starch after the starch had been driven downward and thus there would be reflecting surfaces. This would lead to an increased brightness as brightness is dependent upon the number of reflecting surfaces.

The 12% starch solution on the basis of dry pigment seems to give the most desireable increases in brightness, and the best picking properties throughout. This is true because the starch is

forced down to the sheet by the infrared drying which would give a stronger fiber-to-coating bond and also remove more of the starch from the coating layer. Since there was not as much starch to start with there would be less in the coating layer and an increased brightness would result. The increased pick is due to fact that the water is evaporated so fast that there is no time for the weak zone just above the fiber coating interface to form due to the removal of the liquid by capillary forces.(6) According to Dappen(6) the penetration into the substrate increases with a decreasing amount of adhesive. This explains the higher brightness of the 6% coating formulations.

This author believes that the increases in migration toward the fiber surface are due to the fact that the steel plate upon which the drawdowns were made was absorbing the radiation at a much greater rate than the paper; thus, drawing the liquid phase to it through the sheet.

The graphs of brightness versus drying rate show that the 6% starch solution is by far the brightest. This is to be expected as there is less starch present. The 16% coatings show a slight increase in brightness with an increase in drying due to removal of the starch toward the fiber coating interface.

The interesting part of these curves is that the 12% starch solutions increase very rapidly with increased drying and even surpass the 6% starch coating with the 24 rod application. This would indicate that a great deal of starch moved with the water layer toward the sheet in this case due to the fact that there was more coating on the sheet and thus more room for the starch particles to migrate in the coating layer. The reason for the sudden decrease in brightness with the 6% suspension is probably

due to the fact that at this very high rate of drying there is not time for the starch particles to move with the liquid and so they get hung up back in the coating layer, thus leading to a decreased brightness.

Opacity

The opacity increases with an increase in drying rate as shown in graphs 7,8,9. This is due to the removal of the starch particles from the top of the coating layer down toward the sheet, as mentioned in the discussion on brightness. Opacity will also usually increase with increasing drying rate. In graph number 10 it doesn't due to a supposed error in the analysis, if the middle point were dropped or removed the opacity would behave as expected. With the removal of starch from the coating toward the sheet there are less fiber interfaces and thus, by the Kubelka-Munk theory, less transmission of light. Drawing a conclusion on the starch migration in a 6% starch coating is rather difficult as the effect of the starch will be greatly minimized.

The rest of the opacity data seems to follow as expected, that is, it reaches a maximum value and then starts to taper off. This tapering is due to the starch and clay suspension having reached the maximum opacity they would if just on their own. The air dry at 12%, graph 11, decreases much faster because all the starch stays right where it is in the coating layer and does not move much as the evaporation and capillary effect of the sheet just about cancel each other. Therefore there is a uniform distribution of starch and clay at the high coat weight, and at the other coat weights there is also uniformity, although not as great, as the capillary action tends to predominate with decreasing adhesive(6).

Gloss

Curves 13-15 of Drying Rate versus Gloss seem to indicate that there is a definite increase in gloss with increasing drying rates except for the very high starch concentrations. At 16% starch there is a consistent drop in the gloss with an increase in the drying rate. This effect would be due to the fact that the starch particles are again transported with the moisture to the hot surface; i.e., to the metal plate on which the sheet rests. This would tend to leave an open area on the surface of the coating that would be fairly devoid of starch and thus would not finish as well and would mean a comparitively rough surface. The effect of the plate being hot seems to be most pronounced at the highest drying rates. The other cases where the infrared unit is 24 and 36 inches away from the sheet the energy, thus heat, absorbed does't seem to be too great. With the 6 and 12% starch coatings the gloss increases with increased drying rate due to the starch being pulled toward the heating unit and then suddenly drops with a rise in the steel plate temperature.

The graphs of Gloss versus Coat Weight also show that the greater the rate of drying the greater the increase in gloss. Graphs 16-18 illustrate that the gloss will increase with increased drying until it reaches a point, at a high drying rate, where the starch begins to migrate into the sheet due to the heating of the metal base plate. This accounts for the dip in the high drying rate curves. The only graph below the air dried curve for gloss is at the 16% starch level. In this case one would suppose that there is so much starch in the coating that when it is heated at the high (Number 1) rate it all moves toward the suddenly heated base plate thus leaving a surface again

devoid of the gloss giving starch. The rise toward the end with a very heavy coat weight is probably due to the clay particles themselves being pushed into more uniform alignment on the surface and thus filling in the voids left by the departing starch.

CONCLUSIONS

The most important single conclusion that can be drawn as a result of this work is that there is always an optimum temperature and rate of drying for any given coating or any desired finished quality. The example of gloss indicates this very clearly. When the coating was heated at a moderate rate by an infrared burner the gloss improved considerably. However, when the coating was dried at a very high rate, so high that the metal surface underneath the sheet (as a dryer drum) began to absorb the heat from the infrared unit, the gloss decreased significantly. This would tend to indicate that it might not always be best to dry a sheet as fast as possible, or at such a high temperature with infrared, it would seem to be much better to have several relatively cool units, rather than one very hot unit pointing directly at a drum.

Increasing of optical properties can probably be best achieved by using an infrared burner on the back-side of a coated sheet, as this tends to drive the adhesive toward the hot surface along with the moisture and to thus open up more reflecting surfaces for brightness and less transmitting surfaces for opacity. Gloss will be decreased by using this method. Pick strength of the coating will generally be increased by this method.

The author would like to express his appreciation to Western Michigan University, and in particular to Dr. Stephen Kukolich, for the materials and guidance given throughout the preparation of this thesis.

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