THE DRYING AND CURING OF YELLOW LEAF TOBACCO BY AIR CONDITIONING METHODS

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I. INTRODUCTION

The flue curing process of tobacco essentially consists of curing tobacco by means of artificial heat, and is a combination of both physical and chemical changes in the leaves. It is characterized by large barns, open hearth fires, and the sheet metal heat distributing flues. The operation is technically inefficient, and readily lends itself to improvement.

The flue curing process of tobacco is executed in nearly the same manner as when originally developed, excepting the recent use of oil burners. There are no clear set rules for the process. Each grower depends upon past experiences, and general rule-of-thumb schedules. Such haphazard methods may not be expected to produce optimum results.

The barns are usually of crude construction, with no system of conditional distribution. Their inability to produce uniform conditions, the wasteful and laborious firing process, combined with the partial destruction of large quantities of good tobacco leaf make their problem of economic importance.

It is logical to believe that by accurately controlling air conditions, it may be possible to determine those conditions most favorable to curing. This work is a continuation of that done by Delamar in 1938 at the Virginia Polytechnic Institute.

The objectives of this work are to experimentally cure yellow leaf tobacco, by means of controlled temperatures and humidities, from the ripe to the optimum cured state, for the purpose of obtaining the curing and drying characteristics during the entire processing.

II. REVIEW OF THE LITERATURE

Types of Tobacco: In general, there are four distinct types of tobacco grown in this country(9). These are commonly called Bright or Yellow leaf (flue cured), Dark Leaf (fire cured), Sun Cured, and Burley (air cured). The dark leaf tobaccos are in demand chiefly for export purposes(10). The Bright leaf tobaccos are used extensively in cigarette blends, and also in snuffing and chewing tobaccos. It is commercially the most important of the four types. The Bright leaf tobacco belts cover the south central section of Virginia, and the Piedmont and Coastal Plains of North Carolina, South Carolina and Georgia. Small quantities are also grown in northern Florida. Tobacco is the chief money crop of these districts.

Assorting Flue Cured Tobacco: Because of the varying characteristics of flue cured tobacco grown on the same land and stalk, it becomes necessary to grade the leaves according to a standard practice. Consequently, the United States Department of Agriculture has developed a system of grading which indicates the belt in which the leaf was grown, the stalk position, and the character of the leaf(7,9). This method is presented in the following table which lists the group, quality, and color of the tobacco.

KEY TO THE CLASSIFICATION OF TOBACCO

Groups	Qualities	Colors
A - Wrappers	1 - Choice	L - Lemon
B - Leaf	2 - Fine	F - Orange
C - Cutters	3 - Good	R - Red
X - Lugs	4 - Fair	D - Dark-red
N - Nondescript	5 - Low	G - Green
S - Scrap	6 - Common	

Thus, by substituting symbols for words, Cutters of Good quality in Orange color should be written C3F. By this method a convenient and simple method of classifying tobacco is set up.

If it is desired to indicate the locality in which the tobacco is grown, a further classification number is added before the Group letter of the classification number. The common belts in which flue cured tobacco is raised are designated by the numbers given in the following table.

TYPES OF FLUE CURED TOBACCO - CLASS ONE

(1) 11(a) Old Belt; North Carolina and Virginia
(2) 11(b) Middle Belt; North Carolina and Virginia
(3) 12 New Belt; North Carolina
(4) 13 South Carolina and south-eastern North Carolina
(5) 14 Georgia and Florida

Thus, if the example cited in the preceding paragraph were grown in Georgia, the classification number would become 14C3F.

The Physical Properties of Tobacco: There are several distinctive physical properties of tobacco that are of importance in tobacco trade. These are weight per unit area, color, elasticity, grain development, aroma, "burn", and physiological strength(10). These factors are generally controlled by the stalk position, the growth environment, and the quality of the curing process. Leaf texture generally concerns the relative prominence of fine grains and veins on the leaf surface, in addition to the density and structure of the leaf. Thus, a thin leaf having an open structure of the leaf tissue, a high cellulose content and a well defined aggregation of the grain forming material may be predicted to burn well(10).

In general, grain development, aroma, burning qualities and the physiological strength determine the specific product to be made from the tobacco. Factors such as flexibility and thickness determine the type of processing required in the manufacture of tobacco commodities.

The following table is given as representative of cigarette and cigar type tobaccos(10).

TABLE A

COMMERCIALLY IMPORTANT PROPERTIES OF REPRESENTATIVE CIGARETTE AND CIGAR TYPE LEAF TOBACCO

	Flue cured (cigarette)	Maryland (cigarette)	Cigar Wrapper	Cigar Filler
Weight per square ft.	0.25-0.32 oz.	0.14-0.21	0.10-0.14	0.18
Thickness inches	0.0047-.0055	0.0043-0.0051	.0043-.0051	0.0043
Grain Development	Lacking	Not abundant	Abundant	Moderate
Elasticity	Moderate	Deficient	Elastic	Elastic
Moisture Content	17% - 20%	11% - 14%	12%-15%	12%-15%
Color	Lemon-orange	Brown-red	Clear brown	Dk. brown
Burning Qualities	Rather poor	Excellent	Excellent	Fair
Aroma	Pronounced	Not pronounced	Mild	Strong
Physiological Strength	Strong	Mild	Mod. strong	Strong

The Chemical Properties of Tobacco: The chemical composition of tobacco has also been shown to play an important part in the selection of tobacco for various uses. Essentially, cigarette types are generally high carbohydrate tobaccos(7,10), while cigar types are generally high in nitrogen compounds, and are almost free from starch and sugars. In addition, it has been shown that the chemical composition of the leaf varies considerably from the bottom to the top position on the stalk(7). A typical average analysis of different types of tobacco is given in the following table(10).

TABLE B

PERCENTAGE COMPOSITION OF REPRESENTATIVE CIGAR AND CIGARETTE TYPES OF TOBACCO ON A WATER FREE BASIS

Constituent	Flue cured Cigarette All leaf	Maryland Cigarette All leaf	Pennsyl. Filler Leaf web	Conn. broadleaf binder whole leaf
Starch	3.02	3.34	0.00	0.00
Reducing sugar (as dextrose)	9.40	1.40	0.12	0.21
Invert sugars (as sucrose)	1.08	0.20	0.00	....
Pectic acid (as Ca pectate)	10.81	16.01	9.15	9.14
Protopectin (as Ca pectate)	1.40	0.70	0.10	0.45
Pectin (as Ca pectate)	0.00	0.00	0.20	0.18
Cellulose (crude fiber)	10.81	17.20	8.72	13.28
Citric acid	1.84	1.46	5.02	6.31
Malic acid	3.27	2.77	5.52	3.20
Oxalic acid	2.11	1.73	2.75	2.55
Protein	6.38	9.06	11.75	8.23
Amides and amino acids	2.91	2.49	5.73	8.71
Ammonia	0.01	0.06	0.27	0.55
Nicotine	2.25	0.73	4.49	2.92
Nitric acid (as NO_3)	0.03	0.11	0.80	3.19
Total resins	7.12	5.60	8.16	5.20
Plant wax	0.29	0.20	0.25	0.22
Total ash	16.00	12.88	19.41	20.01
Total nitrogen	2.04	2.18	4.28	4.84

From this data it may be concluded that the difference in the quantity of the fertilizer nitrogen, in the case of cigar and cigarette types, constitutes a significant factor in the nitrogen carbohydrate ratio(10), and associated differences in leaf composition. In addition, there is a relation between the physical and chemical properties of tobacco leaf(10). It may be noted that the two cigarette types, Maryland and flue cured, differ in that the Maryland tobacco has a high content of pectin and cellulose, while the flue cured is rich in starch and sugar.

THE GROWTH AND PHYSIOLOGY OF TOBACCO

<u>The Growth of Curable Tobacco</u>: The prime prerequisite for good curing is that of ripe tobacco(9). In addition, it is advantageous to cultivate the plant with emphasis on the production of large and even textured leaves(9,11). Consequently, the plants are nurtured in such a manner as to induce abnormal growth activity in the leaves. The young, growing tobacco plant has a deep green color and a smooth texture, the color indicating richness in nitrogenous matter of which the living or vital part of the leaf is composed(9). It is these complex nitrogen compounds that are active in the building up of a food supply. When the plant has reached its maximum ability to manufacture food, a flower head develops, and food is translocated from the leaves to the seed head(9). In order to obtain the maximum food for the leaves, the flower head is removed, or "topped", thus preventing the formation of seeds. However, topping causes shooters to grow out from the axils of the leaves. Consequently, these shooters are removed, or "suckered", thus leaving a large quantity of food for utilization in the plant leaves. This accumulation of food increases both the size and quantity of the leaves. Finally, this accumulation of food, or starchy material, causes the leaf to become brittle(9,11), and snap easily when folded. This is an indication of the degree of ripeness.

It is desirable that rainfall be plentiful and well distributed(7).

The best results are obtained in seasons which have most of the rainfall in the growth period, and less during the maturing season. Poorly distributed rainfall causes serious damage to the final crop. Excessive rainfall during the maturing season may cause secondary growth, and in extreme conditions destroys the curability of the tobacco(7,9).

<u>The Plant Cell</u>: The general plant cell may be considered as a double walled sac, which is filled with cell sap. The outer wall consists of a cellulose membrane, while the inner wall is composed of semi-liquid protoplasm, which acts as a cell lining. The complete wall is a stiff, porous gel that preserves shape with limited distortion(15).

Since the cell wall encloses the sap, movement to or from the cell of material must be accomplished by diffusion or osmosis. The cellulose wall is permeable to nearly all substances dissolved in water, while the protoplasm is only semi-permeable, and controls the action(15). Any outward escape of material is termed exmosis, while an influx of material is termed endosmosis. The osmotic pressure developed is directly proportional to the solution concentration, the absolute temperature, and is increased by the hydrolysis of starch to sugar(14).

<u>The Generation of Food</u>: The method by which the leaf assimilates carbon dioxide and upon combination with water produces sugars is generally termed photosynthesis(13). The simplified action is given by the following empirical equations(12).

(1) $H_2O \quad CO_2 = CH_2O \quad O_2$

(2) $6CH_2O = C_6H_{12}O_6$ (sugar)

Upon the formation of sugar, two counter actions take place, one converting sugar to starch or plant food, and the other converting starch to sugar. These two actions are given by the following two equation (18,27)

$$(1)\quad nC_6H_{12}O_6 - (n - 1)H_2O = (C_6H_{10}O_5)n \cdot H_2O$$

(sugar) (starch)

$$(2)\quad (C_6H_{10}O_5)n \cdot H_2O \quad (n - 1)H_2O = n\,(C_6H_{12}O_6)$$

(starch) (sugar)

Such actions are produced in the leaf by the action of the green plastids or stroma, which is the material basis through which the chlorophyl is distributed, and which makes assimilation possible(13). The stroma carry the ferments which split the first unstable product of the chlorophyl-carbon dioxide combination, thus causing further transformation to carbohydrates. It also manufactures the starch from the sugar formed by the carbon dioxide assimilation. This same process is accomplished by the leucoplasts, which convert sugar that has been translocated from the leaves.

Chlorophyl is the material which gives green plants their color, and which, combined in the stroma, is capable of assimilating carbon dioxide for the purpose of food production(12). It is formed in plants which have plastids that may change under light to chlorophyl. In the process of curing, the chlorophyl is destroyed, the process being termed etiolation. This action is accomplished in the first period of the curing process.

Water in the Leaf and Transpiration: So long as the tobacco leaf retains its vitality, the evaporation of water from the leaf is complicated by a number of physiological and anatomical peculiarities of the evaporating surface. Thus, the initial drying must be considered as a physiological process. Transpiration may be regarded as the rate at which water is lost from the plant, and divides itself into two distinct phases; namely, evaporation proper, which takes place in the intercellular spaces, and the diffusion of the water vapor thus formed through the stomatal openings to the outside air(6).

Evaporation proper takes place at the surface of the parenchymatous cells lining the intercellular spaces of the leaf(16). These spaces are constructed with outlets of variable openings, known as stomata. The surface between these stomata is covered with a solid layer of epidermal cells, which are coated with a cuticle that is only slightly permeable to water or water vapor(16). Thus, in the fully developed leaves, stomatal transpiration may be ten to twenty fold that of cuticular transpiration(16). In addition, although the stomata openings constitute only one to two per cent of the total leaf area, transpiration takes place almost as rapidly as if the cuticle did not exist and the intercellular cavities were open to the air. Under extreme conditions the rate of evaporation may be eight tenths that of a free water surface(16). If the rate were proportional to the area, these values would not be greater than one one hundredth. Thus, it is apparent that the stomata are capable of abnormal water vapor diffusion capacity.

Stomata have the ability to vary the diameter of the opening, and thus execute some control over the rate of vaporization. The external factors involved in this action are light and the water content of the leaf. Thus, light causes stomata to open while darkness causes a reduction in stomata diameter(16). A high watercontent causes the stomata to open wide, while a deficiency of water results in a reduction in stomata diameter. Such action may be explained by the physiological formation and conversion of starch as activated and supplied with light and water(16). In the mesophyl cells starch is formed in light and dissolved in darkness, while in the guard cells starch disappears in light and accumulates in its absence. A deficiency of water is conducive to the transformation of sugar into starch. Thus, it is concluded that an excess of starch in the mesophyl cells causes the stomata to close, and a deficiency of starch causes them to open. A sufficient amount of water in the cell sap causes sugar to accumulate, with the consequent opening of the stomata. Under extreme conditions, such as very severe wilting or a rise in temperature of 104°C., the hydrolysis of starch is rapidly increased, while the converse process is entirely suppressed(16). This causes a large increase in the osmotic pressure of the guard cells, which become saturated with water, and open abnormally wide, and often lose their capacity to close. Such conditions over a period of time may lead to complete desiccation of the leaf.

Complete closure of the stomata evidently leads to transpiration by means of the cuticle. However, it is not true that varying the size of the stomatal opening will produce a corresponding variation in the rate of evaporation. The epidermis with its stomatal pores may be viewed as a multi-perforated areation system. Therefore, because of the great number and small size of these pores, diffusion proceeds practically at the same rate as if a septum did not exist. Thus, decreasing the diameter of the pores by fifty to seventy-five per cent does not materially affect the rate of evaporation(16). However, further narrowing does cause an appreciable check in the rate of water loss.

A further control is exercised in the plant by the method of intercellular evaporation reduction(16). When the cell walls are abnormally dry, a lesser degree of cell saturation is experienced which in turn sets up a high suction tension. Since there is a tendency toward equilibrium between the suction tension of the cell contents and the colloidal cell walls, a water shortage will reduce intercellular transpiration.

The degree of cell saturation depends upon the permeability of the protoplasm. Thus, if the protoplasm is impermeable to the cell sap, osmotic pressure will attain its highest value which draws water from the cell walls with maximum force. Conversely, if the permeability of the protoplasm increases, the pressure of the sap on the cell wall diminishes. Thus, part of the cell sap is pressed out of the cell by the contracting wall, which covers the outer wall with water, thereby causing an increase in the rate of evaporation. This mechanism is conspicuous when cells die, and the protoplasm loses its semi-permeability.

The effect of temperature must be considered with respect to the fact that so long as the cell is alive, water removal depends upon the permeability of the protoplasm(16). The fluid exuding from the cells is not pure water, but is a solution in more dilute form than the cell sap. Since it is an osmotic process, the passage of water through the protoplasm is directly affected by temperature. Thus, at 32°F the process is only one-fourth to oneseventh as fast as at 68°F.(16).

The protoplasm remains impermeable to substances in the cell sap only as long as it is alive. Upon death, the protoplasm changes from a sol to a gel, with an increase in the degree of dispersion. This miscellae form, or coagulation, causes irregular aggregates to form, leaving canals which are easily accessible by water(17).

The Rate of Evaporation: It has been shown that the temperature of wilted leaves, whose transpiration is reduced, is 7°F. to 11°F lower than turgid leaves under identical air conditions(16). In addition, the rate of evaporation may vary in normal life from ten to eighty per cent.

This rate of evaporation, or transpiration, may be expressed by Dalton's Law, as given below(16).

$$V = K(F - f)\,\frac{760}{P}\,S$$

K = Coefficient of diffusion
F = Saturation pressure of water vapor in the air
f = Observed vapor pressure in the air
P = Parometric pressure
S = Area of evaporating surface

This equation does not hold rigidly in the case of evaporation from small areas. According to Stephan's Law, the rate of evaporation from diminitive openings is proportional to the diameter rather than the area of the opening. Thus, small leaves under identical conditions and having the same area as a large leaf, may lose more water than the larger leaf. In addition, as the leaf approaches desiccation, water is transferred essentially from the veins or vascular bundles to the mesophyl cells bordering the intercellular spaces(17). Thus the evaporating area is that nearest the vascular bundles, and therefore, leaf area cannot be considered a true basis for measuring the drying rate.

Leaves of the same plant show considerable differences in structure, depending upon their environment and stalk position(7,19). According to the Rule of Zalensky, the higher the position of the leaf the smaller are the dimensions of the cells, and the greater the number of stomata per unit area, the size of each stomata being smaller, however. The higher leaves also have a thicker network of vascular bundles, a greater number of hairs per unit surface, and a thicker layer of palisade tissue(16,19). Thus, it is seen that the higher leaves have a greater rate of transpiration than the lower leaves per unit area.

THE CURING OF TOBACCO

Curing Methods: There are four different methods of curing tobacco(9), each of which is particularly adapted to one of the four types of tobaccos. Each of these methods is listed below, and defined according to the present practice.

(1) Flue Curing: Cured entirely by artificial heat in such a manner as to allow no contact with smoke.

(2) Air Curing: Cured with little or no artificial heat, and depending upon atmospheric conditions alone.

(3) Fire Curing: Cured by artificial heat applied by means of open fires on the floor of the barn, thus allowing smoke

to contact the leaf.

(4) Sun Cured: Cured by suspending the whole stalk in the the atmosphere where it may come in contact with sunshine.

In curing yellow leaf types, two methods may be practiced,(9,11) namely picked leaf or priming, and the whole stalk method. The picked leaf method consists of removing individual leaves from the stalk as they approach ripeness, stringing them upon sticks, and racking the sticks in the barn where the tobacco is to be cured. The whole stalk method consists of removing the entire stalk when most of the leaves are ripe, and supporting it in a barn where it is cured. The picked leaf method is more costly, but produces a higher quality, more uniform product. The only advantage of the whole stalk method is that of cheap harvesting. However, it is the general practice to cure yellow leaf tobacco by the picked leaf method.

The Flue Curing Process: A general outline of the steps required to transform green tobacco to the marketable product is presented below.

(A) Harvesting
    (1) Picking
    (2) Transporting to the barn shed
    (3) Stringing the leaves upon support sticks
    (4) Racking the sticks in the barn
(B) Firing
    (1) Yellowing the tobacco at low temperatures
    (2) Fixing the color at intermediate temperatures

        (3) Killing and drying the leaves at relatively high temperatures and low humidities.
        (4) Ordering the tobacco at low temperatures and high relative humidities
(C) Packing
        (1) Detaching from sticks and grading
        (2) Binding into hands
        (3) Packing to allow fermentation to ensue
(D) Transporting to auction warehouse

There are three operations of this process that determine the quality of the tobacco produced, disregarding growth fallacies; listed in order of their importance, they are:

1. Curing
2. Picking
3. Packing

The other steps involved are not herein discussed, for they are self-explanatory.

The picking of the tobacco is generally done by hired help and family members. It is necessary that the tobacco be of a uniform degree of ripeness, since under-ripe tobacco required a longer curing period than the ripe. Therefore, if non-uniform tobacco is placed in a barn, the best results may not be anticipated. It is economically sound to use only high grade leaf pickers, thus insuring uniform tobacco of the correct degree of ripeness.

The actual curing of the tobacco takes place in three periods,(9,11) or intervals of different conditions. These are the "yellowing period", the "fixing period", and the final "killing period". At the end of the third period, the leaf is very brittle, and will break readily upon handling. It is therefore necessary to allow the leaf to absorb moisture, which lends flexibility to the leaf; thus, the leaf may be easily handled. This period is generally termed "ordering". For the purpose of clarity, these periods shall be designated as periods one, two, three and four, respectively.

The "packing down" process is executed in darkened rooms by packing the cured tobacco in suitable piles(11). It is in this stage that certain bacteriological and chemical actions take place that develop taste, odor, and a deeper color in the leaf. In addition, small fallacies in the curing will often disappear in this process, generally improving the appearance of the leaf. This process requires from one to four months. After completion, the tobacco is ready for the markets.

<u>The Curing</u>: The actual curing of tobacco is accomplished in three periods, as designated in the preceding paragraph. Further digression is necessary for a complete understanding of the process, and is consequently discussed under the heading of each of the periods.

<u>Period One</u>: Period one is the most important stage of the process, for it is here that the quality of the cure is chiefly determined. In this period the color of the tobacco changes from green to a lemon yellow color. In all green vegetation there are three important pigments. Listed below are the names, colors, and chemical formulae of these dyes(12).

(1) Chlorophyl-a	Bluish green	$C_{55}H_{72}O_5N_4Mg$
(2) Chlorophyl-b	Yellowish green	$C_{55}H_{70}O_6N_4Mg$
(3) Carotin	Yellow	$C_{40}H_{56}$
(4) Xanthophyl	Yellow	$C_{40}H_{56}O_2$

The total chlorophyl is usually present in the quantity of one per cent (dry basis) and in the ratio of chlorophyl-a to chlorophyl-b of three to one(12).

The process of the change in color is a highly complex physiological one designated by the terms etiolation and chlorosis(9,12). The action is that of changing the chlorophyl to the transparent leucophyl or other colorless compounds(12), leaving only the yellow pigments as colors. The yellowing period takes place while the leaf is still alive(9). Thus it is a living or vital process. Any factor that destroys the plant life prematurely will cause inferior cured tobacco to result(9).

The rate of change of the color and the relative area in which the color has changed are indicative of the yellowing process, and specify the point at which new air conditions must be imposed. If the high humidities employed in this period are not reduced after yellowing is completed, sponging, which is a fungus growth on the leaves, takes place(9). Such action is highly deleterious, and must be prevented to insure high quality leaf.

The physical conditions commonly employed in the first period are limited over a narrow range, and therefore require delicate control and careful operation. The temperatures employed vary from

80°F. to 120°F., depending upon the character of the leaf and the practice followed by the farmer. The temperature in this period should never exceed 120°F.(9), for above this temperature the leaf is rapidly killed, and will fail to yellow properly. The relative humidities employed generally vary from 80 per cent to 85 per cent at the beginning of the period, and gradually decrease to 45 per cent or 50 per cent at the end of the period. The humidity in tobacco barns is a natural function of temperature, the drying rate of the tobacco, and the external air conditions. It may be observed that localized heating, and wall cooling lead to very poor control of this factor, regardless of the fact that humidity, in this period, is highly important.

The time required for proper yellowing depends upon the conditions to which the leaf is subjected, and the character and type of leaf. Complete yellowing is usually accomplished within 24 to 36 hours.

Period Two: The second period is usually thought of as being in a state of intermediate conditions. The temperature at the beginning of this period is usually within 100°F. and 120°F., depending upon the temperature employed in the first period. As the curing proceeds the temperature gradually rises to between 130°F. and 140°F. at the end of the period.

The relative humidity varies with the other functions, usually starting the period at 45 per cent to 50 per cent, and gradually decreasing to 30 per cent or 35 per cent at the end of the period.

The end-point of this period is reached when it is considered that the maximum amount of green has "run out" and the leaf has the desired color, odor, and surface appearance. The time generally required varies between 10 and 18 hours.

Period Three: The third, or killing period is characterized by high temperatures and low relative humidities. The leaf, at this point, may be considered killed, and the main portion of its original water content removed, leaving the web part of the leaf essentially dry. However, the stems and the larger of the vascular bundles still retain their green color and a large portion of their original water content. Consequently, if these are not dried, they will feed water to the leaf, thus encouraging rotting and fungi growths. The temperature required to accomplish the stem drying is relatively high. Since the leaf has been killed, no harm may be incurred by the use of more extreme conditions. The initial temperatures of this period vary between 130°F. and 140°F., and are gradually increased to around 170°F. at the end of the period. Temperatures of as high as 200°F. have been employed, with no reported ill effects. However, it is doubtful if such practice is advisable in view of the fact that ammonia and other volatile matter may distil from the tobacco. In addition, fire hazards develop rapidly as the higher temperatures are approached,(8) for the tobacco is tinder dry, and the flues are necessarily at a red heat. Consequently, escapage of hot gases and the danger of leaves dropping on hot flues impart a terrific fire hazard, when it is considered that most barns are constructed of wood.

The relative humidities employed in this period usually start in the proximity of 40 per cent and decrease with an increase in temperature to as low as 25 per cent.

The time required for complete killing depends upon the efficiency of the heating system, and the surrounding atmospheric conditions. A good barn under favorable external conditions may execute killing in one to one and one-half days, while a poor barn may require as much as two and one-half days under identical weather conditions. Extreme difficulty is encountered when killing is undertaken in rainy or foggy weather. It is highly desirable that the relative humidity be as low as possible, for this factor determines the final equilibrium water content. The killing process is completed when the stems of the leaves will snap easily when bent(8,11), and the typical brown color of the stem is produced.

Period Four: At the end of the third period, the leaves are extremely brittle, and serious material damage would be incurred upon handling. Consequently, the fourth period is designated to lend the leaves flexibility. This is accomplished by allowing the leaf to absorb moisture from the surrounding air, thus becoming pliable and readily handled. This is generally done by opening the barn doors and windows, and allowing the fire to extinguish itself.(11) The rate at which the leaves gain water is determined chiefly by the relative humidity of the surrounding air(1,28). The temperature is allowed to fall until it approaches that of the external air. Many farmers place pans of water in the barn in an effort to increase the rate of water regain. The leaf is moved from the barn when it becomes flexible enough to be safely handled.

The Tobacco Barns: The tobacco barn is usually a rather crude structure which was designed and constructed by the farmer as economically as possbile. The basis of design is simply that of past experience and practice. Consequently, it is illogical to believe that maximum efficiency is attained, even though some barns are of excellent construction.

The materials of barn construction, the characteristics of various barns, and their relative cost are given in the following table.

TABLE C

THE TYPES OF TOBACCO BARNS

Type	Characteristics	Relative Cost
(1) Log or pole; clinked	Poor seal, readily affected by external conditions; not durable	Low initial cost; Reworked yearly
(2) Single board; slat over the crack	Poor seal, readily affected by external conditions; poor insulation	Low initial cost; High fuel costs
(3) Single board; tar paper cover with slats	Good seal, affected by external conditions; good insulation; durable	Medium first cost; Low fuel costs
(4) Galvanized sheet metal board base	Excellent seal, less affected by external conditions, highly durable	High first cost; Low fuel costs; Low Maintenance
(5) Hollow tile block; cement joints; metal roof	Excellent seal; slightly affected by external conditions; good insulation; very durable	High first cost; low maintenance; low fuel costs; simple replacement

The furnace is generally constructed of two or more layers of brick, well cemented, and having a curved ceiling. It is relatively durable, and easily repaired, although frequent and careful chinking is required.

The flues and fittings are generally sold under the name of "tobacco flues". Essentially, they are circular ducts, lap sealed, of 15 to 20 pound galvanized iron. These flues are not very durable, and under service conditions they rust through very rapidly, requiring frequent replacement. This inability of flues to withstand the conditions under which they are employed is a source of fire hazard which causes destruction of both barns and tobacco.

The roof sheathing is usually constructed of shingles or sheet metal. In either case, it is not the practice to use an extensive base sheathing. The cost of the two are nearly the same, although the sheet metal is more difficult to mount. There are certain advantages of shingles that favor their use instead of sheet metal. However, the metal roof is more satisfactory with respect to leaks and fire danger. The shingle roofs are generally conceded to deliver better results under normal weather conditions by virtue of their ventilation capacity.

The barns are usually equipped with a door at the ground level and a window higher on the front side. Thus, by opening and shutting these apertures the farmer may execute a crude humidity and thermal control. Thermometers are usually installed in the barns, about four feet from the ground level, and a few paces from the door. The farmer must open the door and enter the barn to make a reading. In addition, it must be remembered that this area is directly over the hot flues, in a free air space. Consequently, it is evident that the temperature read does not correspond with the actual mean barn temperature.

The tobacco leaves are supported on sticks by means of string, and the sticks are suspended from racks built in the barn. The horizontal space between sticks varies from five to twelve inches, depending upon the size and quantity of leaves on the stick. The vertical spacing is designed to allow a distance of 3 to 10 inches between the tip of the upper leaves and the level of the rack below, such distances varying with the size of the leaf and the farmer's ideas. The distance from the ground level to the first rack is usually between six and eight feet, depending upon the degree of safety involved and the firing habits of the farmer. It is not a wise habit to place leaves close to the walls of the barn because of the lower temperatures prevalent in these areas.

Thus, it is seen that the tobacco barn is usually fully packed. Therefore, since the only method of distribution of heat and air is by natural conduction and convection, non-uniform conditions will prevail. In addition, care must be exercised in the barn filling to place the sticks geometrically uniform, thus preventing excessive air channeling.

THE THEORY OF DRYING

The Definition of Drying: Drying is defined as a process by which water is removed from a system or structure, in which the amount of water is relatively small(2,29). Air drying consists of the vaporization and removal of water vapor from the solid by an air medium(2,22,29).

Equilibrium Conditions: At any given temperature and humidity a hygroscopic material will reach a definite water content. Thus, water is adsorbed or desorbed to reach this definite or equilibrium(1,20,26,28). A rise in temperature causes a decrease in the water content, while a decrease in humidity causes a decrease in the equilibrium water content. Thus, under equilibrium conditions, the vapor pressure of the water in the solid equals that of the air(1,26,28).

Organic materials of a fibrous or colloidal structure have equilibrium water contents that vary regularly and through wide ranges, depending upon the air conditions. Theoretically, the adsorption and desorption curves of this function should coincide. However, experimental data does not uphold this, for the desorption curve indicates a higher moisture content than the adsorption curve for identical conditions(1,28). Therefore, drying rates should be expressed by the desorption curve. The weight of the moisture adsorbed by a material after it has been dried is termed "regain".

Bound and Unbound Water: A saturated and wetted solid has the same partial pressure of water in air as that of liquid water. Excesses of water in the solid do not raise this partial pressure, but as water is removed, a critical value will be reached where the partial pressure of the water in the solid begins to decrease.[1,20,21,22,30] Above this saturated condition, water is considered as unbound, while below the critical point the water is considered as bound.[1,20,28] Those substances which normally contain bound water are known as hygroscopic materials[1,20].

Unbound water is held in voids, and on the surface of a material[1,20]. Thus it is capable of exerting its full vapor pressure. Bound water is found to exist in numerous formations. The most common of these are cells or fibre walls and organic structures[1,20,21-23,26,29].

Water in fine capillaries exerts an abnormally low vapor pressure[25], because of their high concave manisci. This effect is not truly one of bound water, but its general action is the same, with the exception that the capillarity provides a motive force for the transfer of water to an air surface.

Moisture in cell or fibre walls presents a vapor pressure lowering because of solids dissolved in it[3,23,28], and the adsorptive nature of some combinations. Organic structures present a complex case in that the water present is in both physical combination[1,20]. This water is enclosed in cells, and by cellular walls and cuticles of various natures[1,13,20]. It is present normally as plant sap, which is a complex solution, the transpiration of which depends upon the permeability of the protoplasm of the cells.

The Mechanism of Drying: There are three essential variables that have a direct bearing on the rate of drying. These are temperature, humidity, and the velocity of the air past the drying material. The amount and the structure of the material in which the water is admixed in turn limits the effect of these variables(30). It is therefore necessary to study each of these under constant conditions of the other two variables for the purpose of differentiation. However, the mechanism of moisture movement must be established before the vatiables may be properly evaluated.

The general term used to express the moisture movement is that of diffusion(4,20,22,24,30). True diffusion is not encountered in the case of water movement, for any liquid movement is apparently due to capillarity(25). In the case of drying solids, capillaries are neither circular nor straight. Water is pulled to the surface by capillary pull, if the end of the tube is not sealed from the air. The small diameter of the capillary causes water to recede toward the smaller end of the tube, as it is evaporated(25). Thus, in the case of molding clays, the surface may be wet during a drying process until practically all of the water is drawn off(24,25). This capillary pull may excede that of atmospheric pressure.

Vapor movement is truly that of diffusion(20,22). If the vapor is formed in the interior of the solid, it must move by molecular diffusion through the air channels to the solid surface. Here must continue diffusion through the surface air film, finally to be taken into the stream of air by eddy diffusion. Vapor formed at the surface of the solid must diffuse only through the surface film(4,30), and be taken up by eddy diffusion into the air stream.

There are three resistances to diffusion that determine the drying characteristics of solids. These are presented below, with the rating of the various resistances(10,12,22,24,30).

(1) Evaporation of the liquid at the solid surface.
    (a) Resistance to internal diffusion small compared with resistance to surface diffusion to the air stream.
(2) Evaporation at the solid surface
    (a) Resistance to internal diffusion large compared with resistance to surface diffusion to the air stream.
(3) Evaporation in the interior of the solid
    (a) Resistance to internal diffusion of liquid great as compared with total vapor removal resistance.

With regard to the above statements, several quantitative deductions may be made. These are listed below, and represent the factors that govern the rate of drying(4,30).

(1) The driving force which supplies the heat required for vaporization is the difference in the air temperature and the drying solid temperature.
(2) The overall diffusional driving force is represented by the difference in the partial pressure of the water in the solid and the partial pressure of water vapor in the surrounding air.
(3) The water content of solid material in the path of the diffusing vapor is in equilibrium with this vapor.

The actual drying process divides into two major periods, which are determined by the variation in the rate of drying. These two cases are the constant rate period(4,20,21,22,30), in which the drying rate remains constant, and the falling rate period, in which the rate of drying steadily decreases.(4,20,21,22,30) The falling rate period may further be subdivided into a zone of unsaturated surface dryihg,(21,22,30) and a zone of internal drying.

The Constant Rate Period: The constant rate period is limited by the rate of surface diffusion to the air(22,30). This drying process is analagous to water evaporation, for the solid assumes the wet bulb temperature. The drying rate is affected directly by temperature and humidity conditions of the air. The air velocity determines the constancy of the air conditions, and increases the drying rate in accordance with the eight-tenths power of the mass velocity(21,30). This period terminates at a condition in which the surface of the solid is no longer completely wet; this condition is termed the critical water content. At this point the drying rate begins to decrease.

The Falling Rate Period: The falling rate begins under a condition at which the internal liquid diffusion controls the rate of vaporization(20,21,22,30). Under this condition, part of the surface is wetted, this area being diminished as drying proceeds. Thus the drying rate decreases, for the rate definition is based upon exposed area. If the drying rate decreases at a constant rate, it is termed the period of constant falling rate, or zone of unsaturated surface drying. In this case, water moves to the surface of the solid at a slower rate than it is removed(20,22,30).

Finally, when the surface becomes dry, the plane of vaporization gradually recedes into the interior of the solid, the depth of this plane being determined by the large internal resistance to liquid diffusion$^{(22,23,30)}$. The material between the air surface and the plane of vaporization is in equilibrium with the vapor partial pressure in this space. Since this plane of vaporization recedes progressively further into the solid as drying proceeds, greater diffusional resistances are set up, which cause a decrease in drying rate. This stage is generally termed internal diffusional drying.

Thus, it is seen that drying is essentially controlled by the rates of water movement, vapor diffusion, and heat transfer. Therefore, each material must be carefully studied before selecting the proper drying conditions.

The Effect of Temperature: The effect of temperature is observed in three manners. An increase in temperature increases the rate of heat transfer to the material, increases the vapor pressure of the water, and decreases the relative humidity. All of these factors are conducive to a more rapid drying rate.

The Effect of Humidity: The humidity of the circulating air determines the driving force for the diffusional transfer of vapor from the solid to the air stream$^{(4,20,30)}$. During the constant rate period, this difference in humidity is directly proportional to the drying rate$^{(4,30)}$. It also plays a large part in the zone of unsaturated surface drying, but the rate of drying does not conform to the first power of the humidity difference$^{(4,20,21,30)}$.

However, in the zone of internal diffusional drying, humidity has little effect, other than determining the final equilibrium water content(1,28). In general, the effect of relative humidity is to increase vapor pressure and temperature gradients between the solid and the air.

The Effect of Air Velocity: Air velocity affects the rate of drying by decreasing the stagnant air film adjacent to the solid,(4,20,30) and determines the constancy of the air conditions in the dryer. In most drying operations the air velocity remains constant, regardless of its effect. The rate of drying in the constant rate period is determined by the coefficients of heat transfer and diffusion(4,30,21). It has been shown that high air velocities past a solid cause turbulent air currents, which in turn reduce the effective stagnant air film adjacent to the solid. This decrease in film thickness causes an increase in the rate of heat transfer and the rate of diffusion, for the resistance of these two operations is directly proportional to the film thickness.

In the falling rate period, the air film resistance is only part of the total resistance to diffusion and heat flow.(4,20,21,22,30) Therefore, air flow becomes progressively more unimportant as drying proceeds, for the relative resistance of the surface film decreases as the zone of vaporization receded further into the solid. The general effect of air velocity in the zone of unsaturated surface drying is to increase the upward concave of the rate of drying curve(4,22). In the zone of internal drying, air velocity becomes of negligible importance(21). Thus, it is seen that in the falling rate period, the air velocity employed is of secondary importance.

The Effect of Radiant Heat: Drying solids which receive radiant heat are subject to a more rapid drying, since the temperature of the solid increases, thereby increasing the partial pressure of the water in the solid(21,30). The rate of vaporization of the moisture is governed by the rate of heat transmission to the solid. The driving force for transfer by conduction is the difference in the temperature of the solid and the surrounding air. Although radiation decreases this difference, it increases the rate of vaporization because of the direct application of radiant heat.

Care must be exercised in the application of data from small laboratory samples. In such cases, the ratio of dry to wet area is relatively large(21,22,30). In addition, the single sample is subject to radiation from all sides, while commercial cases are not. Thus, a laboratory test indicates a more rapid rate of drying than would be observed in actual practice. If radiant heat is sufficient to cause vaporization to proceed fast enough, a pressure will build up in the solid, which will cause an extremely high rate of drying. This case is rare, and is termed forced diffusion.

Drying Equations: Drying equations are usually based upon Fick's law of diffusion(20,22), which states that the rate of diffusion is directly proportional to the partial pressure differences. However, the characteristics of the drying process require that equations treat the case under constant drying conditions and falling rate conditions. Several of the more useful equations are given below, primarily to furnish a clearer insight into the mechanism of drying.

(1) The rate of drying from a wet surface for a constant temperature is given by the equation(5,30):

$$\frac{dW}{dT} = RA(H_s - H_a).$$

$\frac{dW}{dT}$ = Rate of drying, (lb./hr./sq.ft.)

A = Area, (sq.ft.)
H_s = Saturated absolute humidity, (lb.H_2O/lb.air)
H_a = Actual absolute humidity, (lb.H_2O/lb.air)
R = Diffusion constant

(2) The rate of drying is complicated by the effect of air velocity, but is reported to act as follows(9):

$$\frac{dW}{dT} = 0.027\ V^{.8}(P_s - P_a)$$

V = Velocity of a parallel stream of air, (m./sec.)
P_s = Partial pressure of water surface, (m.m. Hg.)
P_a = Partial pressure of water in air, (m.m. Hg.)

(3) If the drying rate is found to be directly proportional to the loss in free water, the following equation may be successfully applied(30):

$$\theta_c = \frac{W_o - W_c}{KW_c}$$

θ_c = Time of constant rate drying, (hr.)
W_o = Initial free water, (lb.H_2O/lb. dry stock)
W_c = Critical free water, (lb.H_2O/lb. dry stock)
K = Drying coefficient, (1/sec.)

(4) If the solid possesses negligible bound water, and it may be assumed that the thermal conductivity and vapor diffusivity are constant in the zone of vaporization, while the thermal effects other than the latent heat of water are negligible, the following equations may be written(20):

$$\frac{P_z - P_a}{t_a - t_c} = \frac{Ag(k_n \quad Lk_g)}{r(k_m \quad Lk_g/c)} = \frac{U}{Kr}$$

$$Ag = h_g/k_g \text{ and } A_n = h_m/K_m$$

$$U = \frac{1}{1/h_g \quad L/h_m} \text{ and } K = \frac{1}{1/k_g \quad L/k_m}$$

P_z = Zone partial pressure, (m.m. Hg)

P_a = Actual partial pressure, (m.m. Hg.)

t_a = Actual temperature, (deg. C.)

t_z = Zone temperature, (deg. C.)

h_g = Coefficient of heat transfer through the air film, (Cal./hr./sq.cm./deg.C.)

k_g = Coefficient of diffusion for water vapor through the air film, (gm./hr./sq.cm./m.m.Hg.)

k_m = Coefficient (specific) of water vapor diffusion in solid, (gm.cm./hr./sq.cm./m.m.Hg.)

L = Distance from surface to the limit of the zone of evaporation, (cm.)

r = Latent heat of vaporization, (Cal./gm.)

U = Overall coefficient of heat transfer, (Cal./hra/sq.cm./deg.C.)

K = Overall coefficient of vapor diffusion, (gm./hr./sq.cm./m.m. hg.)

The value of these equations may be found in their manner of relating the complex operation of drying. These are of further value in the examination and correlation of drying data.

Drying Limits: Certain types of material may not be dried at excessive rates because of the detrimental effects of case hardening, surface checking(5,21,30), and high temperatures. Case hardening is the result of too rapid drying of materials which set up a surface condition that causes an excessively low rate of diffusion. It is often called skin effect, because the interior water is virtually trapped.

Both of these cases may be alleviated by employing conditions conducive to a slower drying rate. However, other materials may be seriously damaged by the temperature employed. In order to design a dryer for such materials, it is necessary that the highest safe temperature be employed.

Loft, Cabinet, and Chamber Dryers: The simplest form of dryer is a chamber equipped with steam coils to supply heat, and some ventilation to decrease humidity. These dryers have proved inefficient because of their non-uniformity of conditions, which in turn leads to a non-uniform product. In addition, they lose the advantages of continuity, and require constant inspection. However, this type of dryer may be improved by employing a series of chambers around a central exhaust, and causing air to be circulated in accordance with the ring furnace principle. This method has the advantage of practical continuity, excellent distribution, and a lower labor cost(31).

In dryers of this type, it is often necessary to employ a definite schedule of conditions, the temperature being the maximum and the humidity being the minimum that the stock may bear without injury(31). The schedule varies with the drying characteristics of the material, and the thickness and the ease of injury of the stock.

Air Circulation: It is highly desirable to employ an adequate and uniform rate of air circulation, thus increasing the rate of evaporation, and insuring better and more uniform control of the operation. A high velocity is advantageous for drying thin material, but it is not as effective in the case of thick materials, bedause of the relatively high internal diffusion resistances found in many materials(25).

If the total air required for drying is small, it is highly desirable to use transverse circulation at a high velocity(32). However, parallel flow must be used in the case of sheet materials.

Dryer Design: The logical order of the steps to be taken in the design of any air dryer are given as follows(32):

(1) Select the type of dryer and drying conditions, using the highest safe temperature.

(2) Sketch diagrammatically the type of equipment to be employed, and write in both heat and material balances.

(3) Calculate the required amount of circulating air.

(4) Calculate the heat requirements.

(5) Select suitable controls.

(6) Calculate the time required for drying.

(7) Calculate and arrange the necessary heating surface.

(8) Calculate friction losses and fan horsepower.

III. INVESTIGATION

PURPOSE

Purpose of Study: The purpose of the investigation is to dry and cure tobacco by means of accurately controlled temperatures and relative humidities from the ripe to the optimum cured state, to obtain the drying characteristics during the process of curing.

This involves the investigation of the effects on the drying rate of the independent variables, temperature, relative humidity, and air velocity. In addition, it is necessary to relate the two inter-dependent variables, water content and the drying rate.

From these relations, the quantitative basis for optimum curing may be established.

PLAN OF INVESTIGATION

A total of fifteen runs were made, ten of which were complete cures, requiring an average of forty hours of dryer operation per run, or a total of 600 hours of dryer operation.

The preliminary runs were made at conditions below which it has been shown that curing could be achieved. These conditions were proportionally and progressively changed until the limits at which curing could be achieved were determined. The runs were then divided into three series, namely the temperature, humidity, and velocity series. Each of these series was run to determine the individual effects of one variable, the other variables being held constant at some condition favorable to curing.

Temperature Series: This series consists of four runs, over a range of temperatures varying from slightly above summer atmospheric conditions to the upper curing limit. The following table presents the schedule of runs.

SCHEDULE I

TEMPERATURE SERIES SCHEDULE - P. I

Run Number	Dry Bulb (deg.F.)	Wet Bulb (deg.F.)	Air Velocity (ft./min.)
3	110	103.5	78
6	105	100.5	78
5	100	96.0	78
4	95	91.5	78

The effect of temperature on the drying rate was readily determined from the data taken during these runs. The values of relative humidity and air velocity were chosen because of the fact that they were near ideal curing conditions, thus minimizing their deleterious effects near the curing limit.

Humidity Series: This series consisted of four runs, which were chosen over a range of humidities varying from the lower limit, as determined by summer atmospheric conditions to the limit of practical air saturation. The following table presents the schedule of runs.

SCHEDULE II

HUMIDITY SERIES SCHEDULE - P. I

Run Number	Wet Bulb (deg.F.)	Dry Bulb (deg.F.)	Air Velocity (ft./min.)
8	80.8	95	78
7	89.2	95	78
4	91.5	95	78
9	92.0	95	78

The effect of relative humidity over the curing range was readily determined from the data taken during these runs. The values of temperature and air velocity were chosen because of the fact that they were the most favorable conditions for curing, thus minimizing the deleterious effects near the curing limit.

Velocity Series: This series consisted of five runs which were chosen over a range of velocities that apparently was suitable under barn conditions, when it was considered that tobacco in barns is racked in depth. The upper velocity limit is determined by excessive leaf shaking and tip drying, while the lower limit is that which permits the air conditions to materially change when passing through tobacco leaves in depth. The velocity series schedule is presented in the following table.

SCHEDULE III

VELOCITY SERIES SCHEDULE

Run Number	Air Velocity (ft./min.)	Dry Bulb (deg.F.)	Wet Bulb (deg.F.)
15	50	100	96
5	78	100	96
14	96	100	96
13	100	100	96
12	115	100	96

The effect of air velocity on the drying rate was readily determined from the data taken during these runs. The values of temperatures and relative humidity were chosen because they were favorable to good curing, and were most effectively controlled. Thus, errors because of non-curing, and slight variations in conditions were minimized.

Composite Run: One run consisting of a gradual change in condition was made to determine if the curing rate could be increased, efficiency increased, and the sponging of the tobacco at high humidities decreased. Sponging of tobacco occurs at high humidities and low temperatures after the tobacco has been partially yellowed. This action, if allowed to proceed, will completely destroy the tobacco for all commercial purposes. Essentially, temperature was gradually increased, relative humidity progressively decreased, while air velocity remained constant. The following schedule was employed in making the run.

SCHEDULE IV

COMPOSITE RUN SCHEDULE - P. I

Time (hr.)	Dry Bulb (deg.F.)	Wet Bulb (deg.F.)	Air Velocity (ft./min.)
19	95	91.5	78
2	100	96.0	78
2	100	91.0	78
2	100	89.0	78
2	105	93.5	78
2	105	89.5	78
2	105	85.0	78
2	110	89.0	78
2	110	84.0	78
2	120	92.0	78
2	120	86.0	78
2	170	102.0	78
2	101	95.0	78

The values of temperature and humidity were alternatingly adjusted, one being held constant while the other varied, and vice versa. By this method, some conception of the effect of these two variables might be obtained. In addition it was hoped to determine which of these was the controlling factor in curing, or if they presented a mutual effect.

Air Friction: One run was made to determine the drag or friction of the air past the tobacco leaves, as they cured. This was executed by determining the tobacco weight with the blower off, and then with it on, at different intervals. The blower was allowed to run during these periods, and was shut off only long enough to determine the weight of the tobacco.

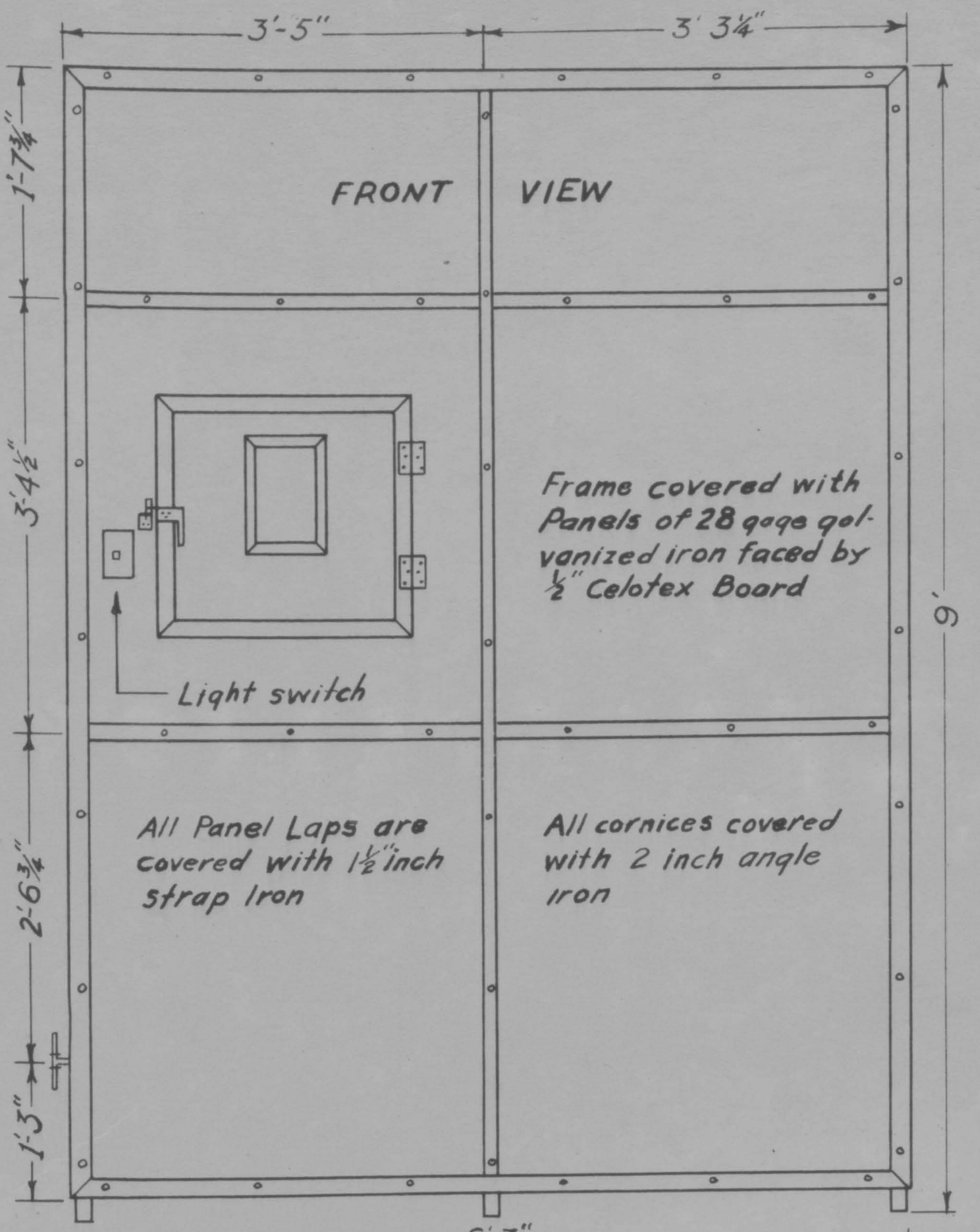
Materials

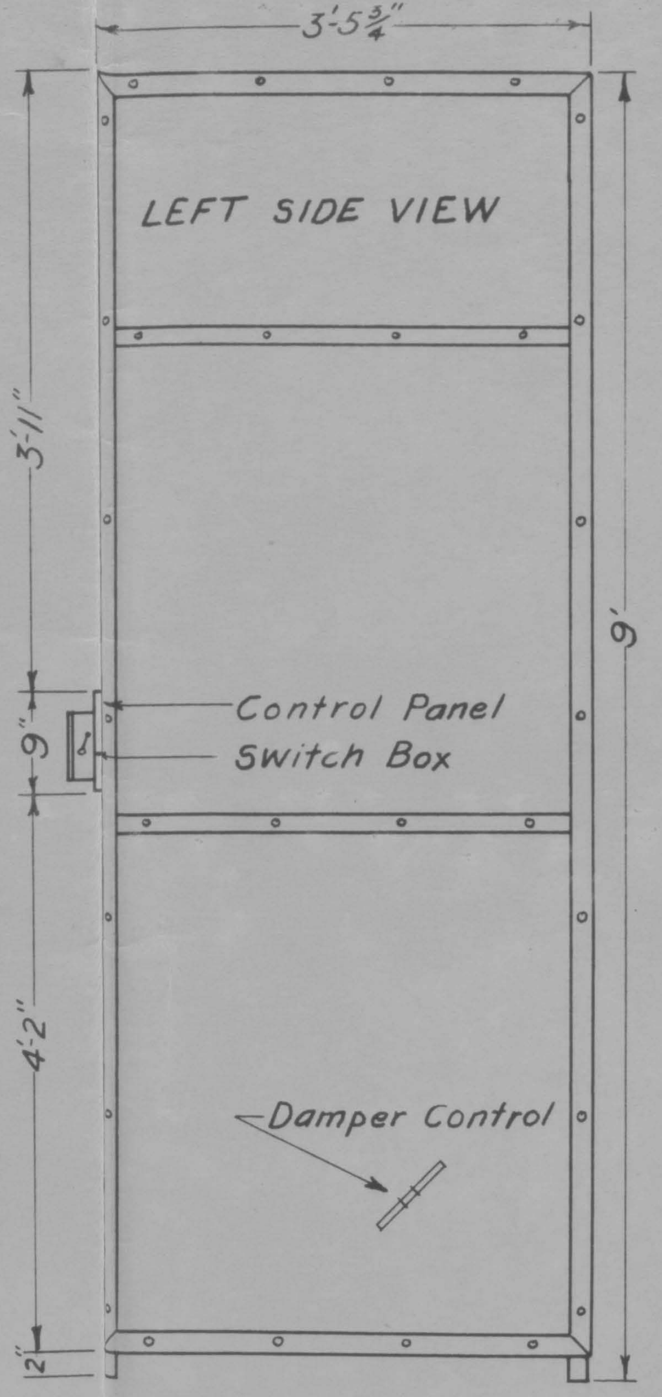
Tobacco: The tobacco used was of the type generally called bright leaf, yellow leaf, or flue cured. Its name is derived from the fact that it develops a lemon yellow or orange yellow upon curing. It is of the "Solanaceoe" family(6), and of the "Nicotiana Tobacum, L." genus. Tobacco is a rank, acrid, narcotic, viscidly pubescent plant, whose leaves are covered with soft downy hair. It is described as having "widespread leaves, ovate, oblong, or lancelate in form. The leaves are alternatingly attached to the stalk spirally(6)".

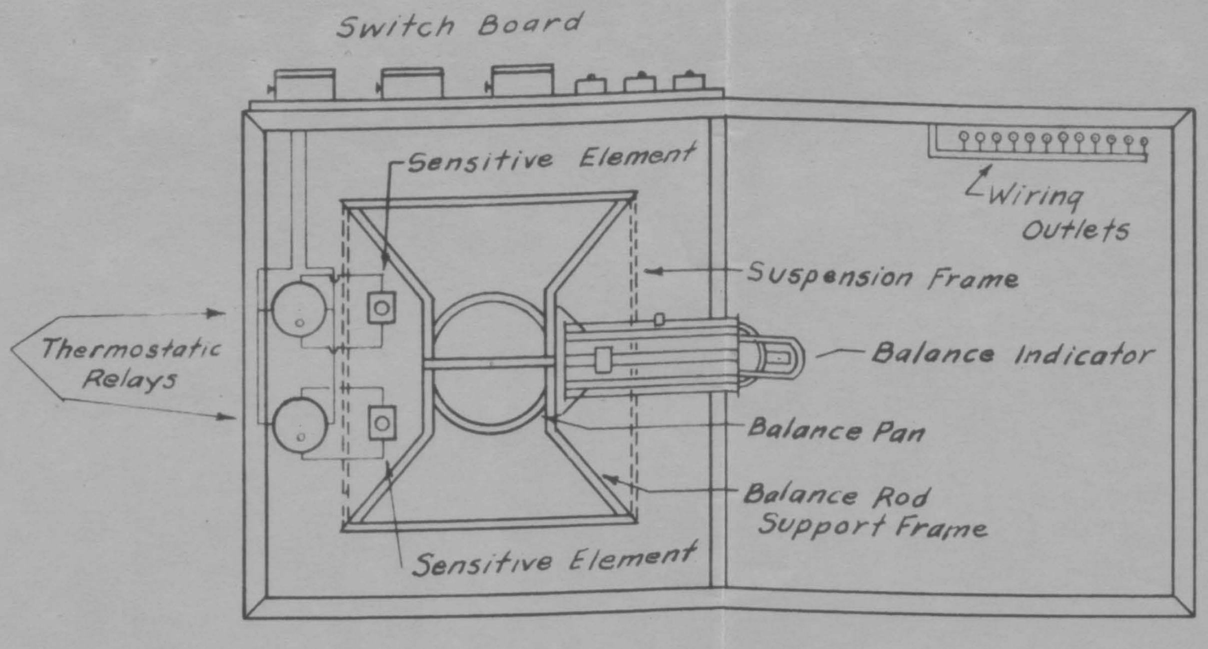
The tobacco was grown on the Virginia Polytechnic Institute Agricultural Experiment grounds at Blacksburg, Virginia. It was carefully harvested at the desired degree of ripeness as periodically required. The leaf was not of a high quality, being infected by surface splotches in addition to being rather small.

Air: Air was drawn from the Chemical Engineering main laboratory and recirculated, humidified, dehumidified, and heated in accordance with the curing schedule.

Steam: Steam was drawn from the power plant steam main running into Davidson Hall. The steam passed through a pressure regulating valve, which held steam pressure constant at 12 pounds per square inch. It was used directly for humidification, and indirectly for spray wa-

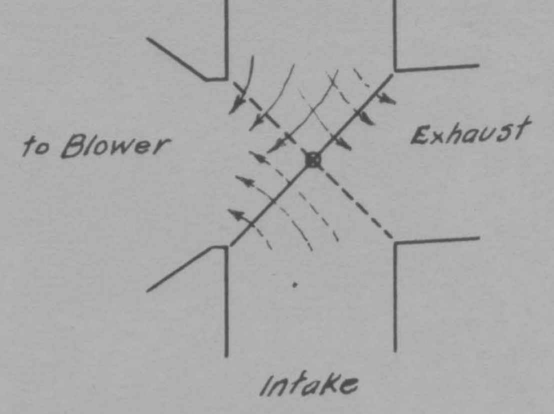




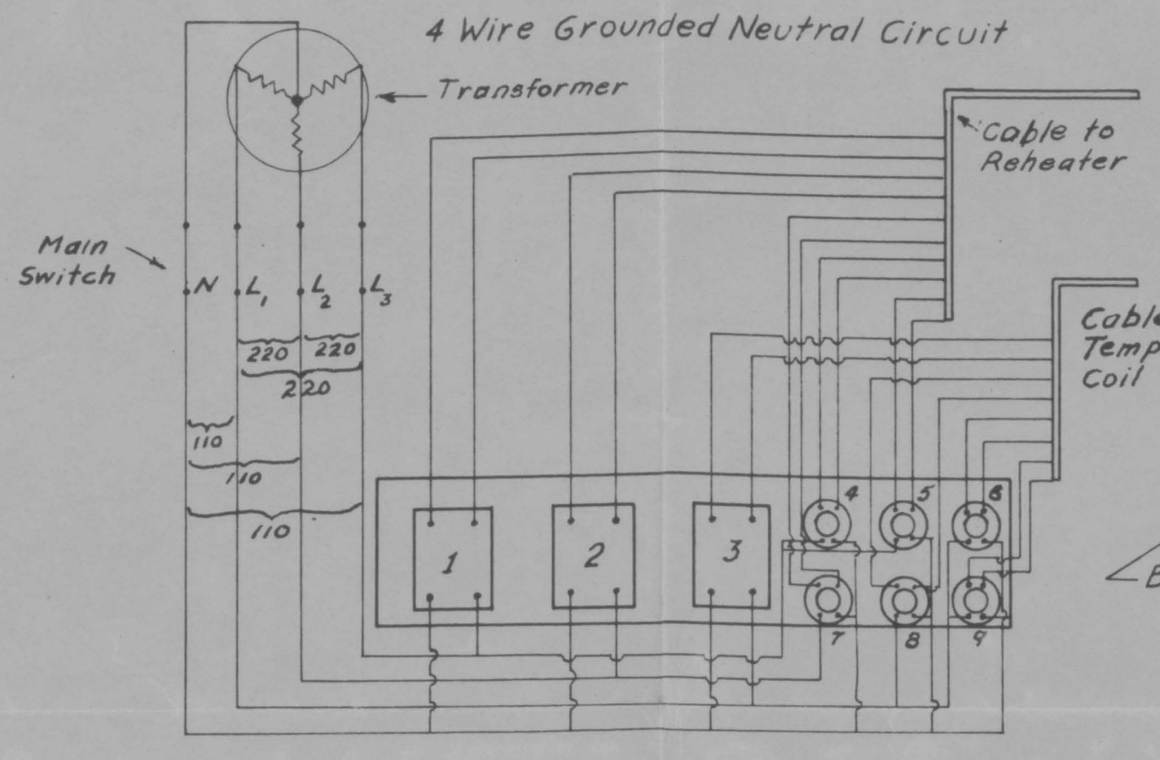


PLAN VIEW

Detail – Balance Mount – Thermostatic Relays

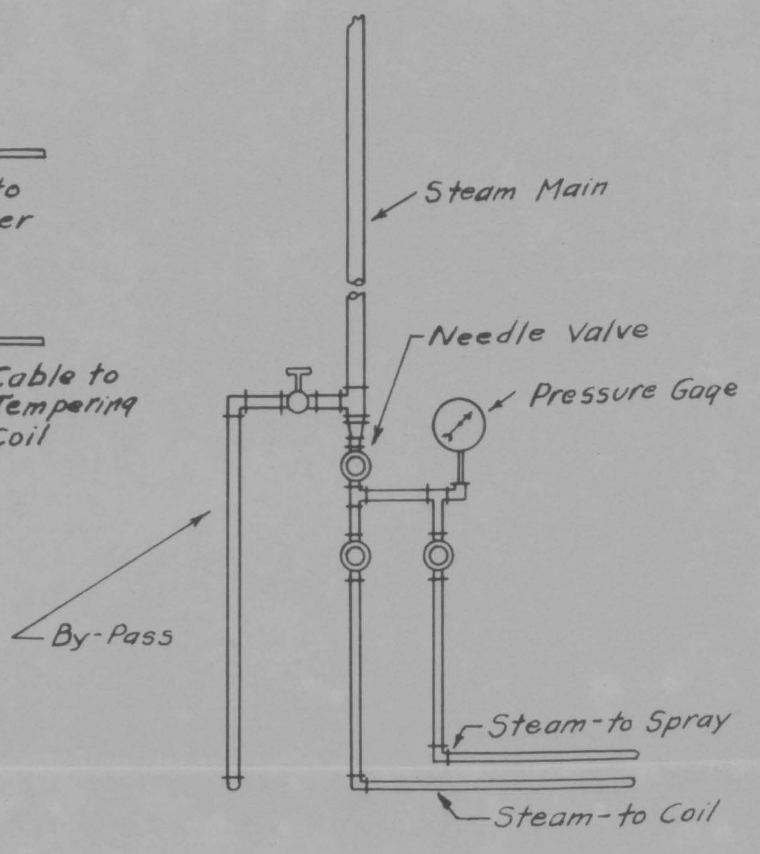


DETAIL OF CROSS AND DAMPER



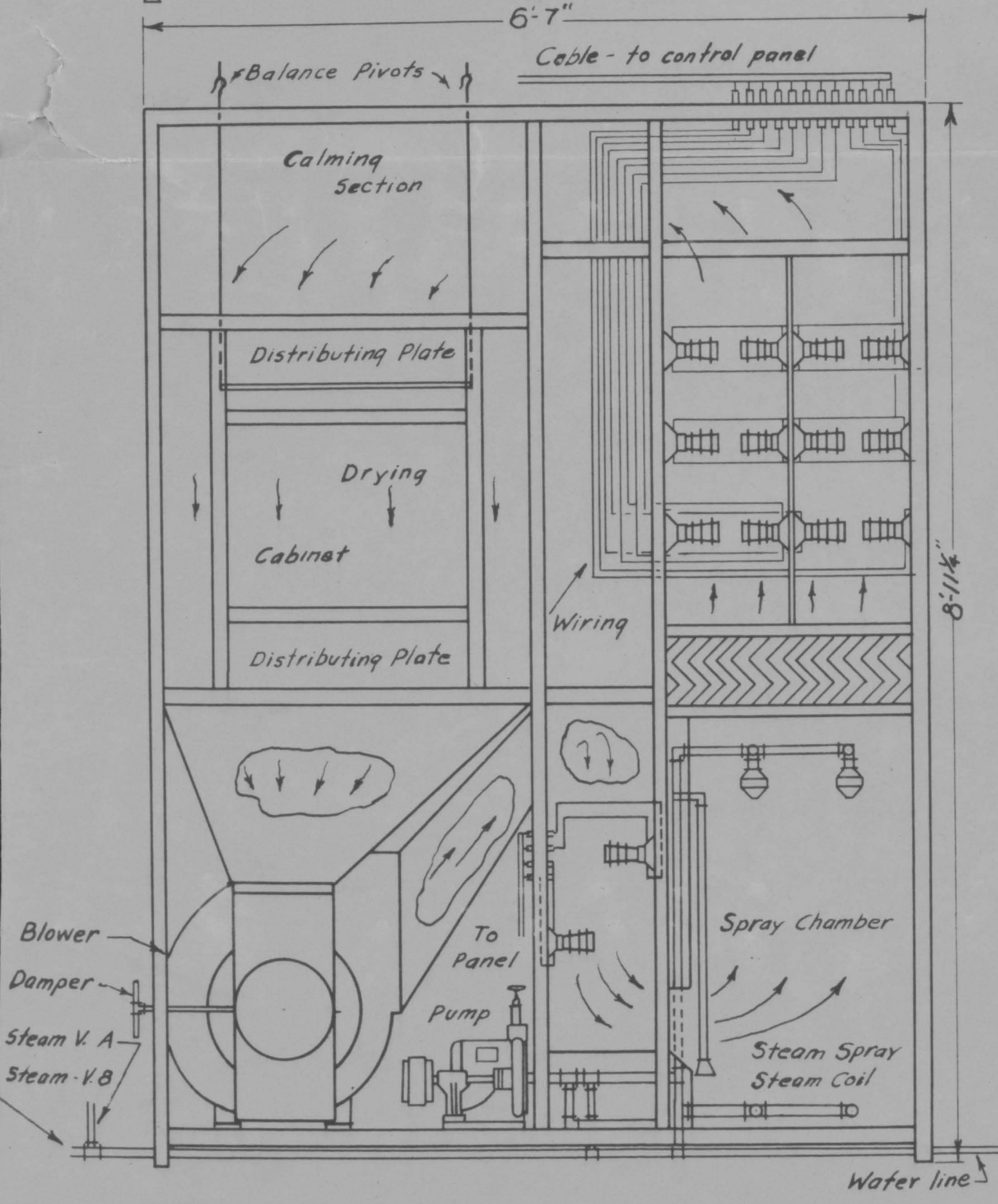
CONTROL PANEL DETAIL

① 36 Watts - Reheater
② 36 Watts - Reheater
③ 24 Watts - Temper
④ 12 Watts - Reheater
⑤ 6 Watts - Regulator
⑥ 12 Watts - Temper
⑦ 18 Watts - Reheater
⑧ 6 Watts - Regulator
⑨ 12 Watts - Temper



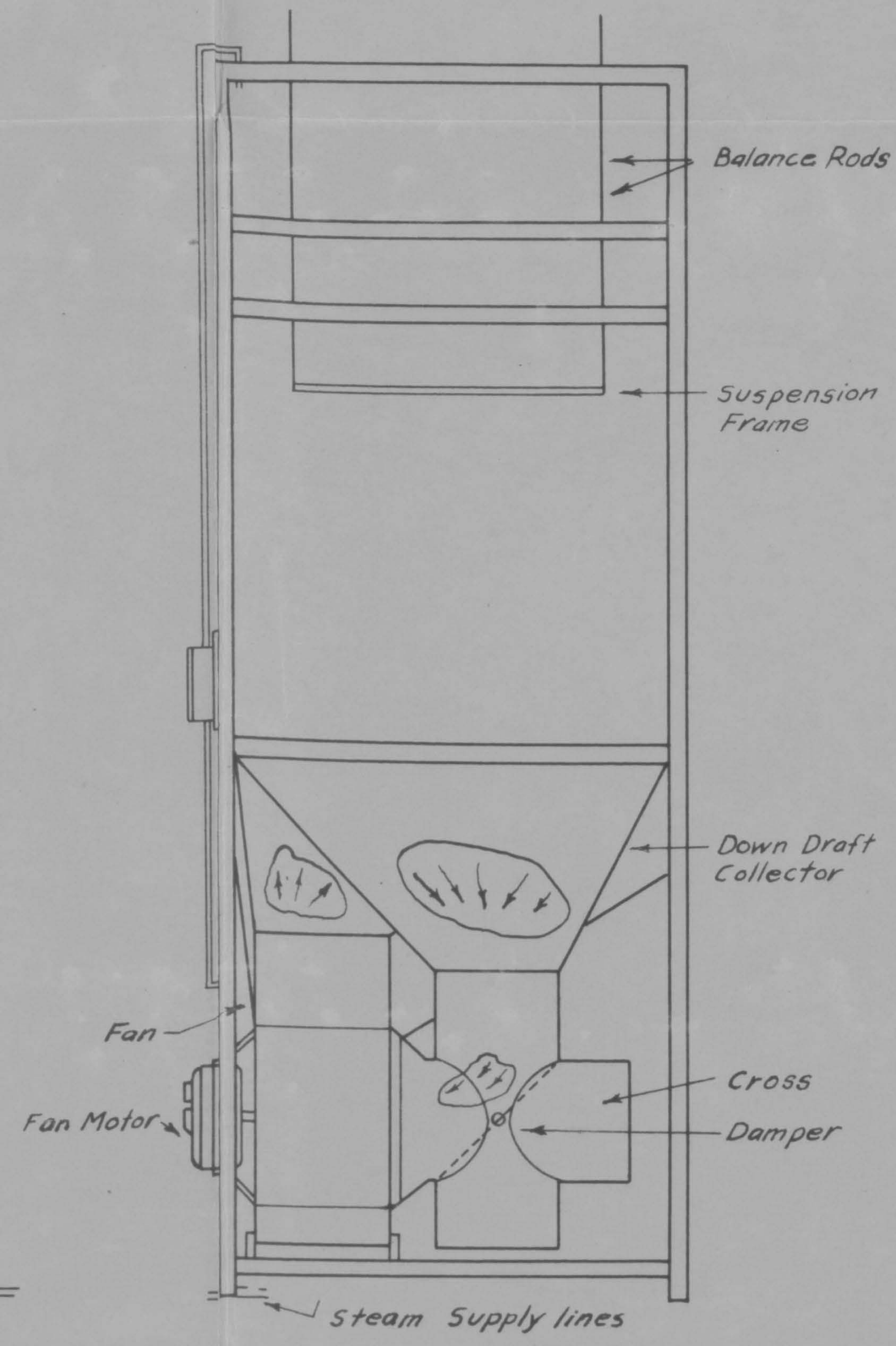
STEAM SUPPLY DETAIL

Showing Humidification Control



Front View With Door and Panels Removed

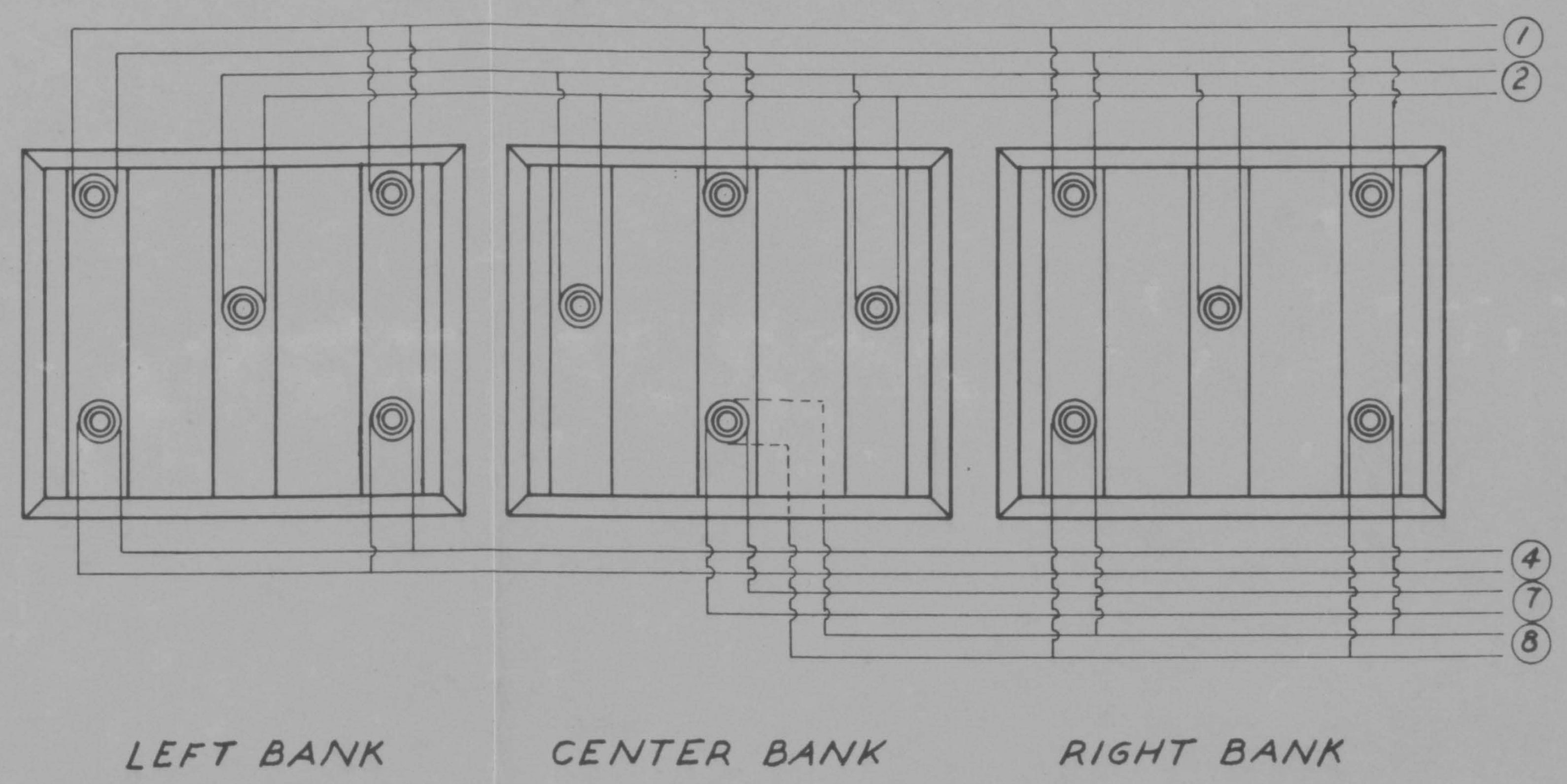
See Detail { ① Steam Control
② Heating Control Panel
③ Balance Mount



LEFT SIDE VIEW – PANELS OFF

Note – Pump View Omitted

See Detail { ① Duct Cross
② Heating Coil



REHEATING COIL DETAIL

Showing heating element arrangement, etc.

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF CHEMICAL ENGINEERING
BLACKSBURG, VA.
APRIL 5, 1939

DETAIL AND ASSEMBLY OF CONDITIONED AIR DRYER

EMPLOYED IN 1938 TOBACCO DRYING

DESIGNED BY – C.D.D. – A.H.C. – H.B.S.
DRAWN BY – H.B. SMITH
TRACED BY – " " "
CHECKED BY – DR. A.H. COOPER A.H.C.

ter heating. The steam line was suitably dripped before reaching the needle control valve.

Water: Water was drawn from the water main located in the Chemical Engineering Main Laboratory, which was supplied at 90 pounds per square inch pressure. It was used for dehumidification and spray humidification of the air.

Apparatus

The Dryer: The dryer(see Plate I) consists of a cabinet, bypass, tempering coil, spray chamber, reheating coil, and distributing tunnel. It is constructed of 1¼ inch cross beams, and is braced both laterally and horizontally with suitable diagonal beams. The frame is covered with 20 pound galvanized sheet iron, arranged in sections, which are covered with ½ inch celotex in panels, thus facilitating ready access to the interior. All cornices are covered with 2 inch angle iron, and all joints are overlapped with 1¼ inch strap iron. The dryer is constructed in accordance with the design shown in Plate II.

Blower: The blower (Plate I) was of the constant speed, centrifugal type, the motor being rated at ¼ H.P., 1725 R.P.M., 220 volts, 3 phase, 60 cycles. The blower was connected on the intake side to a cross equipped with a damper, thus facilitating total, part, or no recirculation. The exhaust side lead directly to the top of the tempering coil bank.

Spray Pump: The pump (Plate I) was of the centrifugal volute type which was belt driven from a small a.c. motor. The pump was rated at 30 feet head at 1720 R.P.M. The motor was rated at ¼ H.P., 1750 R.P.M., 7.8 a.c. amps., 110 volts, single phase, 60 cycles. The pump supplied spray water for the humidification spray. Line valves were employed, thus facilitating part, total, or no recirculation of the water.

Heating Elements: Two banks (Plate I) of electrical heating elements were employed, one being a tempering bank, and the other being a reheating bank. These elements were of the radiant bowl type, mounted with screwed socket and unglazed porcelain frame, rated at 660 Watts and 105-120 volts.

The tempering bank was equipped with nine heating elements, met by a downward air draft. The heating bank was equipped with eighteen heating elements met by a rising stream of air.

Wiring: The wiring (Plate I, Detail 2) was arranged to a control panel, which was equipped with three switch boxes, and five plug switches. Two reheating circuits of six elements each were connected to two of the switch boxes. The third switch box controlled a tempering circuit of four elements. Two reheating circuits of two elements each were connected to two of the plug switches. One reheating element was attached to one of the plug switches, while the remaining element was connected to an automatic temperature controller. Two tempering circuits of two elements each were connected to the remaining plug switches. The remaining tempering element was connected to an automatic temperature controller. Thus, any combination of heating elements could be employed.

Controls: Temperature control (Plate I, Detail 1) was facilitated by two Precision Temperature Regulators, which were of the organic vapor activated, mercury contact, relay type. Each of these was rated at 115 volts, 10 a.c. amps., and 60 cycles. Their advertised accuracy was within 1/50 deg. C. The sensitive elements were suspended from the top of the dryer at two representative points by means of a removable porthole. Humidity regulation was facilitated at high humidities by a manually operated needle valve. Low humidities were regulated by a globe valve on the water spray pump line, and by a needle valve on the water tank heating coil.

Anemometer: The anemometer used was of the whirling vane type, having a four inch diameter. The instrument was manufactured and calibrated by the J. P. Frietz and Sons Company, and measured feet traveled by moving air. Velocities were determined in the cabinet of the dryer at five different positions.

Balance: The balance used (Plate I, Detail 1) was of twenty-one kilogram capacity of the pulp balance type, manufactured for the Fisher Scientific Company, and equipped with a tare weight neutralizer. The balance was mounted on top of the dryer, the pan supporting a light angle iron frame. Four jointed copper rods were suspended from this frame, and passed through the dryer. The tobacco support frame was attached to these rods on the inside of the dryer. The tobacco was strung on sticks, and the sticks were mounted in balanced positions on the rod frame.

Timing: The watch used for all time records was a Bulova Lincoln wrist watch, which was equipped with a second hand.

Thermometry: Wet and dry bulb thermometers were mounted on a parallel frame, which was suspended by a tension wire from movable arms, thus facilitating location in the best position for reading without obstructing the cabinet entrance. The wet bulb was covered with a light bunting wick, which was automatically fed from a water tank on top of the dryer.

Procedure

Preliminary Operations: The air was initially set in motion by starting the motor, such procedure being executed to prevent excessive heating of the radiant electrical elements. The air velocity and rate of recirculation were set in accordance with the run schedule. The wet and dry bulb thermostatic regulators were set to approach the air conditions required for the run.

The dryer was allowed to run until the desired equilibrium conditions were reached. In the meantime, tobacco of the desired stalk position and degree of ripeness was harvested. This was strung on sticks with cotton twine, and held in readiness for installation.

The dryer was re-checked, and the desired conditions and balance were exactly adjusted. The tobacco sticks were then installed in parallel on the rod frame as rapidly as possible, by means of the dryer door. An initial reading was immediately made.

Air Conditions: The air conditions were determined by the schedule of runs, as deemed advisable for the most thorough examination of the curing process. Relative humidity was set by the wet bulb temperature, which was determined by the temperature - humidity relationships given by the Carrier Psychromatic Chart. Air velocity was adjusted by the per cent free space on the down draft distributing plate.

Water was used to dehumidify the air in the third period by means of the cold water spray, and to facilitate rapid adiabatic humidification in the ordering period. In addition, it was found that if the spray tank were allowed to contain water at a three inch level, an excellent damping effect was set up, thus preventing sudden changes in the air conditions due to faulty operation of the control instruments.

Steam was used to provide air humidification in the first, second, and fourth periods. It was introduced by a diffusing nozzle in such a manner as to roll into the air stream. The relative humidity was controlled by a needle valve connected on the steam line.

Recirculation of Air: Air recirculation was facilitated by means of a duct cross which was equipped with a damper. Thus, total, partial, or no recirculation could be effected by proper adjustment of the damper. During periods of high humidity, complete recirculation was employed. At high temperatures and low relative humidities, about 50 per cent of the air was recirculated.

Data Taken During One Run: The initial data taken during each run consisted of the following:

(1) The green weight of the tobacco and sticks

(2) The dry bulb temperature

(3) The wet bulb temperature

(4) The air velocity in the cabinet

(5) The time of tobacco installation

Readings were made at intervals of one hour during the first part of the yellowing period, and every two hours during the remainder of the time, excepting transition periods when readings were made immediately before and just after attaining the new condition.

Further data concerning the drying rates was periodically taken in the following order:

(1) The weight of the tobacco and sticks

(2) The time of the reading

(3) The dry bulb temperature

(4) The wet bulb temperature

Notes were taken during each run with regard to the appearance of the tobacco, and the manner of dryer operation.

A check of the switchboard, blower, and wet bulb water supply was made at each interval. Oiling and other minor adjustments were periodically attended.

The time of each period was determined by the following method:

(1) End of Period One -- 75 per cent of the leaf area yellowed

(2) End of Period Two -- color and appearance developed

(3) End of Period Three - drying rate approaches zero

(4) End of Period Four - leaf becomes flexible

IV. RESULTS

Results: The results of the experiments are presented in the following tables and curves. Runs One and Two show the difficulty of obtaining reliable data under manually operated conditions. In addition, they are below the curing range, and are the result of an endeavor to come into this range. Runs Three, Four, Five, and Six compose the temperature series, according to Schedule I. Runs Four, Seven, Eight, and Nine compose the humidity series, according to Schedule II. Run Ten was of a composite nature, and run according to Schedule III. Runs Eleven, Twelve, Thirteen, and Fourteen compose the velocity series, and are presented in XVIII. Table I and Figure 1 represent the relation between the green and dry weight of tobacco.

Basis of Calculation: All drying rate curves are plots of the drying rate versus the water content of the leaf averaged over the same time interval. The basis of all curves is the bone dry weight, which was determined by the equation $W = 6.075 E$. All curing curves are plots of the instantaneous water content versus time.

The Effect of The Air Conditions: The essential results of the investigation are presented in tables and figures Eleven through Eighteen.

The drying rate was found to vary with the water content, temperature, relative humidity, and the air velocity. Temperature played an exaggerated part in the drying rate during the first few hours of curing. The maximum temperature that could be employed without killing the tobacco was found to be 110 deg. F, while the optimum range was between 95 and 105 deg. F.

Relative humidity was found to play an important part in the initial stages of curing. However, its importance gradually and progressively decreased with a decrease in water content. The minimum relative humidity was found to be 75 per cent, while the best range was found to be between 80 and 85 per cent relative humidity.

The maximum air velocity was found to be 90 feet per minute. Velocity has little effect on the drying rate in the initial stages of curing, and a negligible effect in the final stages.

The feasibility of air conditioning methods appeared in that the time required for curing a uniform optimum product varied between 48 and 50 hours, thus indicating large savings in labor and fuel.

TABLE 1

GREEN AND BONE DRY WEIGHTS OF TOBACCO LEAVES

Bone dry weights determined at 178 deg. F. and 5% relative humidity when no further loss in weight was observed.

Green Weight Grams	Dry Weight Grams	Green Weight (corrected)	Dry Weight (corrected)
2,529	518	2,339	328
2,826	578	2,636	388
3,800	711	3,610	521
4,322	913	4,132	723
3,356	693	3,166	503
3,885	763	3,695	573
3,360	726	3,170	536
3,612	753	3,422	563
2,478	572	2,288	382
1,850	500	1,660	310
3,100	730	2,910	540
1,187	289	1,108	211
1,152	288	1,074	210
1,296	312	1,218	234
1,297	332	1,219	253

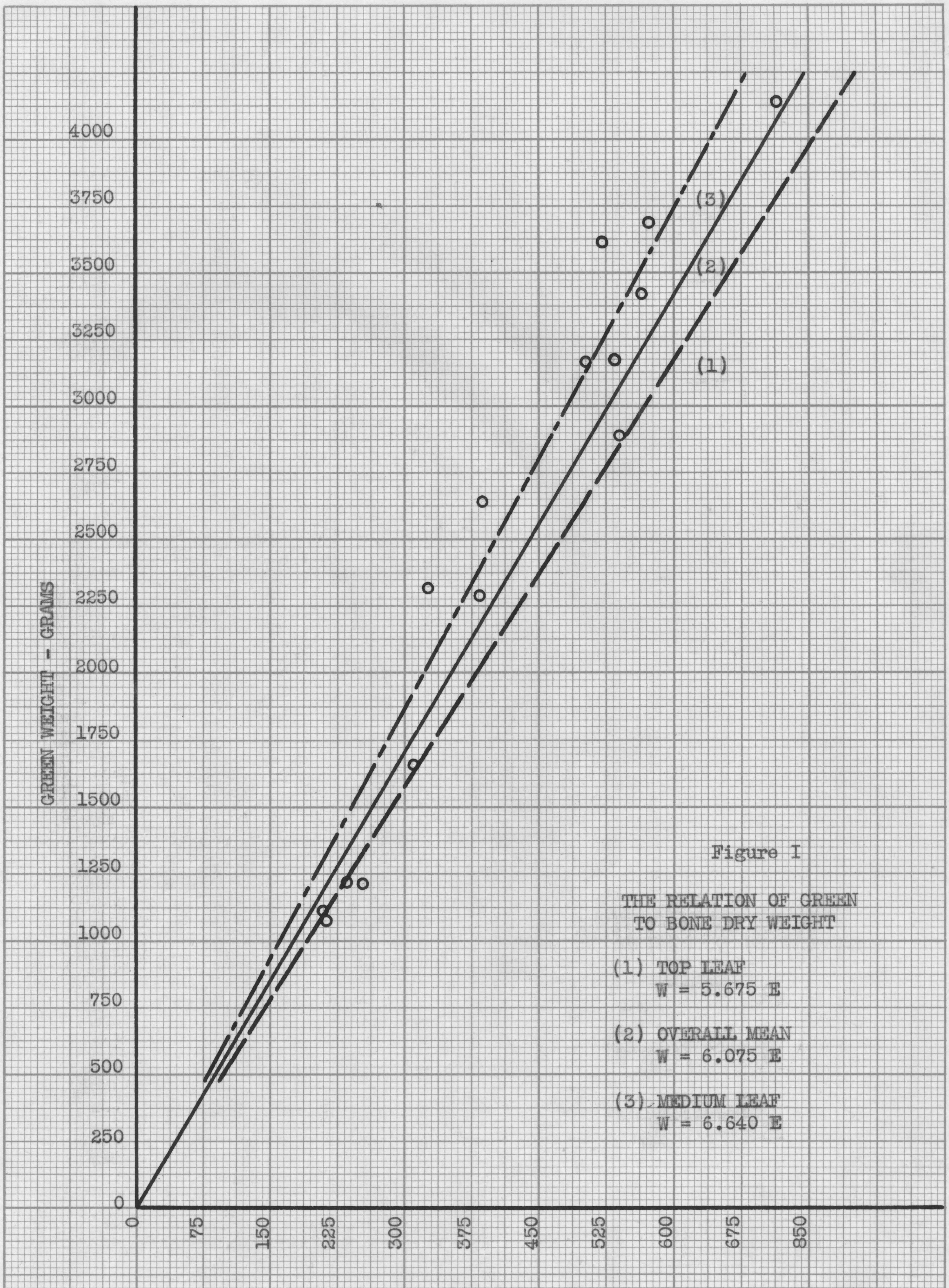


Figure I

THE RELATION OF GREEN TO BONE DRY WEIGHT

(1) TOP LEAF
W = 5.675 E

(2) OVERALL MEAN
W = 6.075 E

(3) MEDIUM LEAF
W = 6.640 E

TABLE II

DRYING RATE OF TOBACCO

RUN NUMBER ONE MANUAL OPERATION INITIAL RUN

BONE DRY WEIGHT 417 GRAMS LEAF FAILED TO CURE

Time Hr.	Weight Gm.	Temperature °F Wet Bulb	Temperature °F Dry Bulb	Wt. Loss Gm.	Total Water Gm.	Water Cont. G/G*	Drying Rate $\frac{\text{Gm. water}}{(\text{Gm.})(\text{Hr.})}$
0.00	2,529	86.0	103.0	000	2,112	5.070	0.000
0.50	2,256	87.0	112.0	273	1,839	4.442	1.310
1.00	2,054	84.5	110.0	202	1,637	3.930	0.970
1.50	1,914	85.0	114.0	140	1,497	3.600	0.673
2.00	1,809	83.0	108.0	105	1,392	3.342	0.504
2.50	1,714	85.0	114.0	95	1,298	3.115	0.457
3.00	1,633	83.0	111.0	81	1,216	2.917	0.389
3.50	1,400	88.0	119.0	233	983	2.358	1.117
4.00	1,329	88.0	118.0	71	912	2.190	0.341
4.50	1,260	85.0	113.2	69	843	2.022	0.331
5.50	1,206	97.0	112.0	54	789	1.895	0.130
6.50	1,161	88.0	112.0	45	744	1.782	0.108
7.00	1,145	88.0	113.0	16	728	1.745	0.077
7.50	967	101.0	176.0	178	550	1.320	0.855
8.00	817	101.0	178.0	150	400	0.962	0.721
8.50	732	101.0	172.0	85	315	0.756	0.408
9.37	623	100.0	162.0	109	206	0.495	0.302
10.50	552	98.0	160.0	71	135	0.324	0.150
11.50	518	101.0	166.0	34	101	0.243	0.082
12.00	520	101.0	166.0	-2	103	0.248	-0.010
12.63	518	85.0	112.0	2	101	0.243	0.010

G/G* Grams of water remaining per gram dry weight

$\frac{\text{Gm. water}}{(\text{Gm.})(\text{Hr.})}$ Grams water evaporated per gram dry weight per hr.

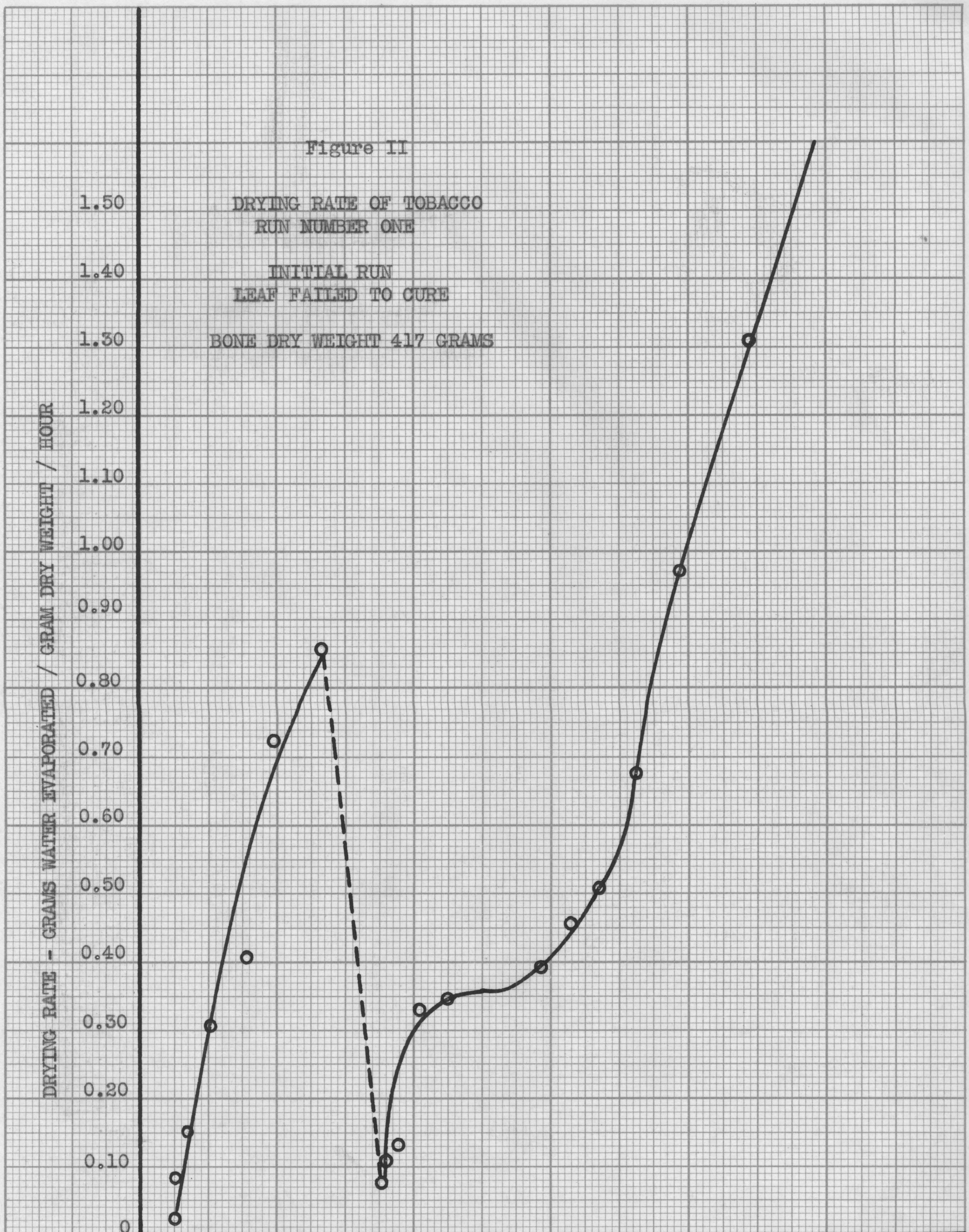
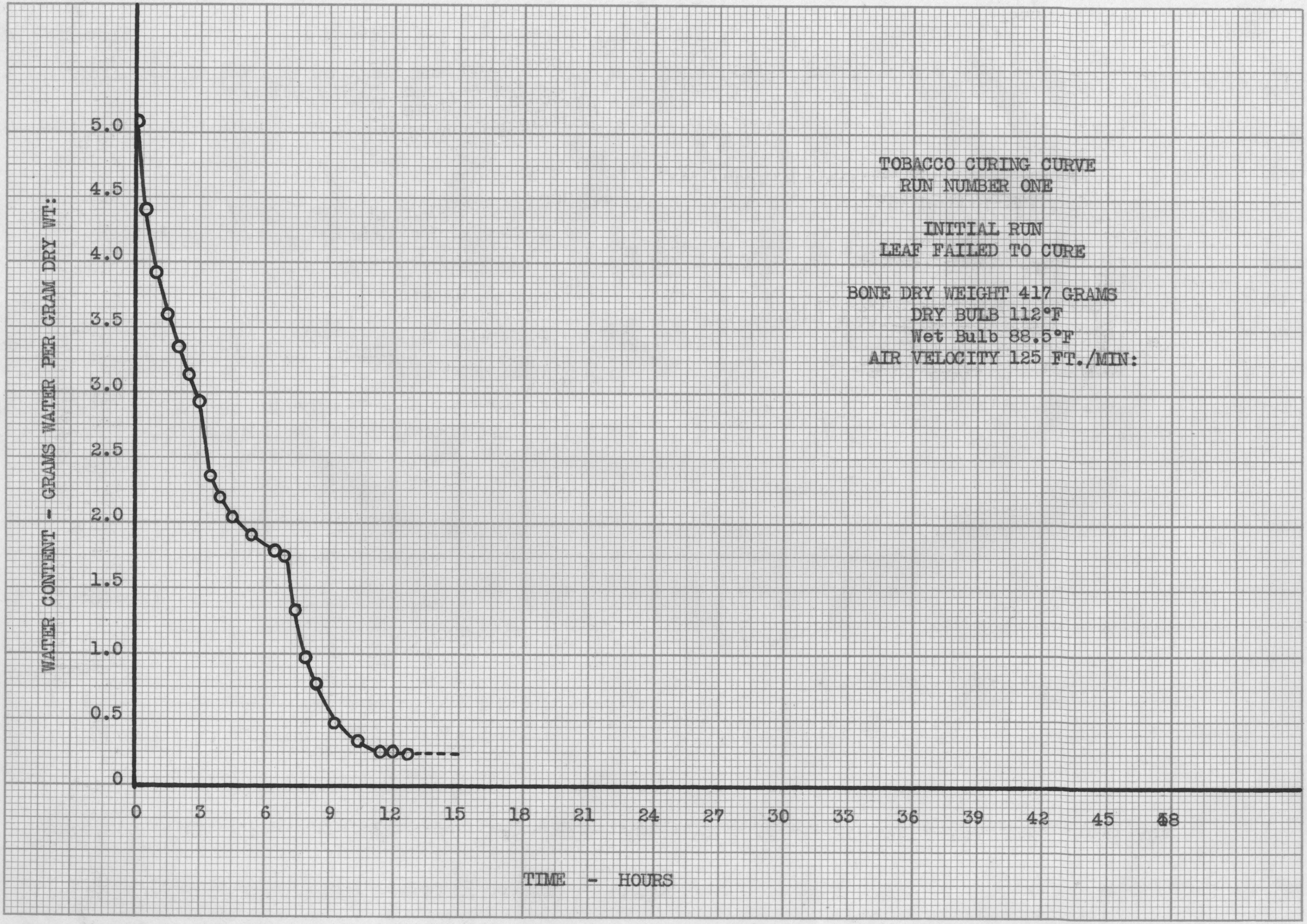


Figure II

DRYING RATE OF TOBACCO
RUN NUMBER ONE

INITIAL RUN
LEAF FAILED TO CURE

BONE DRY WEIGHT 417 GRAMS



TOBACCO CURING CURVE
RUN NUMBER ONE

INITIAL RUN
LEAF FAILED TO CURE

BONE DRY WEIGHT 417 GRAMS
DRY BULB 112°F
Wet Bulb 88.5°F
AIR VELOCITY 125 FT./MIN:

TABLE III

DRYING RATE OF TOBACCO

RUN NUMBER TWO MANUAL OPERATION INITIAL RUN

BONE DRY WEIGHT 466 GRAMS LEAF FAILED TO CURE

Time Hr.	Weight Gm.	Temperature °F: Wet Bulb	Dry Bulb	Wt. Loss Gm.	Total Water Gm.	Water Cont. G/G*	Drying Rate Gm. water / (Gm.)(Hr.)
0.00	2,826	102.0	112.0	000	2,360	5.070	0.000
0.50	2,654	101.0	110.0	172	2,188	4.700	0.740
1.00	2,500	101.0	110.0	154	2,034	4.370	0.662
1.50	2,394	106.0	116.0	106	1,928	4.130	0.456
2.00	2,285	104.0	115.0	109	1,819	3.910	0.468
2.50	2,214	100.0	109.0	71	1,748	3.760	0.305
3.02	2,153	100.0	117.0	61	1,687	3.620	0.254
3.50	2,097	102.0	113.0	56	1,631	3.500	0.249
4.00	2,043	99.0	106.0	54	1,577	3.385	0.232
5.00	2,000	97.0	103.0	43	1,534	3.295	0.093
6.00	1,914	103.0	114.0	86	1,448	3.110	0.184
7.00	1,855	91.0	96.0	59	1,388	2.982	0.127
8.00	1,803	98.0	108.0	52	1,337	2.870	0.115
9.28	1,576	102.0	115.0	227	1,110	2.387	0.380
10.07	1,538	96.0	109.0	38	1,072	2.300	0.104
11.00	1,496	93.0	106.0	42	1,030	2.215	0.965
12.00	1,437	99.0	112.0	59	971	2.082	0.127
13.00	1,382	97.0	113.0	55	916	1,965	0.118
14.00	1,293	91.0	121.0	89	827	1.772	0.191
15.00	1,249	98.0	115.0	44	783	1.680	0.095
16.00	1,227	98.0	107.0	22	761	1.631	0.047
17.00	988	98.0	159.0	239	522	1.119	0.513
19.15	578	102.0	183.0	410	112	0.241	0.410

G/G* Grams of water remaining per gram dry weight

$\frac{\text{Gm. water}}{(\text{Gm.})(\text{Hr.})}$ Gm. water evaporated per gm. dry weight per Hr.

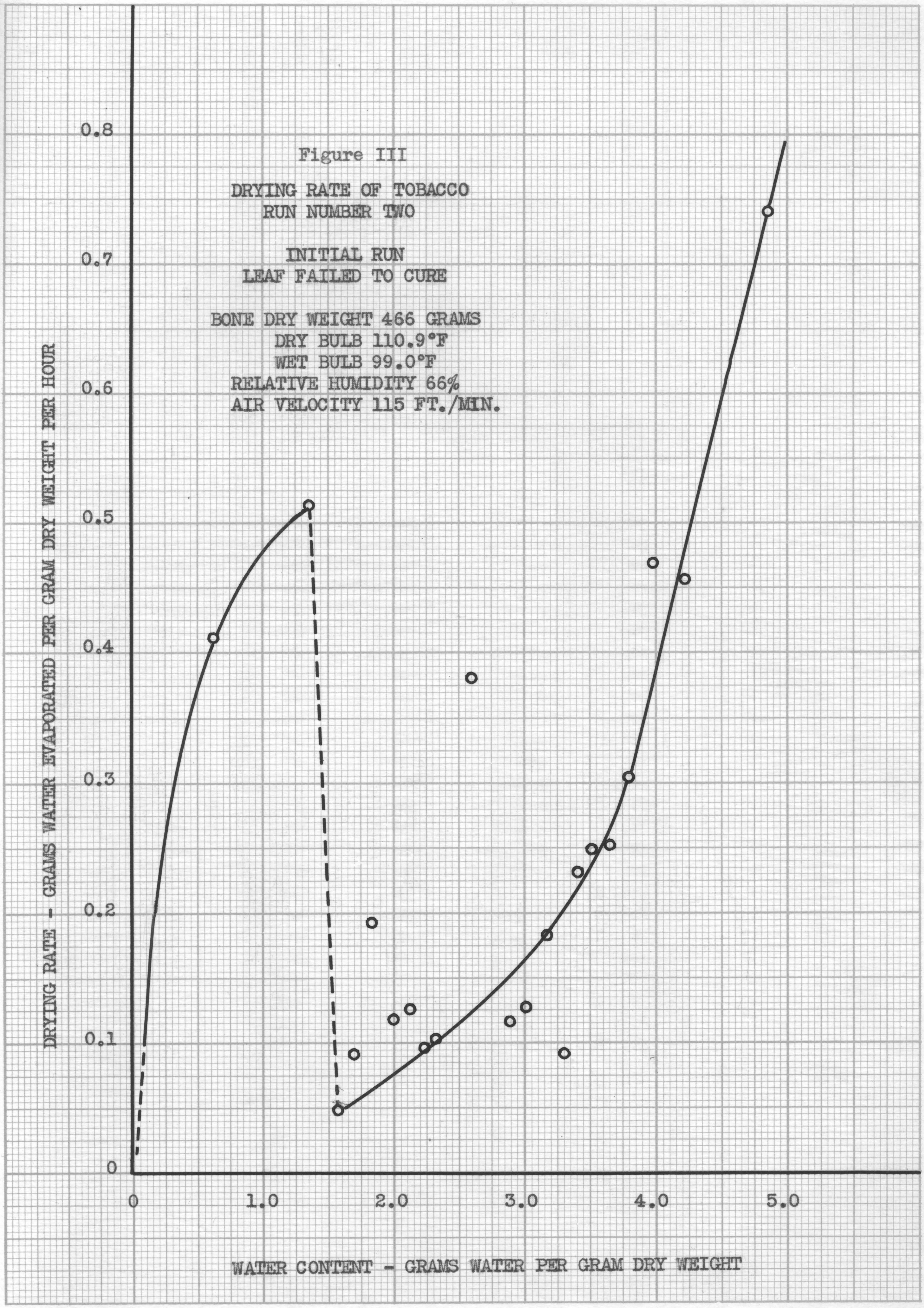
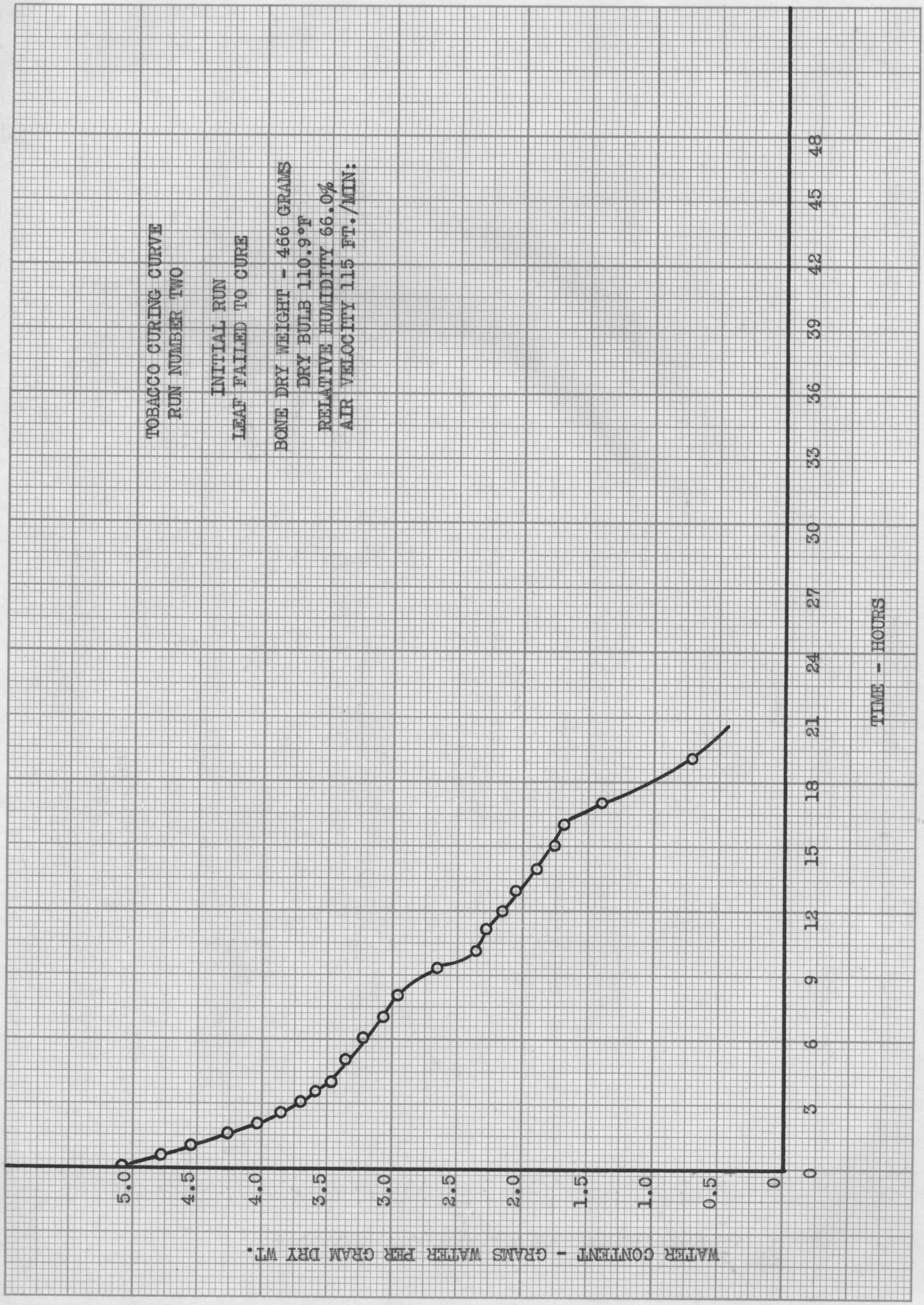


Figure III

DRYING RATE OF TOBACCO
RUN NUMBER TWO

INITIAL RUN
LEAF FAILED TO CURE

BONE DRY WEIGHT 466 GRAMS
DRY BULB 110.9°F
WET BULB 99.0°F
RELATIVE HUMIDITY 66%
AIR VELOCITY 115 FT./MIN.



TOBACCO CURING CURVE
RUN NUMBER TWO

INITIAL RUN
LEAF FAILED TO CURE

BONE DRY WEIGHT - 466 GRAMS
DRY BULB 110.9°F
RELATIVE HUMIDITY 66.0%
AIR VELOCITY 115 FT./MIN.

TABLE IV

DRYING RATE OF TOBACCO

RUN NUMBER THREE 110 DEG. F.- TEMPERATURE SERIES

BONE DRY WEIGHT 626 GRAMS VELOCITY 115 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Cont. *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
PERIOD ONE: Av. Temp. - 110°F. :: Av. Rel. Humidity - 85%						
0.000	3800	000	3174	5.070	5.070	0.000
0.500	3590	210	2964	4.740	4.805	0.672
1.000	3371	218	2745	4.380	4.560	0.697
1.500	3220	151	2594	4.140	4.260	0.483
2.000	3086	134	2460	3.930	4.035	0.306
2.500	3039	181	2413	3.850	3.890	0.289
3.000	2971	68	2345	3.750	3.800	0.217
3.500	2899	72	2273	3.630	3.690	0.230
4.000	2827	72	2201	3.520	3.575	0.230
5.000	2719	108	2093	3.340	3.430	0.173
6.330	2552	167	1926	3.080	3.210	0.201
7.000	2500	52	1874	3.000	3.040	0.125
8.000	2415	85	1789	2.860	2.930	0.136
9.000	2316	99	1690	2.700	2.780	0.158
10.000	2263	53	1637	2.620	2.660	0.085
11.000	2202	61	1576	2.520	2.570	0.098
12.000	2143	59	1517	2.420	2.470	0.094
13.000	2098	45	1472	2.350	2.385	0.072
14.000	2038	60	1412	2.260	2.305	0.096
15.000	1970	68	1344	2.150	2.205	0.108
16.000	1930	40	1304	2.090	2.120	0.064
17.000	1892	38	1266	2.020	2.055	0.061
18.000	1860	32	1234	1.970	1.995	0.051
19.000	1831	29	1205	1.930	1.950	0.046
20.000	1785	46	1159	1.860	1.895	0.073
21.000	1759	26	1133	1.810	1.835	0.042
22.000	1724	35	1098	1.760	1.795	0.056
23.000	1700	24	1074	1.720	1.740	0.384

(OVER)

TABLE IV

DRYING RATE OF TOBACCO

RUN NUMBER THREE 110 DEG. F.- TEMPERATURE SERIES

BONE DRY WEIGHT 626 GRAMS VELOCITY 115 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
24.000	1685	15	1059	1.700	1.710	0.024
25.000	1652	33	1026	1.640	1.670	0.053
26.000	1628	24	1002	1.600	1.620	0.038
27.000	1607	21	981	1.570	1.585	0.034
28.000	1584	23	958	1.530	1.550	0.037
29.000	1565	19	939	1.502	1.516	0.031
30.000	1548	17	922	1.470	1.486	0.027
31.000	1531	17	905	1.445	1.458	0.027
32.000	1508	23	882	1.407	1.426	0.037
33.000	1500	8	874	1.385	1.401	0.013
34.000	1485	15	857	1.368	1.382	0.024
PERIOD TWO: Av. Temp.- 122 Deg.F.:: Av. Rel. Humidity- 50%						
35.000	1460	25	834	1.335	1.352	0.040
36.000	1367	93	741	1.182	1.259	0.149
37.167	1303	64	677	1.080	1.131	0.102
38.498	1249	55	623	0.997	1.039	0.088
39.665	1214	35	588	0.940	0.969	0.056
39.998	1200	14	574	0.918	0.929	0.023
41.000	1188	12	562	0.898	0.908	0.019
42.000	1158	30	532	0.850	0.874	0.048
PERIOD THREE: Av. Temp.-175°F. :: Av. Rel. Humidity - 7%						
43.000	852	306	226	0.361	0.606	0.490
44.000	740	112	114	0.183	0.272	0.179
45.000	711	29	85	0.135	0.159	0.046
45.750	700	11	74	0.118	0.127	0.018

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per hr.

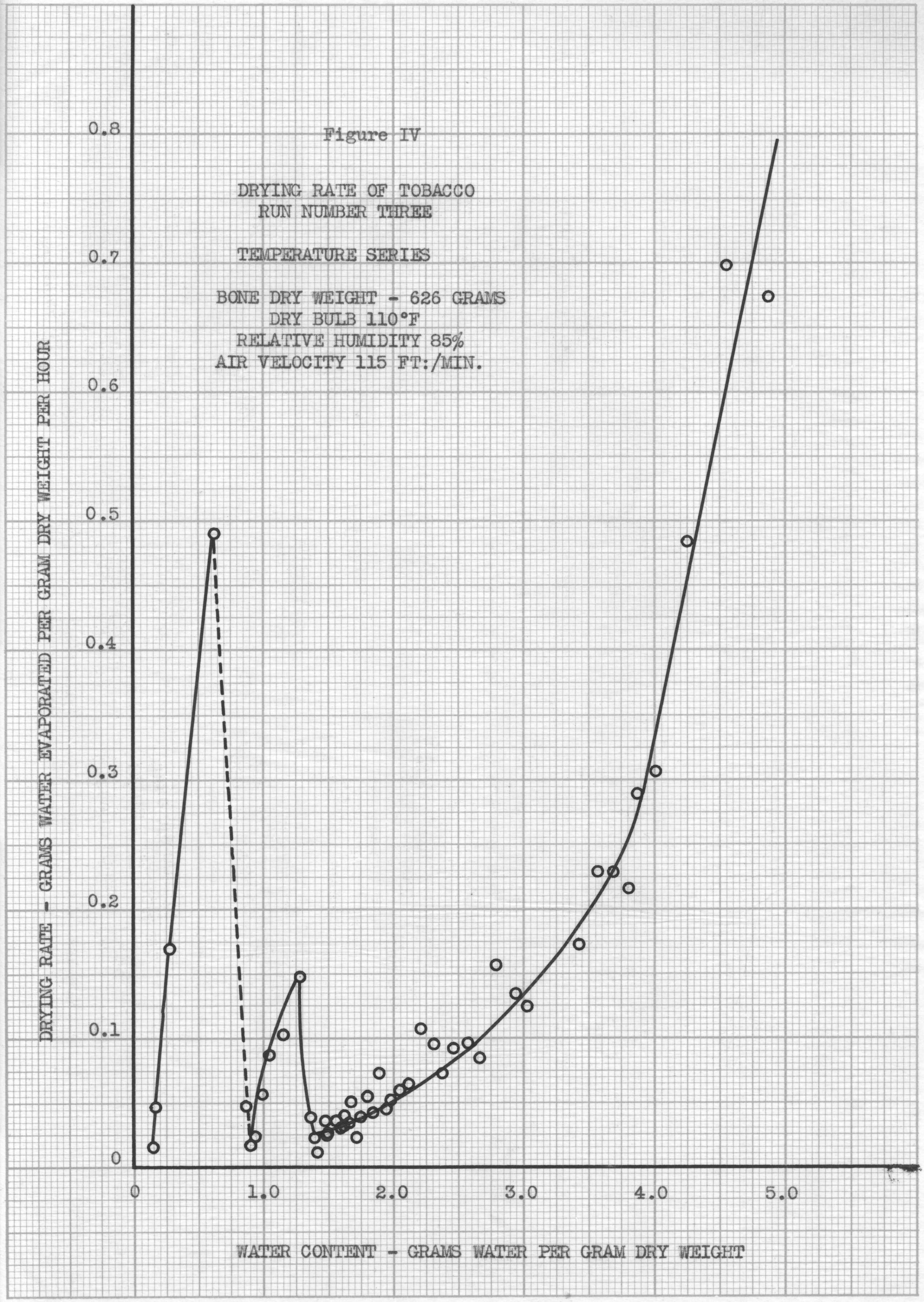


Figure IV

DRYING RATE OF TOBACCO
RUN NUMBER THREE

TEMPERATURE SERIES

BONE DRY WEIGHT - 626 GRAMS
DRY BULB 110°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 115 FT:/MIN.

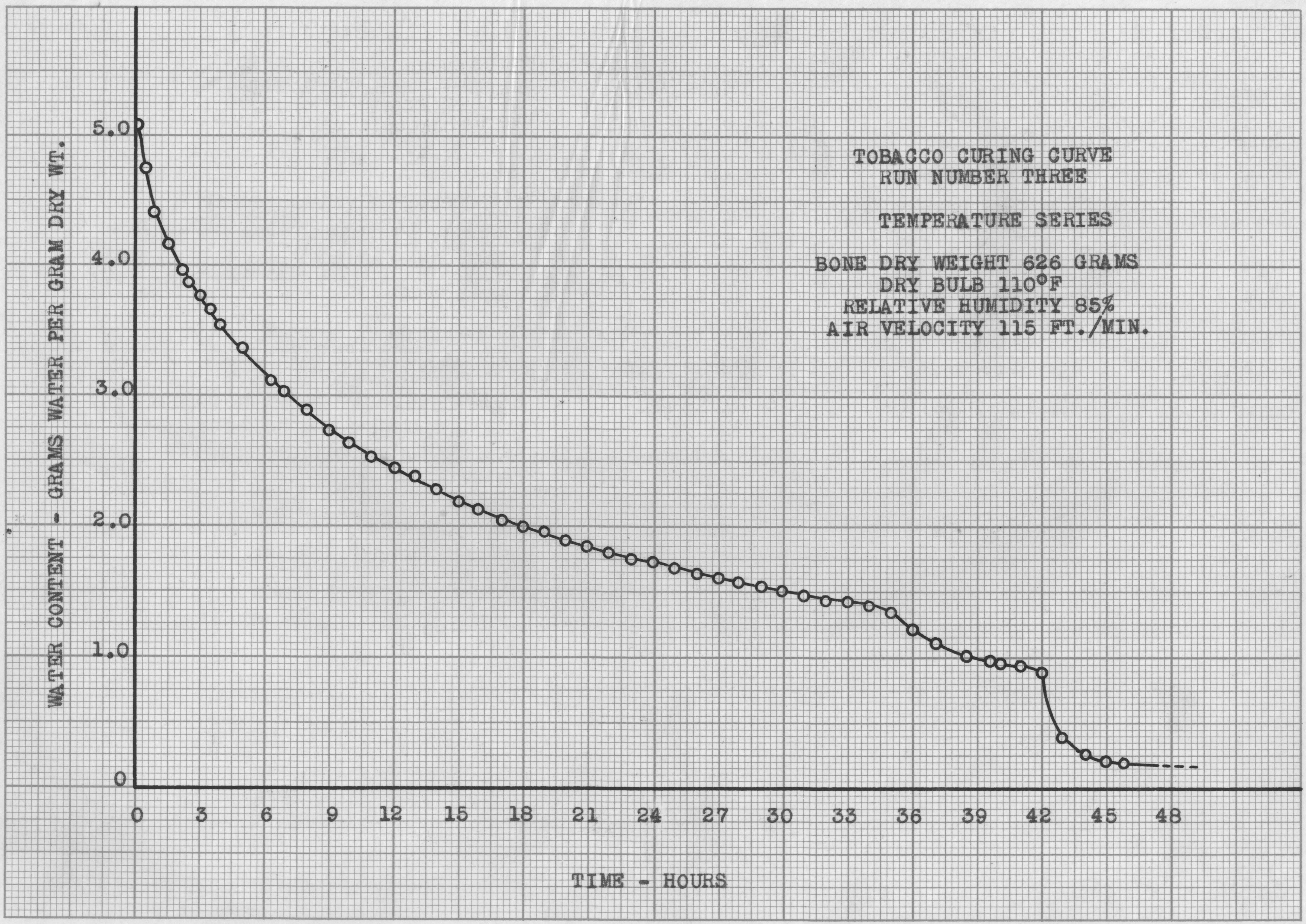

TOBACCO CURING CURVE
RUN NUMBER THREE
TEMPERATURE SERIES
BONE DRY WEIGHT 626 GRAMS
DRY BULB 110°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 115 FT./MIN.
WATER CONTENT - GRAMS WATER PER GRAM DRY WT.
5.0
4.0
3.0
2.0
1.0
0
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
TIME - HOURS

TABLE V

DRYING RATE OF TOBACCO

RUN NUMBER FOUR 95 DEG. F.- 85% REL. HUMIDITY

BONE DRY WEIGHT 712 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
0.000	4322	000	3610	5.070	5.070	0.000
0.583	4281	41	3569	5.020	5.045	0.099
0.916	4260	21	3548	4.980	5.000	0.089
1.249	4235	25	3523	4.960	4.970	1.055
1.749	4200	35	3488	4.905	4.933	0.098
2.249	4180	20	3468	4.870	4.888	0.056
2.749	4135	35	3423	4.820	4.845	0.098
3.249	4105	30	3393	4.770	4.795	0.084
3.749	4080	25	3368	4.730	4.750	0.070
4.749	4001	79	3289	4.620	4.675	0.111
5.749	3935	66	3223	4.530	4.575	0.093
6.749	3857	78	3145	4.425	4.478	0.110
7.749	3790	67	3078	4.330	4.380	0.094
9.749	3669	121	2957	4.160	4.245	0.085
10.749	3605	64	2893	4.070	4.215	0.090
11.999	3538	67	2826	3.975	4.023	0.075
12.750	3493	45	2781	3.910	3.943	0.084
13.750	3442	51	2730	3.840	3.875	0.072
14.750	3378	64	2666	3.750	3.795	0.089
15.750	3326	52	2614	3.675	3.713	0.073
17.000	3267	59	2555	3.590	3.633	0.066
17.750	3230	37	2518	3.540	3.565	0.069
18.750	3180	50	2468	3.475	3.508	0.070
19.750	3137	43	2429	3.415	3.445	0.060
20.750	3094	43	2382	3.353	3.384	0.060
21.750	3053	41	2341	3.290	3.322	0.058
22.750	3010	43	2298	3.230	3.290	0.060
23.750	2968	42	2256	3.170	3.200	0.059
24.750	2928	40	2216	3.110	3.140	0.056

(OVER)

TABLE V

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER FOUR 95 DEG. F.- 85% REL. HUMIDITY

BONE DRY WEIGHT 712 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying Rate G/G/Hr.
25.750	2883	45	2171	3.050	3.110	0.063
26.750	2849	34	2137	3.005	3.023	0.048
28.000	2800	49	2088	2.940	2.973	0.055
PERIOD TWO: Av. Temp.- 112 Deg.F.:: Av. Rel. Humidity- 46%						
28.750	2683	117	1971	2.773	2.857	0.219
29.75033	2510	173	1798	2.530	2.652	0.243
33.750	2053	457	1341	1.888	2.209	0.159
34.750	1996	57	1284	1.806	1.847	0.080
35.883	1935	61	1223	1.720	1.763	0.079
36.750	1886	49	1171	1.652	1.686	0.075
37.750	1844	42	1132	1.593	1.623	0.059
38.750	1804	40	1092	1.537	1.565	0.056
39.250	1791	13	1079	1.520	1.529	0.037
PERIOD THREE: Av. Temp.-170 Deg.F.:: Av. Rel. Humidity- 8%						
39.750	1608	183	896	1.257	1.389	0.514
40.000	1520	88	808	1.135	1.196	0.494
40.800	1344	176	632	0.888	1.012	0.310
41.250	1210	134	498	0.701	0.795	0.418
42.350	980	125	268	0.376	0.465	0.378
43.350	920	32	208	0.293	0.315	0.090
43.850	913	7	201	0.282	0.287	0.020
PERIOD FOUR: Av. Temp.-112 Deg.F.:: Av. Rel. Humidity-94%						
44.183	958	-45	246	0.346	0.314	-0.190
44.516	990	-42	278	0.391	0.369	-0.177
44.849	1000	-10	288	0.405	0.398	-0.047

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per hr.

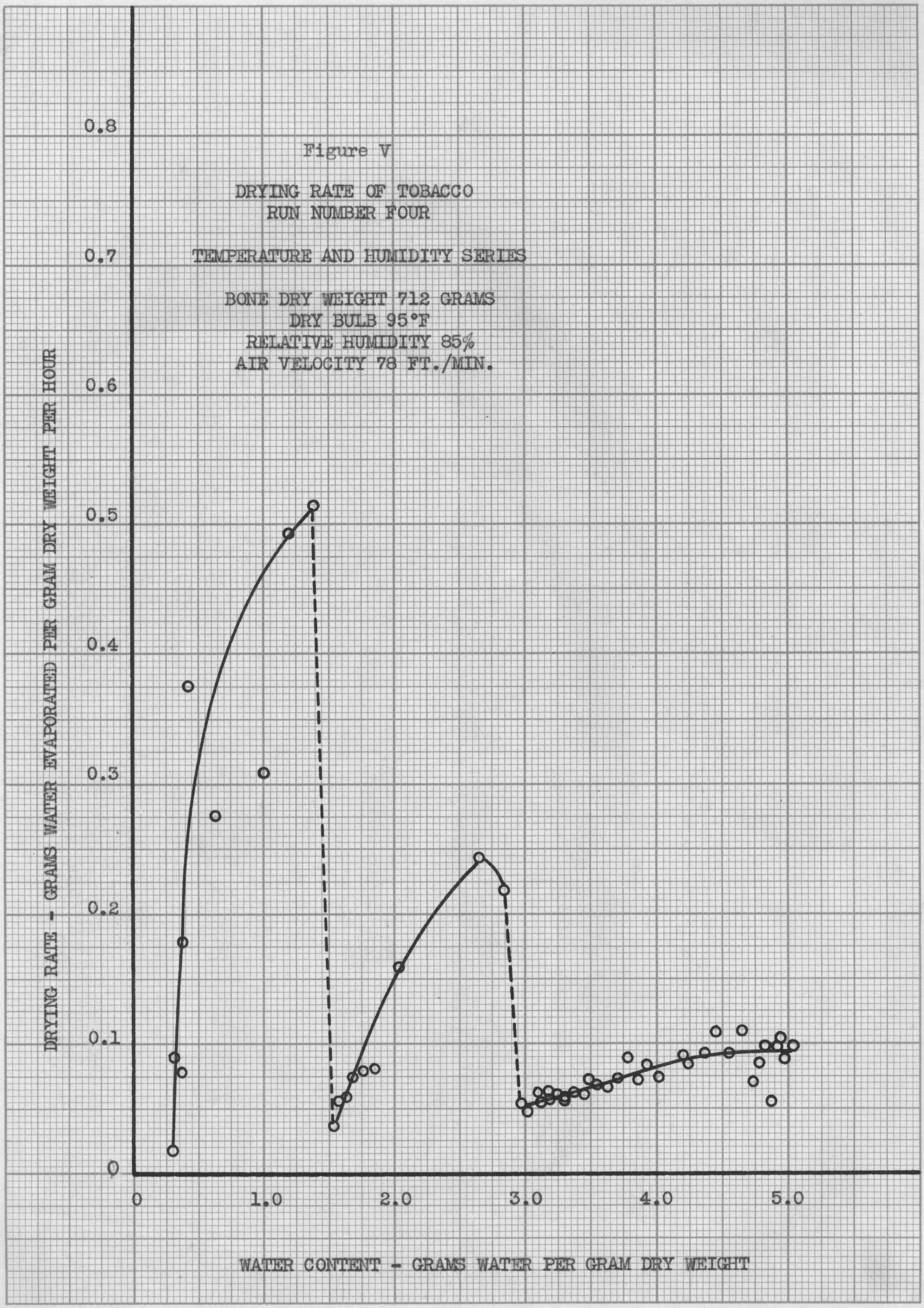


Figure V

DRYING RATE OF TOBACCO
RUN NUMBER FOUR

TEMPERATURE AND HUMIDITY SERIES

BONE DRY WEIGHT 712 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

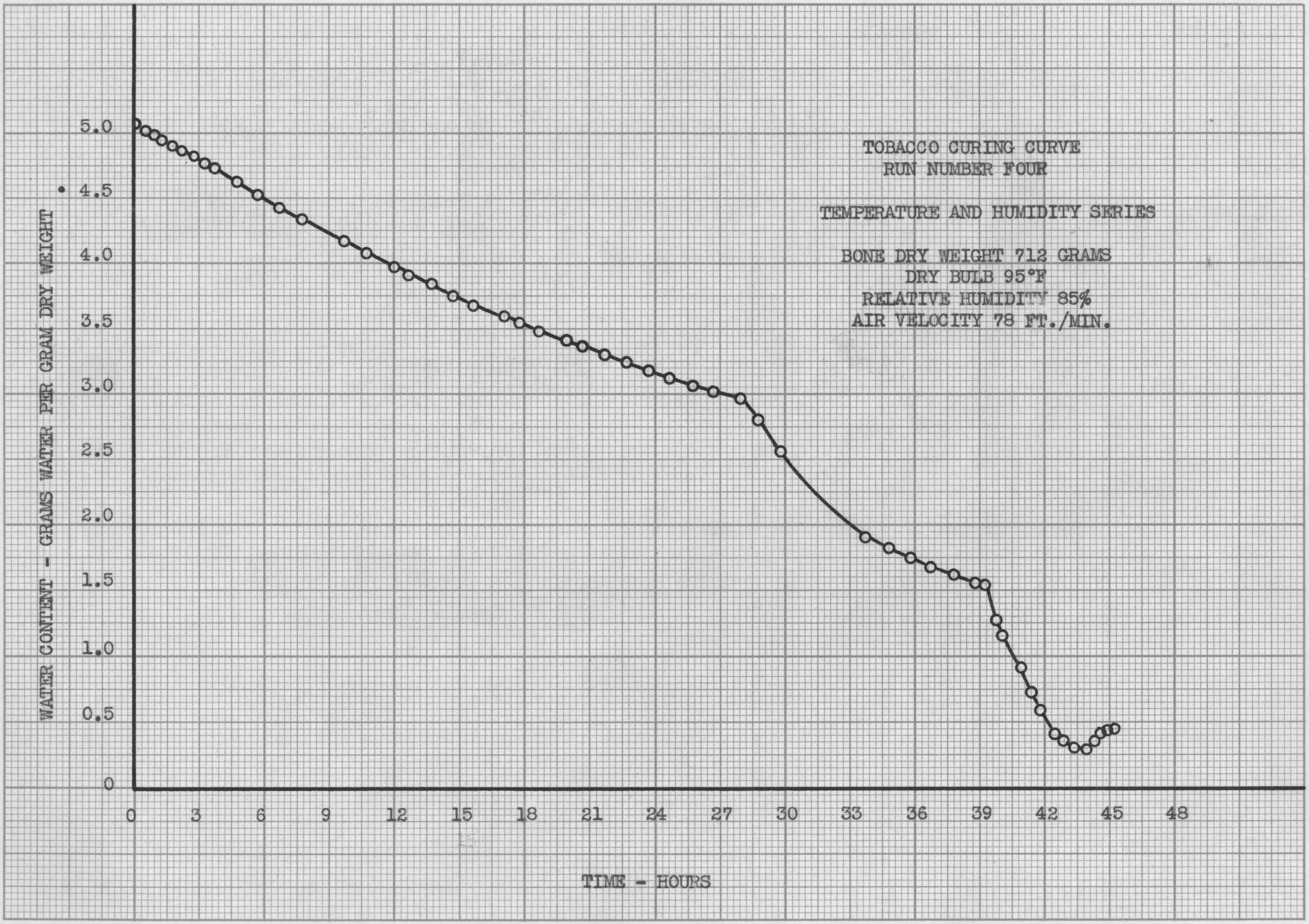

TOBACCO CURING CURVE
RUN NUMBER FOUR
TEMPERATURE AND HUMIDITY SERIES
BONE DRY WEIGHT 712 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.
WATER CONTENT - GRAMS WATER PER GRAM DRY WEIGHT
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
TIME - HOURS

TABLE VI

DRYING RATE OF TOBACCO

RUN NUMBER FIVE 100 DEG. F.- TEMPERATURE SERIES

BONE DRY WEIGHT 712 GRAMS VELOCITY 78 FEET PER MIN.

PERIOD ONE: Av. Temp. - 100°F. :: Av. Rel. Humidity - 85%

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
0.000	3356	000	2803	5.070	5.070	0.000
1.000	3262	94	2709	4.910	4.990	0.170
2.000	3190	72	2637	4.780	4.845	0.130
3.000	3125	65	2572	4.666	4.720	0.118
4.000	3056	69	2503	4.530	4.595	0.125
9.333	2700	356	2147	3.890	4.210	0.121
10.500	2625	75	2072	3.750	3.820	0.116
11.750	2570	55	2017	3.660	3.705	0.080
12.750	2510	60	1957	3.540	3.600	0.109
13.750	2460	50	1907	3.450	3.495	0.091
14.500	2420	40	1867	3.380	3.415	0.097
15.750	2370	50	1817	3.280	3.330	0.073
16.500	2330	40	1777	3.220	3.250	0.097
17.583	2278	52	1725	3.120	3.170	0.087
17.751	2245	33	1692	3.060	3.120	0.051
18.501	2210	35	1657	3.000	3.030	0.085
19.500	2164	46	1611	2.920	2.960	0.083
20.500	2128	36	1575	2.860	2.890	0.065
21.500	2096	32	1543	2.790	2.825	0.058
22.500	2055	41	1502	2.720	2.755	0.074
24.500	2001	54	1448	2.620	2.670	0.049
26.000	1963	38	1410	2.560	2.590	0.046
32.000	1814	149	1261	2.280	2.420	0.045
33.000	1803	11	1250	2.265	2.273	0.020
33.500	1800	3	1247	2.260	2.262	0.011

(OVER)

TABLE VI

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER FIVE   100 DEG. F.- TEMPERATURE SERIES

BONE DRY WEIGHT 553 GRAMS   VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
PERIOD TWO: Av. Temp. - 115°F. :: Av. Rel. Humidity - 49%						
34.000	1702	98	1149	2.080	2.170	0.355
34.500	1655	47	1102	2.000	2.040	0.170
35.500	1553	102	1000	1.810	1.905	0.185
36.500	1465	88	912	1.650	1.730	0.159
37.500	1400	65	847	1.532	1.591	0.118
38.500	1339	61	786	1.420	1.476	0.110
39.500	1310	29	757	1.370	1.395	0.053
40.500	1275	35	722	1.305	1.338	0.063
41.500	1250	25	697	1.260	1.283	0.045
42.500	1220	30	667	1.208	1.234	0.054
43.417	1191	29	638	1.153	1.109	0.057
43.784	1183	8	630	1.138	1.146	0.039
PERIOD THREE: Av. Temp.- 172°F. :: Av. Rel. Humidity- 10%						
44.251	1007	176	454	0.822	0.980	0.683
44.751	873	134	320	0.579	0.701	0.484
45.251	763	110	210	0.380	0.479	0.398
45.751	696	67	143	0.259	0.319	0.242
46.001	693	3	140	0.253	0.256	0.022
PERIOD FOUR: Av. Temp. - 118°F. :: Av. Rel. Humidity- 70%						
46.334	710	-17	157	0.284	0.2685	-0.093
49.701	792	-82	239	0.433	0.358	-0.044

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per Hr.

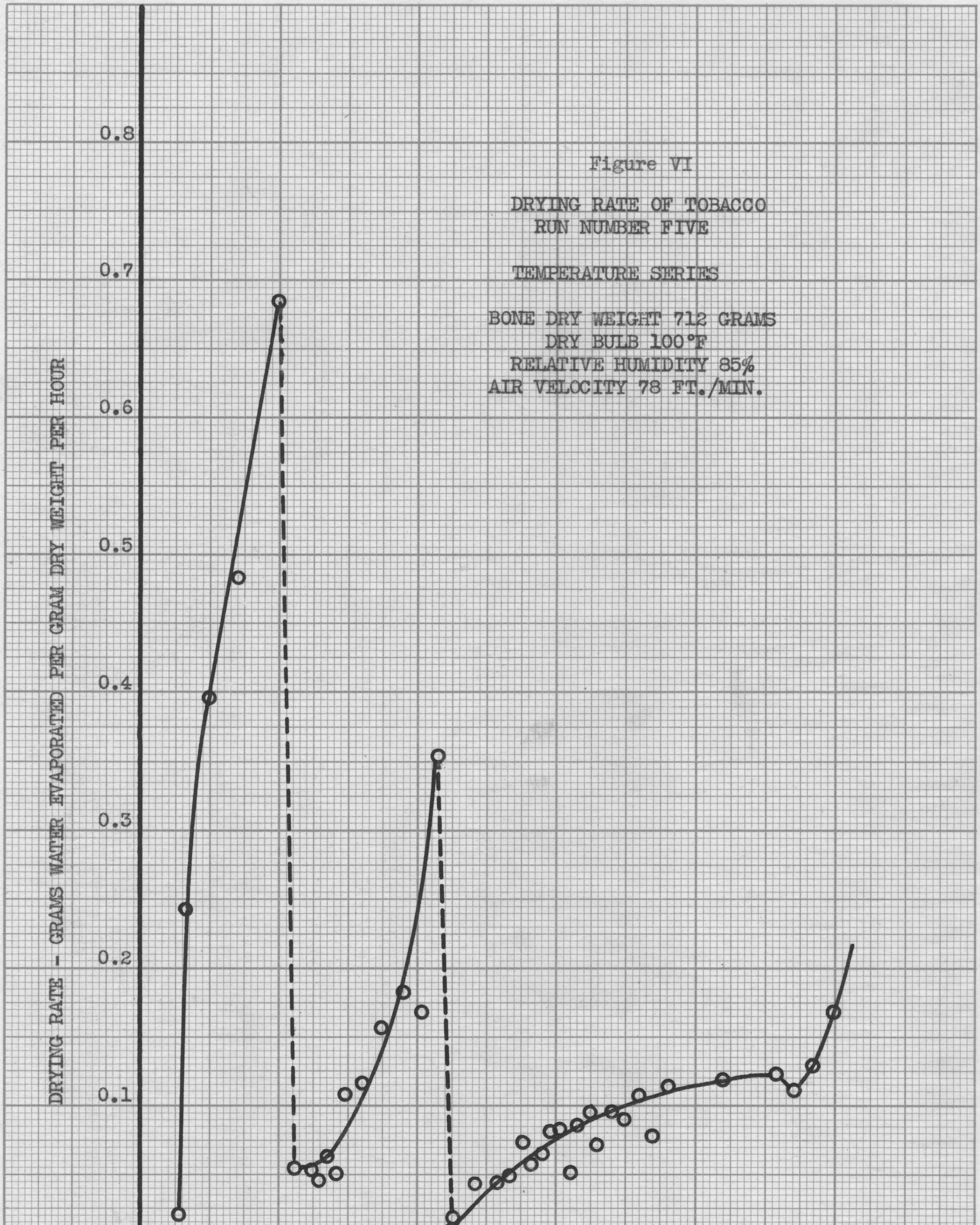
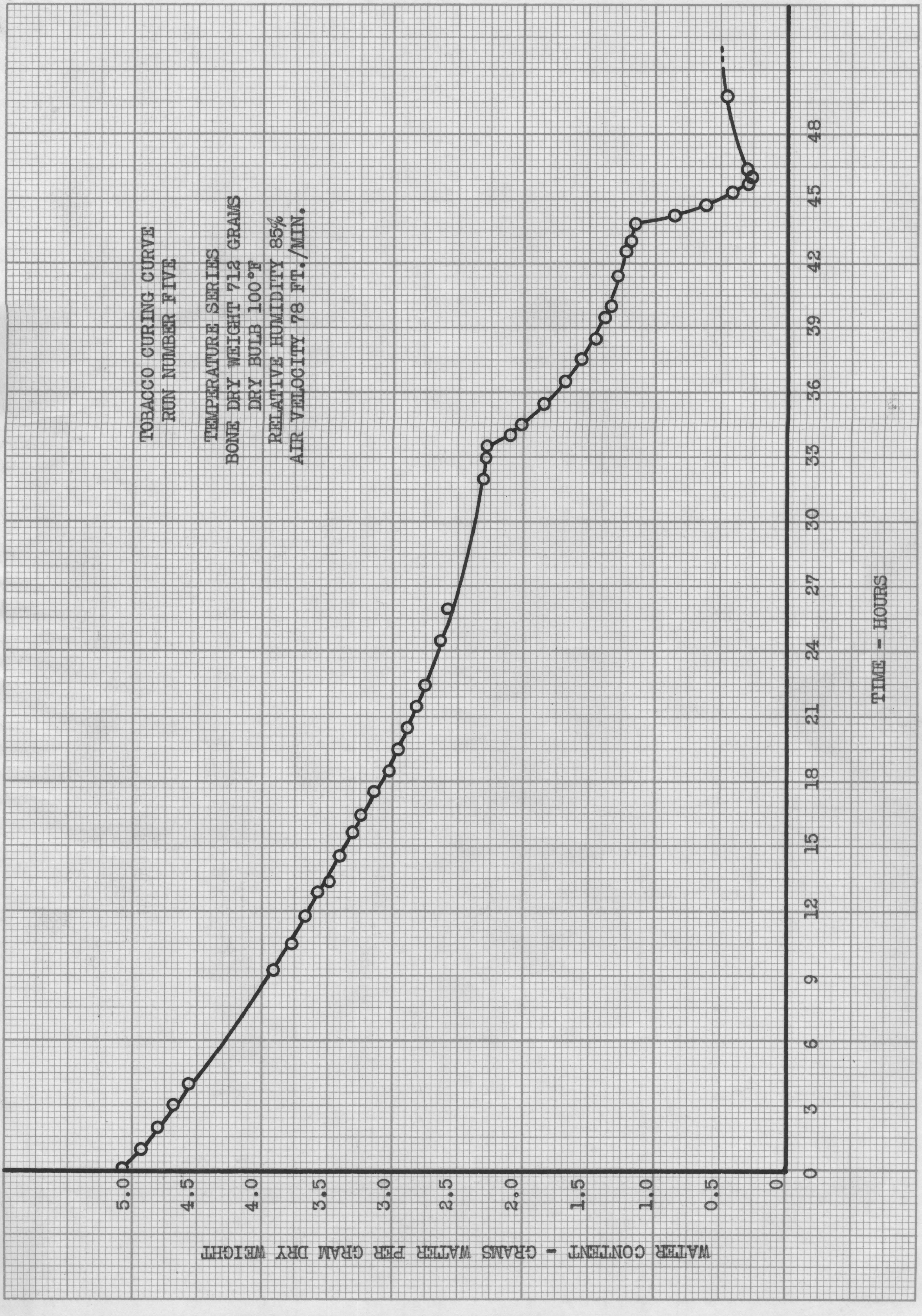


Figure VI

DRYING RATE OF TOBACCO
RUN NUMBER FIVE

TEMPERATURE SERIES

BONE DRY WEIGHT 712 GRAMS
DRY BULB 100°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.



TOBACCO CURING CURVE
RUN NUMBER FIVE

TEMPERATURE SERIES
BONE DRY WEIGHT 712 GRAMS
DRY BULB 100°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

TABLE VII

DRYING RATE OF TOBACCO

RUN NUMBER SIX 105 DEG. F.- TEMPERATURE SERIES

BONE DRY WEIGHT 640 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
PERIOD ONE: Av. Temp. - 105°F. :: Av. Rel. Humidity - 85%						
0.000	3885	000	3245	5.070	5.070	0.000
0.500	3770	115	3130	4.890	4.980	0.395
1.000	3580	190	2940	4.600	4.745	0.594
1.500	3490	90	2850	4.460	4.530	0.281
2.000	3420	70	2780	4.340	4.400	0.219
2.5000	3365	55	2725	4.260	4.300	0.172
3.000	3323	42	2683	4.190	4.225	0.131
4.000	3227	96	2587	4.040	4.115	0.150
5.000	3125	102	2485	3.890	3.965	0.160
6.000	3030	95	2390	3.740	3.815	0.148
7.000	2940	90	2300	3.600	3.670	0.141
8.000	2857	83	2217	3.470	3.535	0.129
9.000	2782	75	2142	3.350	3.410	0.117
15.000	2374	408	1734	2.710	3.030	0.106
16.000	2319	55	1679	2.630	2.670	0.086
17.250	2247	72	1607	2.510	2.570	0.090
18.250	2190	57	1550	2.420	2.465	0.089
19.250	2147	43	1507	2.360	2.390	0.067
20.883	2073	74	1433	2.240	2.300	0.071
21.999	2023	50	1383	2.160	2.200	0.067
23.000	1977	46	1337	2.090	2.125	0.072
24.000	1929	48	1289	2.020	2.055	0.075
25.500	1872	57	1232	1.930	1.975	0.059
26.500	1836	36	1196	1.870	1.900	0.056
28.083	1774	52	1134	1.770	1.820	0.051

(OVER)

TABLE VII

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER SIX 105 DEG. F.- TEMPERATURE SERIES

BONE DRY WEIGHT 640 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
29.083	1746	28	1108	1.730	1.750	0.044
30.083	1717	29	1077	1.680	1.705	0.045
31.083	1691	26	1031	1.610	1.645	0.041
33.083	1647	42	1009	1.580	1.595	0.033
PERIOD TWO: Av. Temp. - 120°F. :: Av. Rel. Humidity - 48%						
33.750	1587	62	947	1.480	1.530	0.145
34.250	1500	87	860	1.340	1.410	0.272
34.750	1437	63	797	1.240	1.290	0.197
35.750	1348	89	708	1.105	1.173	0.139
37.917	1262	86	622	0.972	1.039	0.062
39.750	1200	62	560	0.876	0.924	0.053
41.750	1170	30	530	0.828	0.852	0.023
43.250	1145	25	505	0.789	0.809	0.026
PERIOD THREE: Av. Temp. - 180°F. :: Av. Rel. Humidity- 8%						
43.750	997	148	357	0.558	0.674	0.463
44.250	885	112	245	0.382	0.470	0.350
44.750	820	65	180	0.281	0.332	0.203
46.250	765	55	125	0.195	0.238	0.057
46.750	763	2	123	0.192	0.194	0.006
PERIOD FOUR: Av. Temp. - 115°F. :: Av. Rel. Humidity- 75%						
47.417	821	-58	181	0.283	0.238	-0.136
47.750	847	-26	207	0.324	0.304	-0.122
48.918	891	-44	251	0.393	0.359	-0.069

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per Hr.

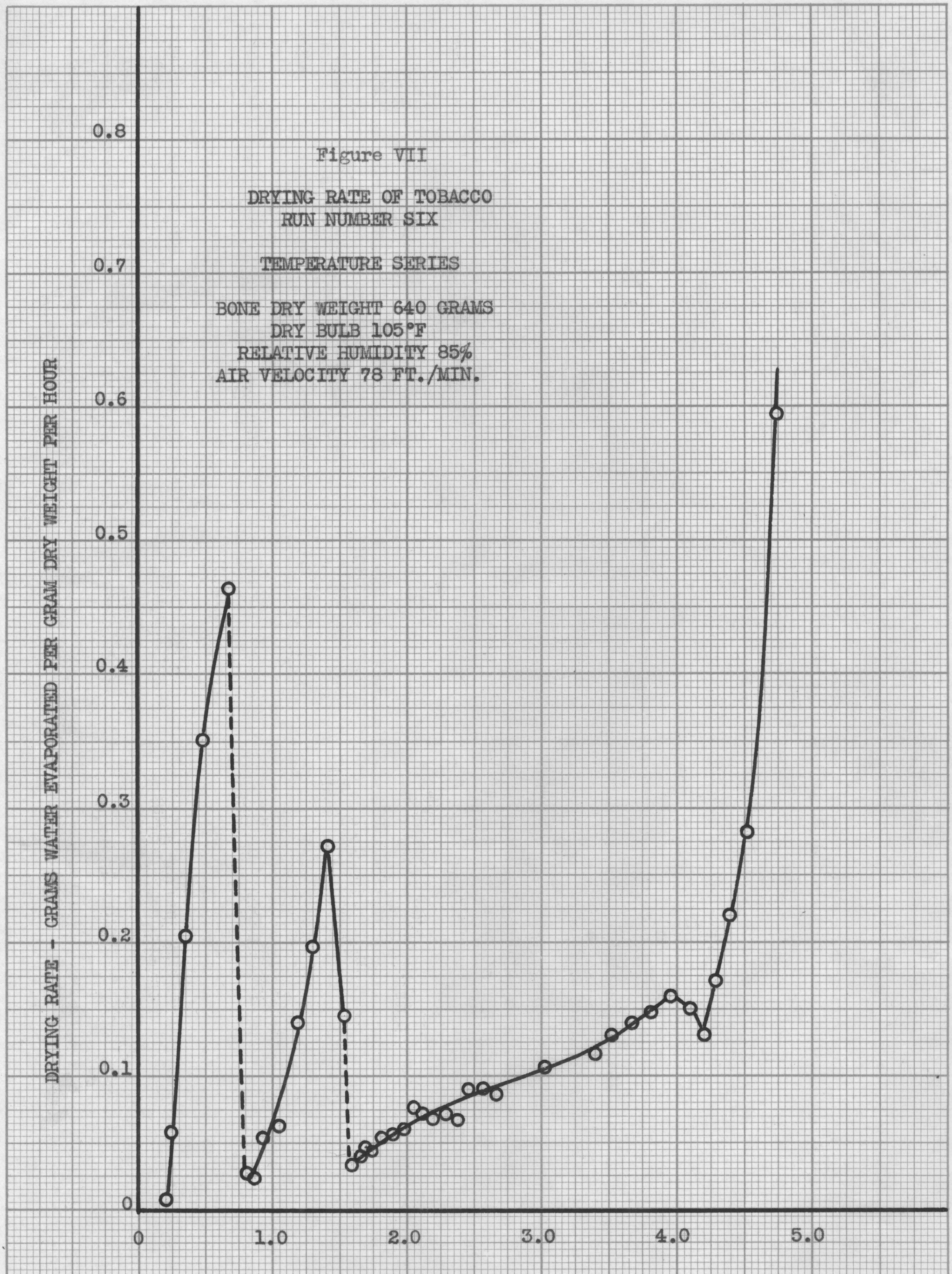
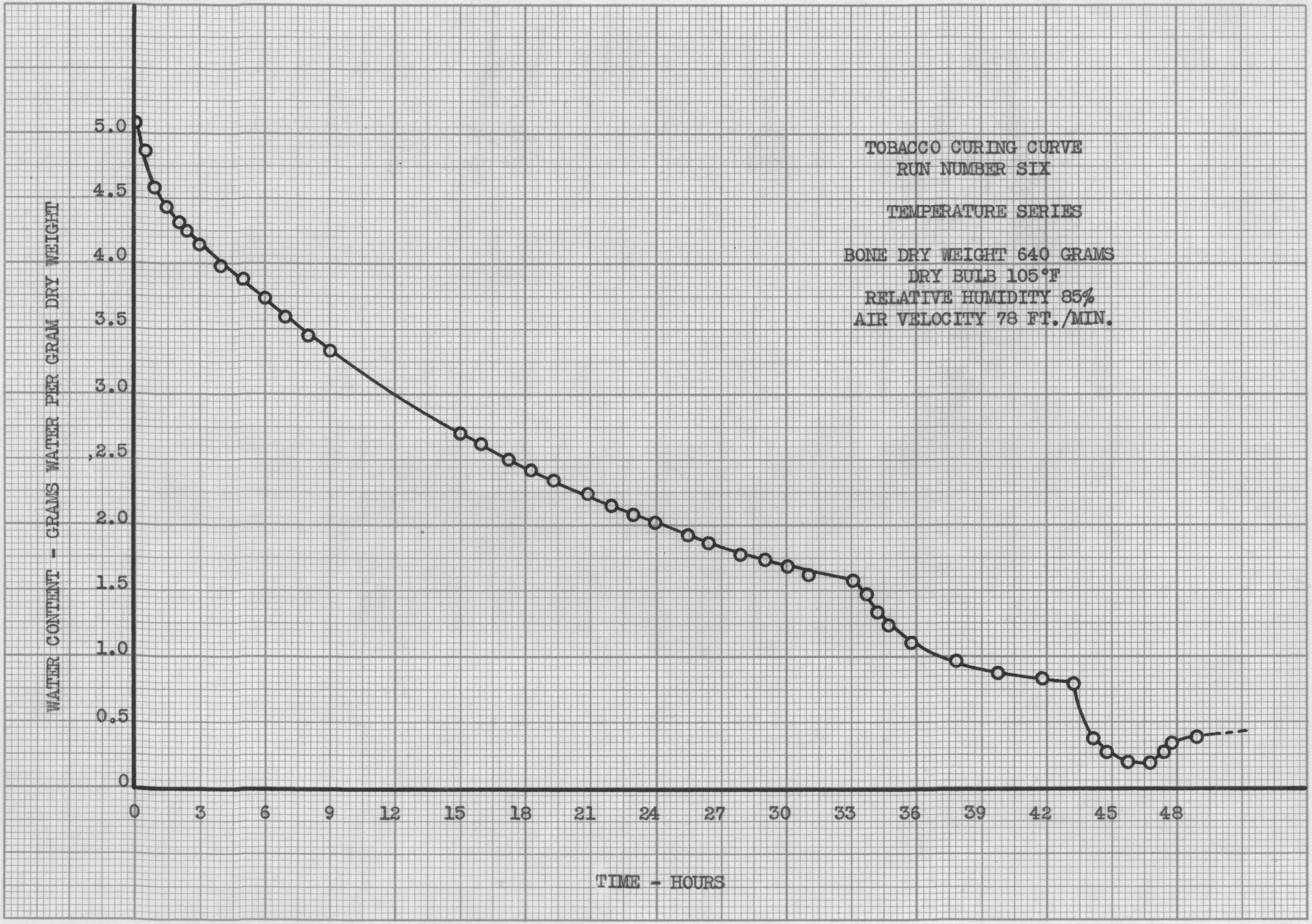


Figure VII

DRYING RATE OF TOBACCO
RUN NUMBER SIX

TEMPERATURE SERIES

BONE DRY WEIGHT 640 GRAMS
DRY BULB 105°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.



TOBACCO CURING CURVE
RUN NUMBER SIX

TEMPERATURE SERIES

BONE DRY WEIGHT 640 GRAMS
DRY BULB 105°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

TABLE VIII

DRYING RATE OF TOBACCO

RUN NUMBER SEVEN 80% REL. HUM. - HUMIDITY SERIES

BONE DRY WEIGHT 553 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
PERIOD ONE: Av. Temp. - 95°F. :: Av. Rel. Humidity - 80%						
0.000	3360	000	2187	5.070	5.070	0.000
0.500	3310	50	27572	4.980	5.030	0.181
1.000	3270	40	2727	4.930	4.955	0.145
2.000	3202	68	2649	4.800	4.865	0.123
3.000	3135	67	2582	4.675	4.738	0.121
9.500	2762	373	2209	4.000	4.338	0.104
10.500	2710	52	2157	3.900	3.950	0.094
10.917	2691	19	2138	3.870	3.885	0.083
12.250	2634	57	2081	3.765	3.818	0.077
13.250	2596	38	2043	3.700	3.733	0.069
14.250	2554	42	2001	3.620	3.660	0.076
16.500	2471	83	1918	3.470	3.545	0.067
19.000	2380	91	1827	3.305	3.388	0.066
21.000	2312	68	1759	3.182	3.244	0.062
23.950	2204	108	1651	2.990	3.086	0.066
26.000	2142	62	1589	2.880	2.935	0.055
28.167	2078	64	1525	2.760	2.820	0.053
30.250	2017	61	1464	2.650	2.700	0.053
31.250	1988	29	1435	2.600	2.625	0.052
PERIOD TWO: Av. Temp. - 112°F. :: Av. Rel. Humidity - 46%						
31.583	1963	25	1410	2.550	2.575	0.136
32.000	1908	55	1355	2.450	2.500	0.239
33.000	1761	146	1208	2.185	2.318	0.264

(OVER)

TABLE VIII

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER SEVEN 80% REL. HUM. - HUMIDITY SERIES

BONE DRY WEIGHT 553 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
34.050	1657	104	1104	2.000	2.095	0.179
35.000	1583	74	1030	1.865	1.933	0.141
36.000	1520	63	967	1.745	1.805	0.114
38.000	1440	80	887	1.600	1.673	0.072
40.000	1367	73	814	1.470	1.535	0.066
40.750	1344	23	791	1.430	1.450	0.055

PERIOD THREE: Av. Temp.- 172°F.:: Av. Rel. Humidity- 19%

41.250	1076	268	523	0.947	1.189	0.970
41.500	1000	76	447	0.808	0.878	0.550
41.750	930	70	377	0.682	0.745	0.507
41.967	900	30	347	0.628	0.655	0.250
42.267	856	44	303	0.548	0.588	0.265
42.498	825	31	272	0.492	0.520	0.241
42.750	795	30	242	0.438	0.465	0.217
43.000	772	23	219	0.386	0.417	0.166
43.250	760	12	207	0.374	0.385	0.087
43.500	749	11	197	0.355	0.365	0.080
43.750	726	23	173	0.313	0.334	0.168

PERIOD FOUR: Av. Temp.- 120°F.:: Av. Rel. Humidity- 70%

44.250	747	-21	194	0.351	0.332	-0.076
44.750	821	-74	268	0.485	0.418	-0.268

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per Hr.

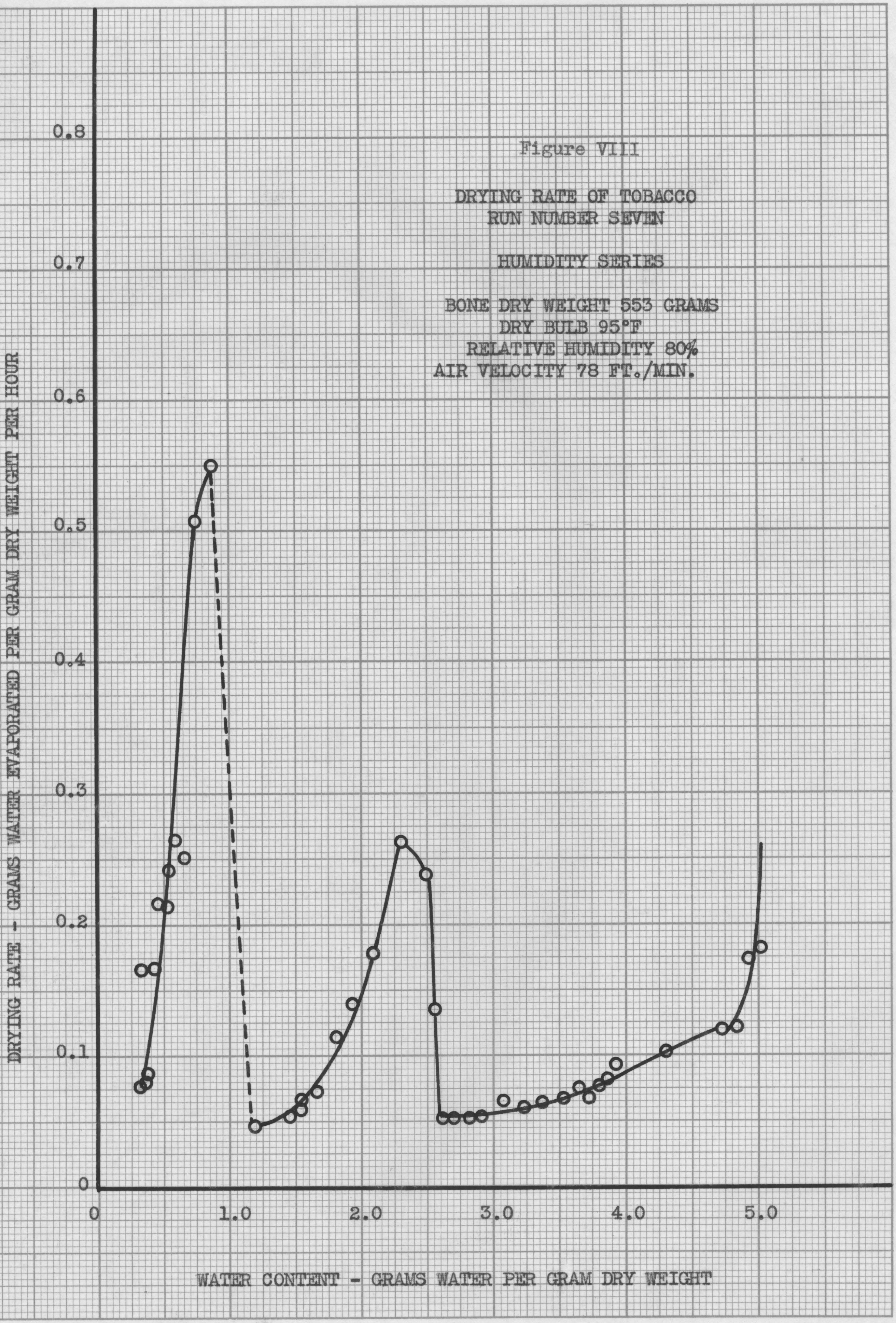


Figure VIII

DRYING RATE OF TOBACCO
RUN NUMBER SEVEN

HUMIDITY SERIES

BONE DRY WEIGHT 553 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 80%
AIR VELOCITY 78 FT./MIN.

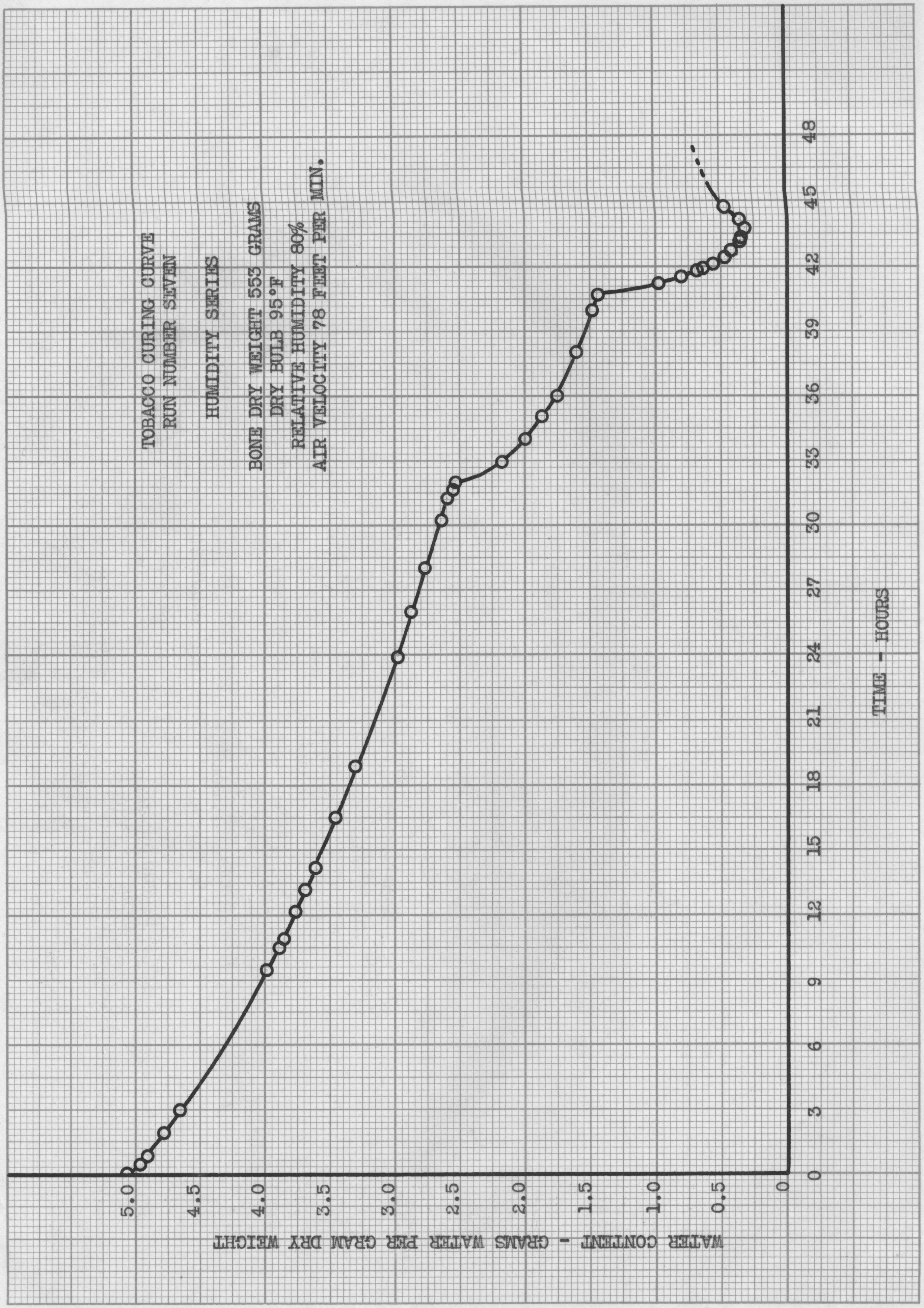

TOBACCO CURING CURVE
RUN NUMBER SEVEN
HUMIDITY SERIES
BONE DRY WEIGHT 553 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 80%
AIR VELOCITY 78 FEET PER MIN.
WATER CONTENT - GRAMS WATER PER GRAM DRY WEIGHT
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
TIME - HOURS
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48

TABLE IX

DRYING RATE OF TOBACCO

RUN NUMBER EIGHT 75% REL. HUM. - HUMIDITY SERIES

BONE DRY WEIGHT 595 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr/
PERIOD ONE: Av. Temp. - 95°F. :: Av. Rel. Humidity - 75%						
0.000	3612	000	3017	5.070	5.070	0.000
0.500	3540	72	2945	4.950	5.010	0.242
1.000	3474	66	2879	4.840	4.895	0.222
1.500	3450	24	2855	4.800	4.820	0.081
2.000	3350	100	2755	4.630	4.715	0.336
2.500	3297	53	2702	4.540	4.585	0.1783
3.500	3180	117	2585	4.340	4.444	0.197
4.500	3079	101	2484	4.180	4.260	0.170
5.500	2980	99	2385	4.020	4.100	0.166
6.333	2900	80	2305	3.880	3.950	0.161
7.500	2798	102	2203	3.705	3.793	0.087
9.500	2635	163	2040	3.430	3.567	0.137
14.500	2268	367	1673	2.810	3.120	0.123
16.500	2160	108	1565	2.630	2.720	0.091
18.500	2050	110	1455	2.445	2.537	0.092
20.500	1968	82	1373	2.310	2.377	0.069
21.750	1920	48	1325	2.230	2.270	0.065
24.917	1800	120	1205	2.025	2.127	0.064
26.917	1741	59	1146	1.927	1.976	0.050
28.499	1694	47	1099	1.850	1.889	0.050

(OVER)

TABLE IX

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER EIGHT   75% REL. HUM. - HUMIDITY SERIES

BONE DRY WEIGHT 595 GRAMS   VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
32.000	1600	94	1005	1.690	1.770	0.045
PERIOD TWO: Av. Temp. - 113°F. :: Av. Rel. Humidity - 41%						
32.367	1572	28	977	1.640	1.665	0.128
33.367	1488	84	893	1.500	1.570	0.141
35.252	1368	120	773	1.298	1.399	0.107
42.085	1208	160	613	1.030	1.164	0.039
PERIOD THREE: Av. Temp.- 171°F.:: Av. Rel. Humidity - 8%						
43.567	1085	123	490	0.823	0.927	0.139
44.500	931	154	336	0.565	0.696	0.278
46.500	783	148	188	0.316	0.441	0.124
48.197	733	50	138	0.232	0.274	0.050
PERIOD FOUR: Av. Temp. - 112°F.:: Av. Rel. Humidity - 68%						
49.000	748	-16	154	0.259	0.246	0.032
49.267	809	-60	214	0.360	0.310	0.378
49.517	843	-34	248	0.417	0.389	0.239

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per Hr.

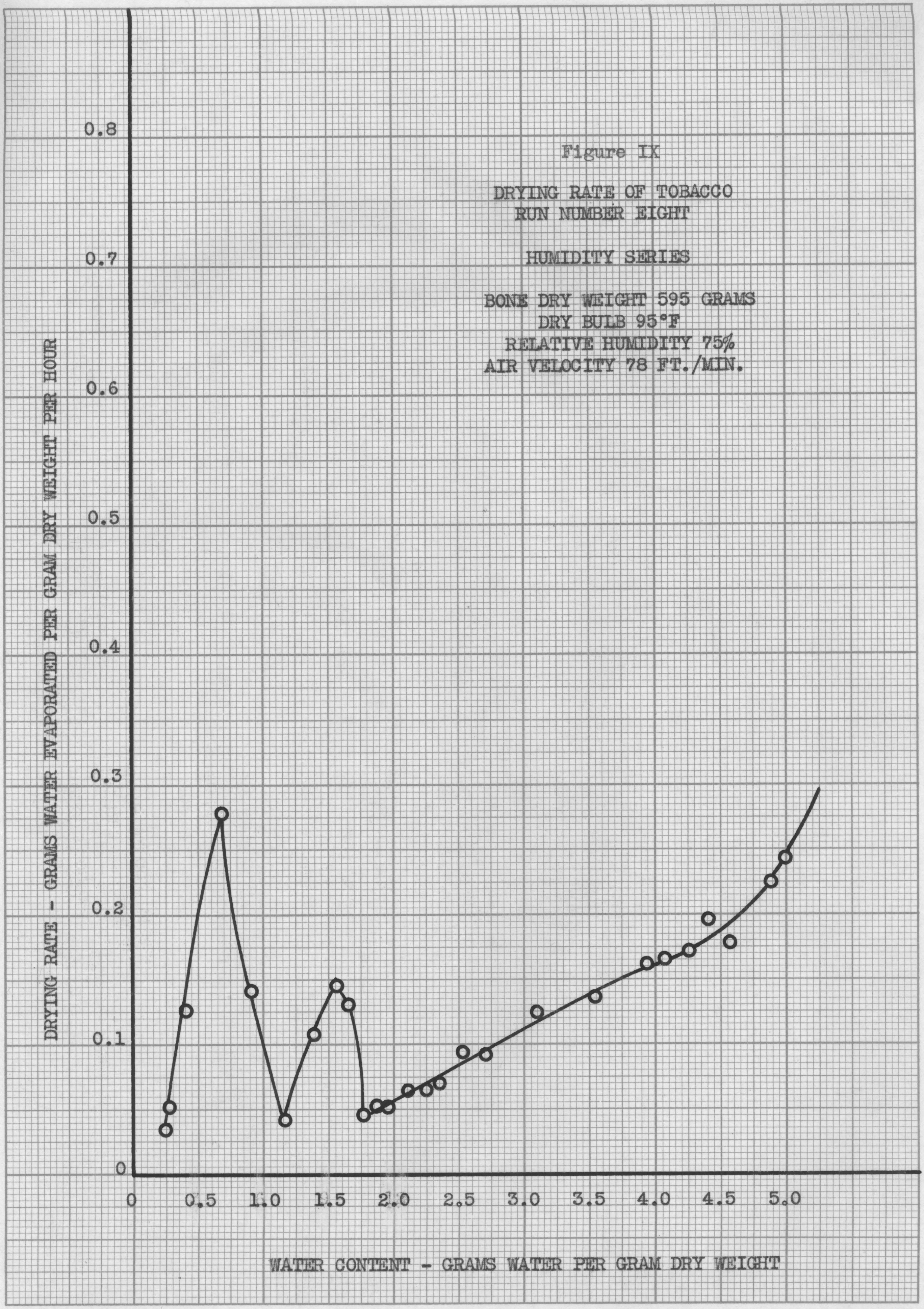


Figure IX

DRYING RATE OF TOBACCO
RUN NUMBER EIGHT

HUMIDITY SERIES

BONE DRY WEIGHT 595 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 75%
AIR VELOCITY 78 FT./MIN.

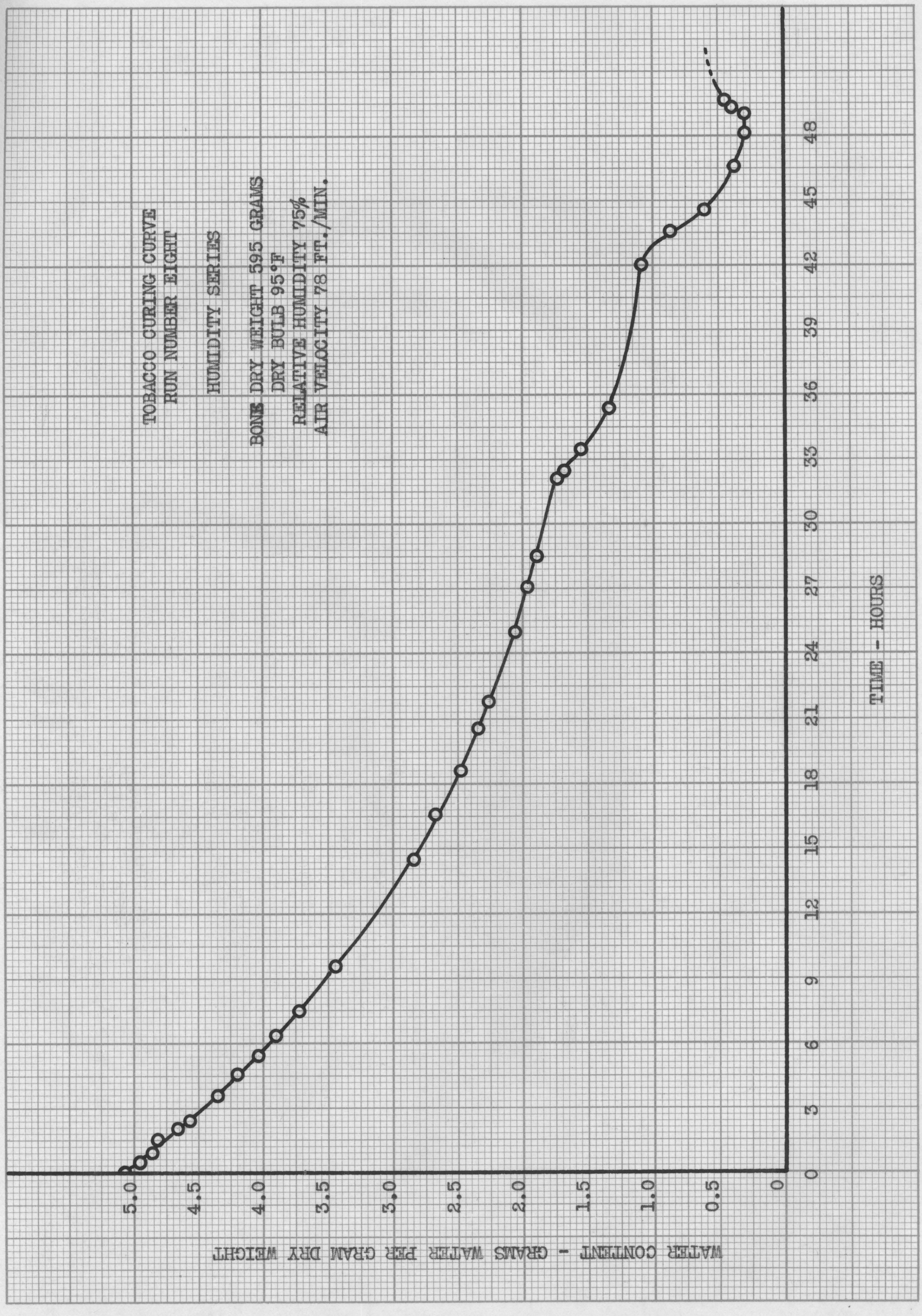

TOBACCO CURING CURVE
RUN NUMBER EIGHT
HUMIDITY SERIES
BONE DRY WEIGHT 595 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 75%
AIR VELOCITY 78 FT./MIN.
WATER CONTENT - GRAMS WATER PER GRAM DRY WEIGHT
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
TIME - HOURS
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48

TABLE X

DRYING RATE OF TOBACCO

RUN NUMBER NINE 90% REL. HUM. - HUMIDITY SERIES

BONE DRY WEIGHT 408 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
PERIOD ONE: Av. Temp. - 95°F. :: Av. Rel. Humidity - 90%						
0.000	2478	000	2070	5.070	5.070	0.000
0.433	2448	30	2040	5.020	5.045	0.170
0.933	2413	35	2005	4.930	4.975	0.172
5.933	2263	150	1855	4.560	4.745	0.074
8.050	2200	63	1792	4.400	4.480	0.073
9.933	2146	54	1738	4.270	4.335	0.070
12.049	2083	63	1675	4.110	4.190	0.073
15.017	1972	111	1564	3.840	3.975	0.092
15.934	1947	25	1539	3.780	3.810	0.067
17.934	1900	47	1492	3.660	3.720	0.058
19.934	1850	50	1442	3.540	3.600	0.061
21.934	1815	35	1407	3.460	3.500	0.043
25.934	1736	79	1328	3.270	3.365	0.049
29.767	1664	72	1256	3.080	3.175	0.046
PERIOD TWO: Av. Temp. - 112°F. :: Av. Rel. Humidity- 38%						
30.267	1636	28	1228	3.020	3.050	0.137
30.834	1571	65	1163	2.860	2.940	0.282
31.967	1456	115	1048	2.580	2.720	0.250
34.017	1300	156	892	2.190	2.385	0.187

TABLE X

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER NINE 90% REL. HUM. - HUMIDITY SERIES

BONE DRY WEIGHT 408 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
36.047	1182	118	774	1.900	2.045	0.143
37.847	1100	82	692	1.700	1.800	0.112
38.9303	1055	45	647	1.590	1.645	0.102
39.930	1025	30	617	1.510	1.550	0.074
PERIOD THREE: Av. Temp.- 178°F. :: Av. Rel. Humidity - 9%						
40.848	846	179	438	1.015	1.293	0.479
41.848	652	194	244	0.600	0.837	0.477
42.665	588	64	180	0.442	0.521	0.219
43.282	572	16	164	0.403	0.423	0.064
PERIOD FOUR: Av. Temp. - 114°F. :: Av. Rel. Humidity -73%						
43.549	603	-31	195	0.478	0.441	-0.285
44.032	643	-40	235	0.577	0.5275	-0.203
44.532	677	-34	269	0.661	0.619	-0.167

*G/G Grams water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per hr.

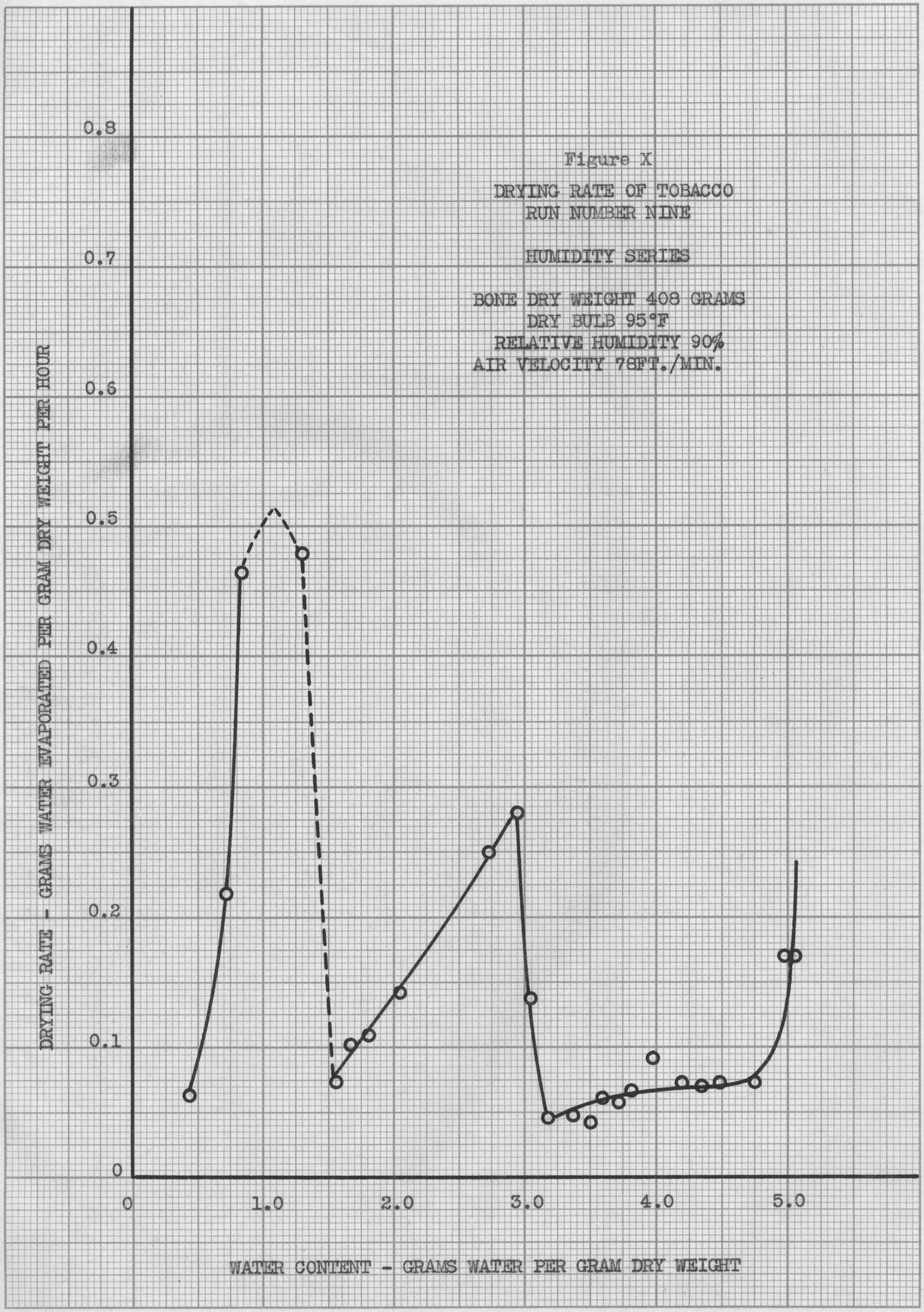


Figure X

DRYING RATE OF TOBACCO
RUN NUMBER NINE

HUMIDITY SERIES

BONE DRY WEIGHT 408 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 90%
AIR VELOCITY 78FT./MIN.

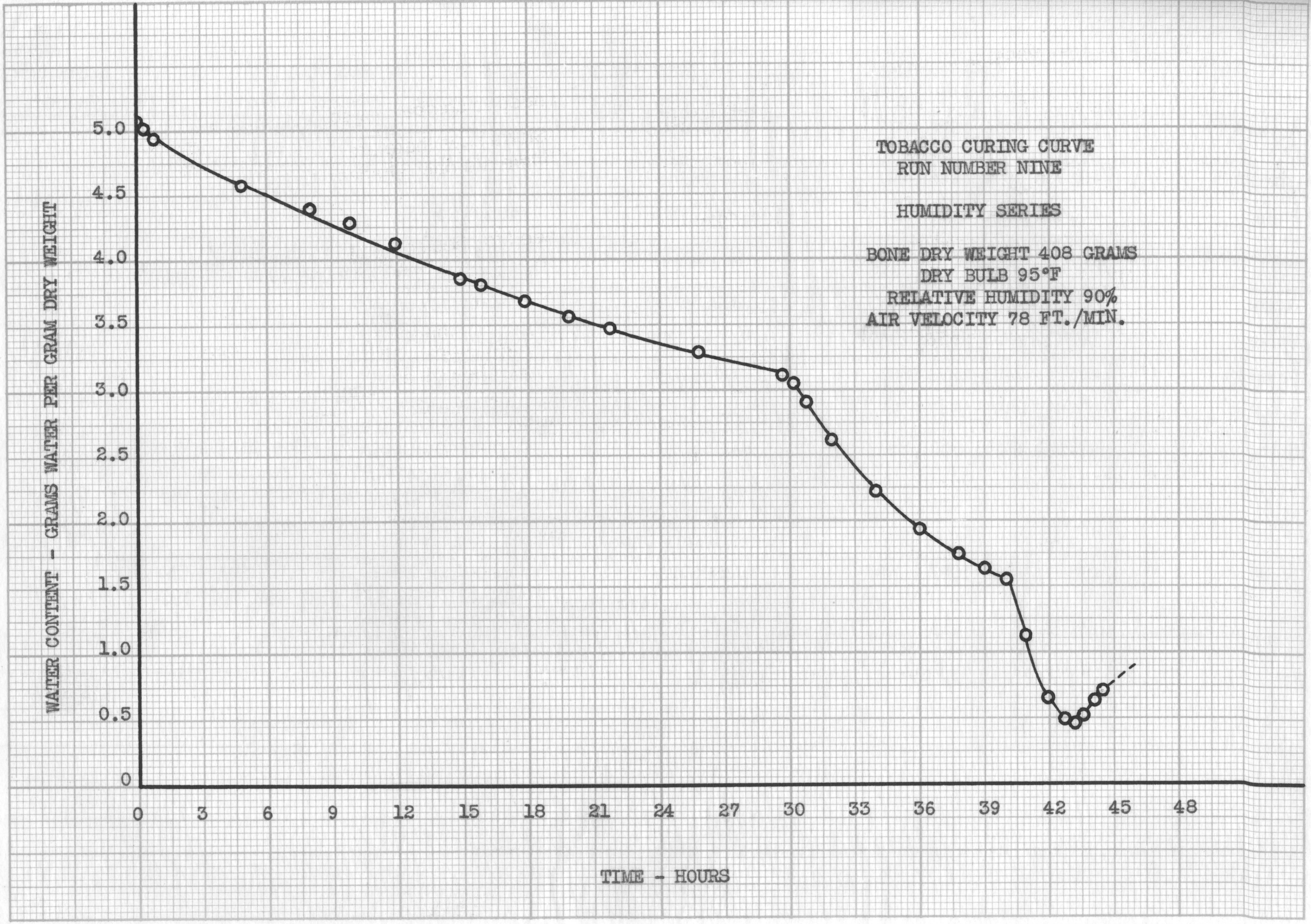

TOBACCO CURING CURVE
RUN NUMBER NINE
HUMIDITY SERIES
BONE DRY WEIGHT 408 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 90%
AIR VELOCITY 78 FT./MIN.
WATER CONTENT - GRAMS WATER PER GRAM DRY WEIGHT
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
TIME - HOURS

TABLE XI

DRYING RATE OF TOBACCO

RUN NUMBER TEN COMPOSITE RUN

BONE DRY WEIGHT 305 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr.
PERIOD ONE: Av. Temp. - 95°F. :: Av. Rel. Humidity - 85%						
0.000	1850	000	1545	5.070	5.070	0.000
1.082	1807	43	1502	4.940	5.005	0.130
2.082	1770	37	1465	4.810	4.875	0.121
3.082	1737	33	1432	4.710	4.760	0.108
5.082	1684	53	1379	4.530	4.620	0.087
7.082	1630	54	1325	4.350	4.440	0.089
9.092	1577	53	1272	4.180	4.265	0.087
11.082	1520	57	1215	3.990	4.085	0.094
13.082	1478	42	1175	3.860	3.925	0.069
15.082	1445	33	1140	3.740	3.800	0.054
18.582	1382	63	1077	3.530	3.635	0.059
19.082	1367	15	1062	3.490	3.510	0.099
CHANGING CONDITIONS: Temp. and Rel. Humidity changed -2 Hr.						
19.832	1352	15	1047	3.430	3.460	0.066
20.332	1342	10	1037	3.400	3.415	0.066
20.582	1338	4	1033	3.390	3.395	0.026
21.582	1300	38	995	3.260	3.325	0.125
23.082	1270	30	965	3.165	3.213	0.067
PERIOD TWO; Av. Temp. - 110°F. :: Av. Rel. Humidity - 45%						
23.582	1257	13	952	3.120	3.143	0.085
24.082	1243	14	938	3.080	3.100	0.092
24.832	1222	21	917	3.010	3.045	0.092
28.332	1136	86	831	2.730	2.870	0.081
28.832	1122	14	817	2.680	2.705	0.092

(OVER)

TABLE XI

DRYING RATE OF TOBACCO (CONT.)

RUN NUMBER TEN COMPOSITE RUN

BONE DRY WEIGHT 305 GRAMS VELOCITY 78 FEET PER MIN.

Time Hr.	Weight Gm.	Weight Loss Gm.	Total Water Gm.	Water Content *G/G	Average Content *Gm/Gm	Drying *Rate G/G/Hr
30.332	1087	35	782	2.560	2.620	0.077
30.832	1067	20	762	2.500	2.530	0.131
32.332	1021	46	716	2.350	2.425	0.100
32.815	1010	11	705	2.310	2.330	0.062
35.665	942	68	637	2.090	2.200	0.081
36.082	928	14	623	2.045	2.068	0.110
37.332	896	32	591	1.940	1.993	0.084
38.499	862	34	557	1.830	1.885	0.096
39.333	812	50	507	1.660	1.745	0.197
41.417	712	100	407	1.340	1.500	0.157
PERIOD THREE: Av. Temp. -175°F.:: Av. Rel. Humidity - 8%						
41.834	655	57	350	1.147	1.244	0.450
42.834	519	136	214	0.703	0.925	0.447
43.667	500	19	195	0.640	0.783	0.075
PERIOD FOUR: Av. Temp. - 99°F.:: Av. Rel. Humidity -83%						
44.167	530	-30	225	0.738	0.689	-0.197
44.584	561	-31	256	0.840	0.789	-0.244
45.084	565	- 4	260	0.854	0.847	-0.003

*G/G Grams of water remaining per gram dry weight
*G/G/Hr. Grams water evaporated per gram dry weight per hr.

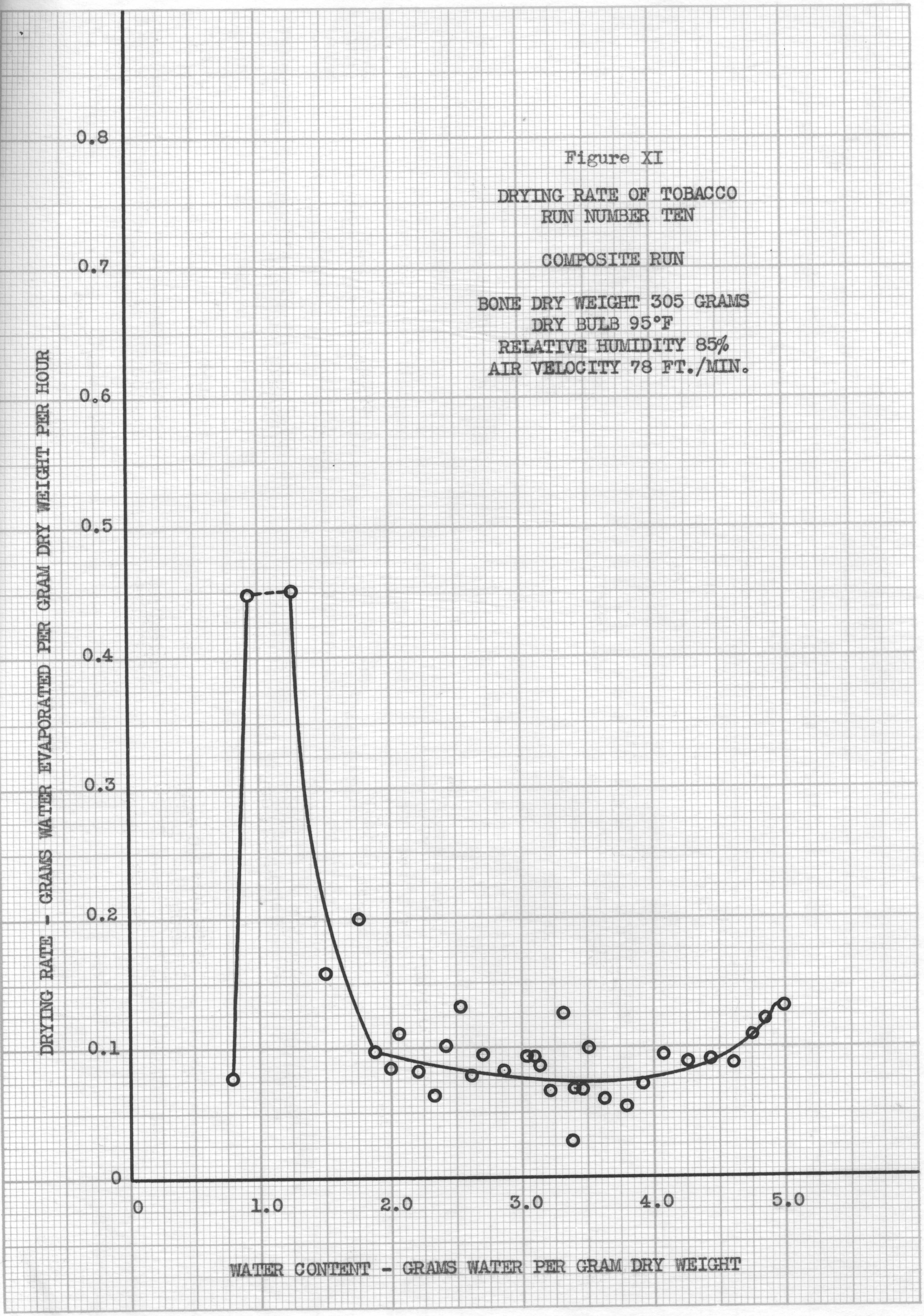


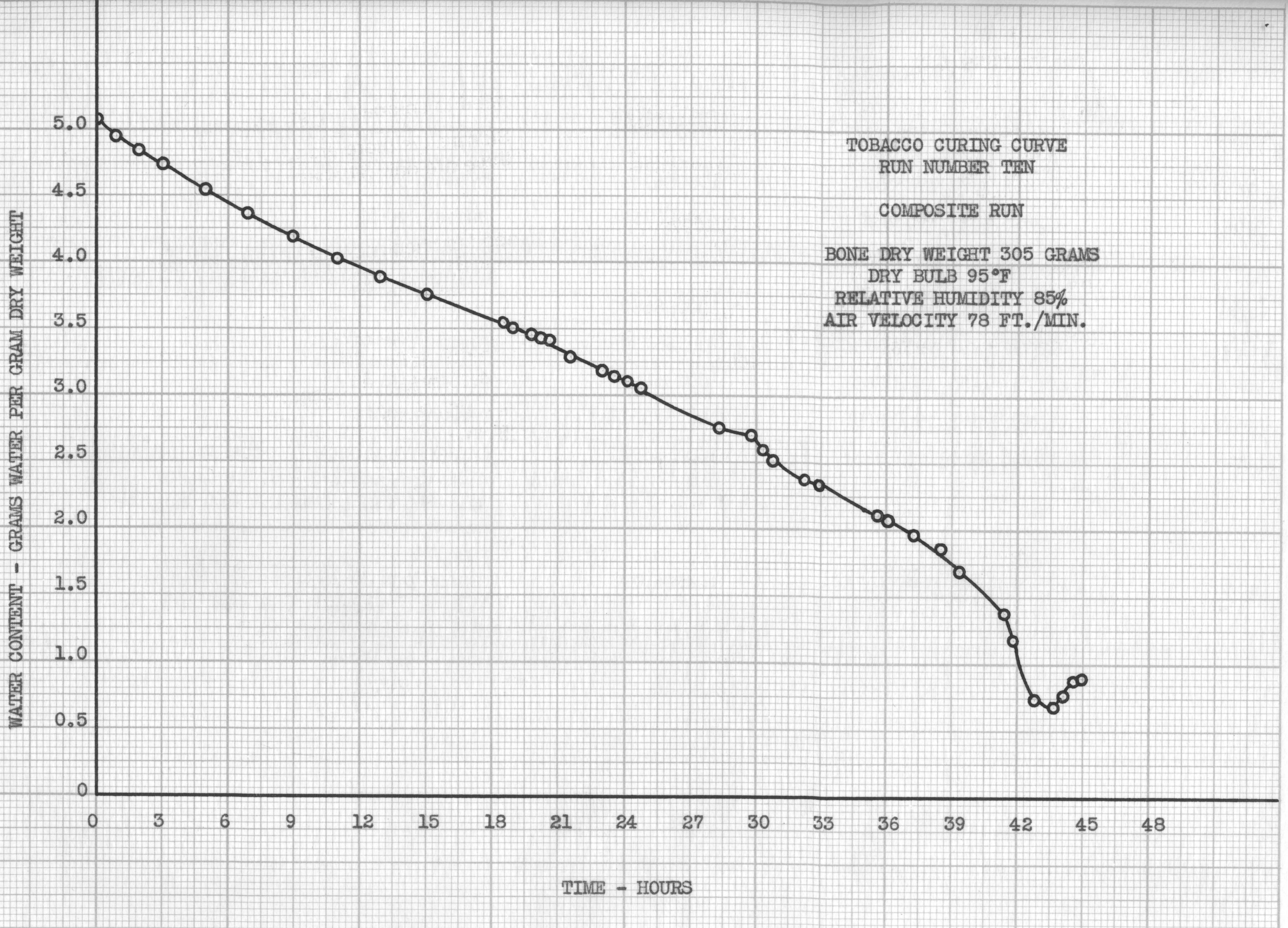
Figure XI

DRYING RATE OF TOBACCO
RUN NUMBER TEN

COMPOSITE RUN

BONE DRY WEIGHT 305 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

11a



TOBACCO CURING CURVE
RUN NUMBER TEN

COMPOSITE RUN

BONE DRY WEIGHT 305 GRAMS
DRY BULB 95°F
RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

TABLE XII

THE GRADUATED EFFECT OF TEMPERATURE ON THE DRYING RATE

RELATIVE HUMIDITY - 85%   AIR VELOCITY 78 FEET PER MIN.

TEMPERATURE SERIES

Run Number	Time Interval Hr.	Temperature Deg. F.	Relative Humidity Per Cent	Content Differ. * G/G	Drying *Rate G/G/Hr.
4	3 - 6	95	85	0.32	0.1067
4	9 - 12	95	85	0.25	0.0833
4	15 - 18	95	85	0.20	0.0667
4	21 - 24	95	85	0.18	0.0600
4	27 - 30	95	85	0.13	0.0433
5	3 - 6	100	85	0.38	0.1267
5	9 - 12	100	85	0.31	0.1033
5	15 - 18	100	85	0.28	0.0933
5	21 - 24	100	85	0.19	0.0633
5	27 - 30	100	85	0.13	0.0433
6	3 - 6	105	85	0.43	0.1433
6	9 - 12	105	85	0.32	0.1067
6	15 - 18	105	85	0.26	0.0867
6	21 - 24	105	85	0.20	0.0667
6	27 - 30	105	85	0.13	0.0433
3	3 - 6	110	85	0.62	0.2067
3	9 - 12	110	85	0.28	0.0933
3	15 - 18	110	85	0.18	0.0600
3	21 - 24	110	85	0.15	0.0500
3	27 - 30	110	85	0.10	0.0333

*G/G Change in water content during the time interval

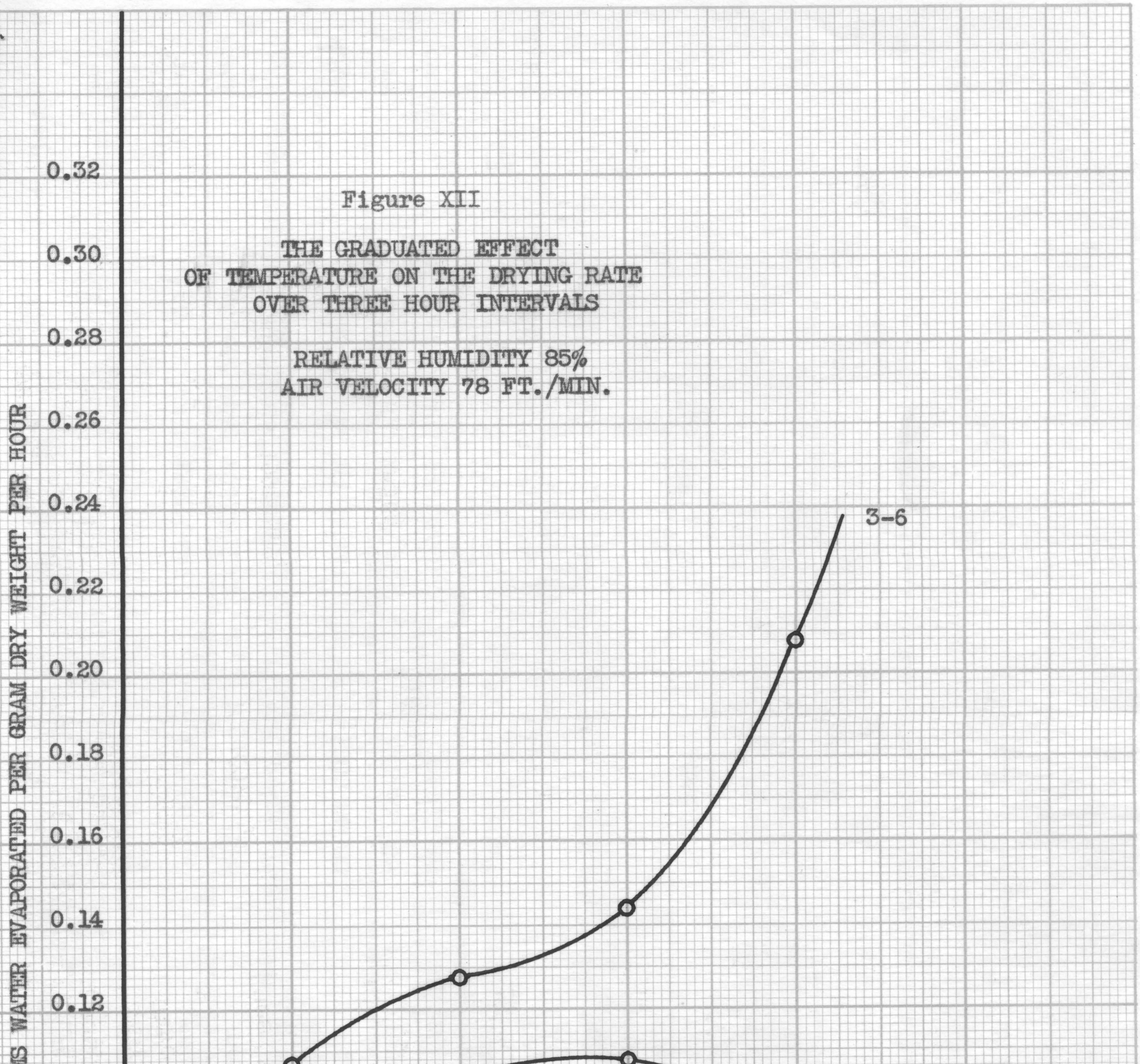


Figure XII

THE GRADUATED EFFECT
OF TEMPERATURE ON THE DRYING RATE
OVER THREE HOUR INTERVALS

RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

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TABLE XIII

THE GRADUATED EFFECT OF RELATIVE HUMIDITY ON THE DRYING RATE

TEMPERATURE - 95 DEG. F. AIR VELOCITY 78 FEET PER MIN.

HUMIDITY SERIES

Run Number	Time Interval Hr.	Temperature Deg. F.	Relative Humidity Per Cent	Content Differ. * G/G	Drying *Rate G/G/Hr.
8	3 - 6	95	75	0.50	0.1667
8	9 - 12	95	75	0.40	0.1332
8	15 - 18	95	75	0.28	0.0933
8	21 - 24	95	75	0.19	0.0633
8	27 - 30	95	75	0.13	0.0433
7	3 - 6	95	80	0.33	0.1100
7	9 - 12	95	80	0.26	0.0867
7	15 - 18	95	80	0.20	0.0650
7	21 - 24	95	80	0.19	0.0633
7	27 - 30	95	80	0.14	0.0467
4	3 - 6	95	85	0.32	0.1067
4	9 - 12	95	85	0.25	0.0833
4	15 - 18	95	85	0.20	0.0667
4	21 - 24	95	85	0.18	0.0600
4	27 - 30	95	85	0.13	0.0433
9	3 - 6	95	90	0.24	0.0800
9	9 - 12	95	90	0.20	0.0667
9	15 - 18	95	90	0.18	0.0600
9	21 - 24	95	90	0.15	0.0500
9	27 - 30	95	90	0.12	0.0400

*G/G Change in water content during the time interval

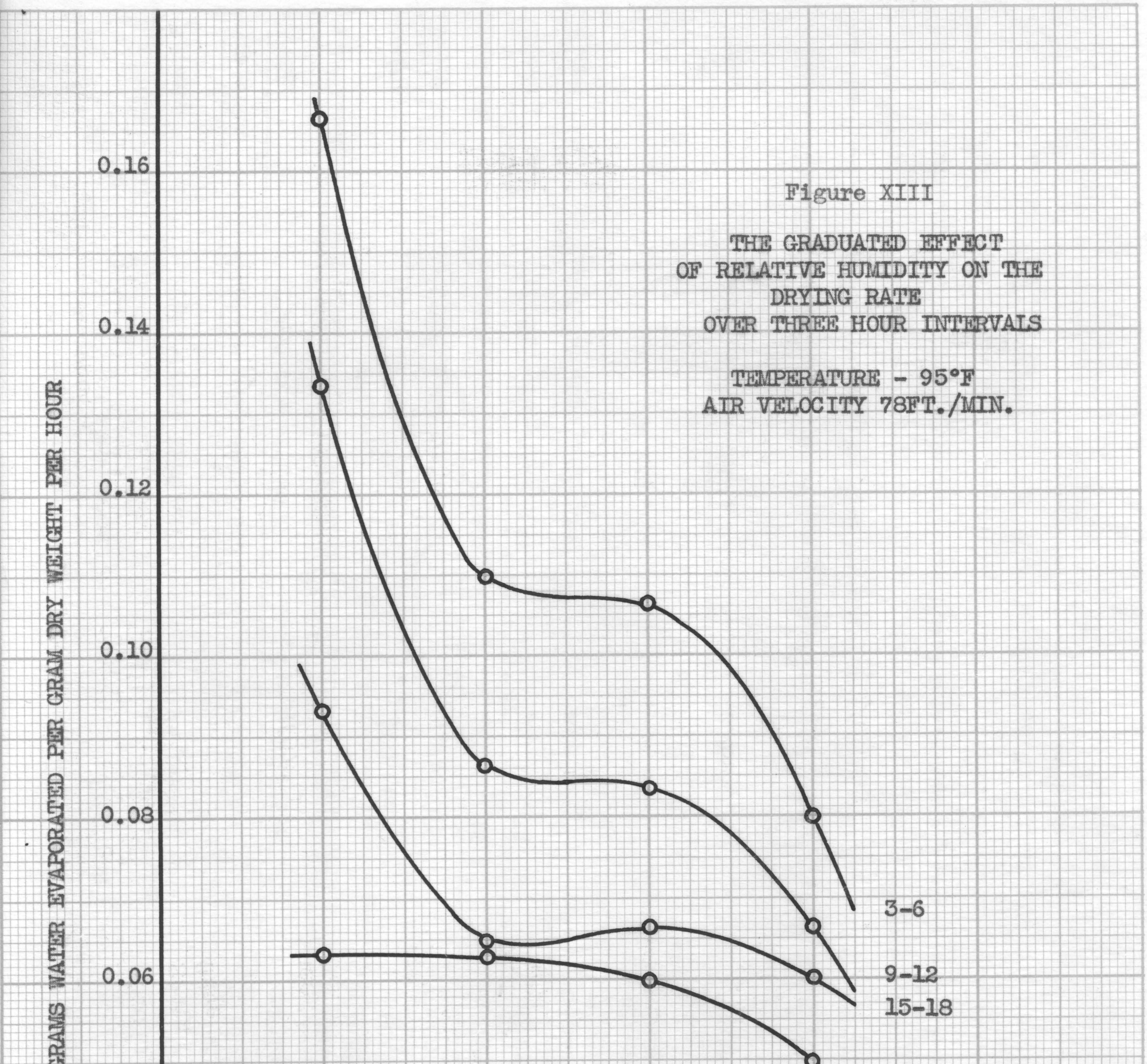

Figure XIII

THE GRADUATED EFFECT
OF RELATIVE HUMIDITY ON THE
DRYING RATE
OVER THREE HOUR INTERVALS

TEMPERATURE - 95°F
AIR VELOCITY 78FT./MIN.

TABLE XIV

THE EFFECT OF TEMPERATURE ON THE AVERAGE DRYING RATE OF TOBACCO

Drying Rates Averaged over 10 Hours

Time Hr.	Run Number	Dry Bulb Deg.F	Relative Humidity Per Cent	Drying *Rate G/G/Hr.
10.0	4	95	85	0.09065
10.0	5	100	85	0.12640
10.0	6	105	85	0.21760
10.0	3	110	85	0.32560

*G/G/Hr. Grams water evaporated per gram dry weight per hour, averaged over the first ten hours of the first period.

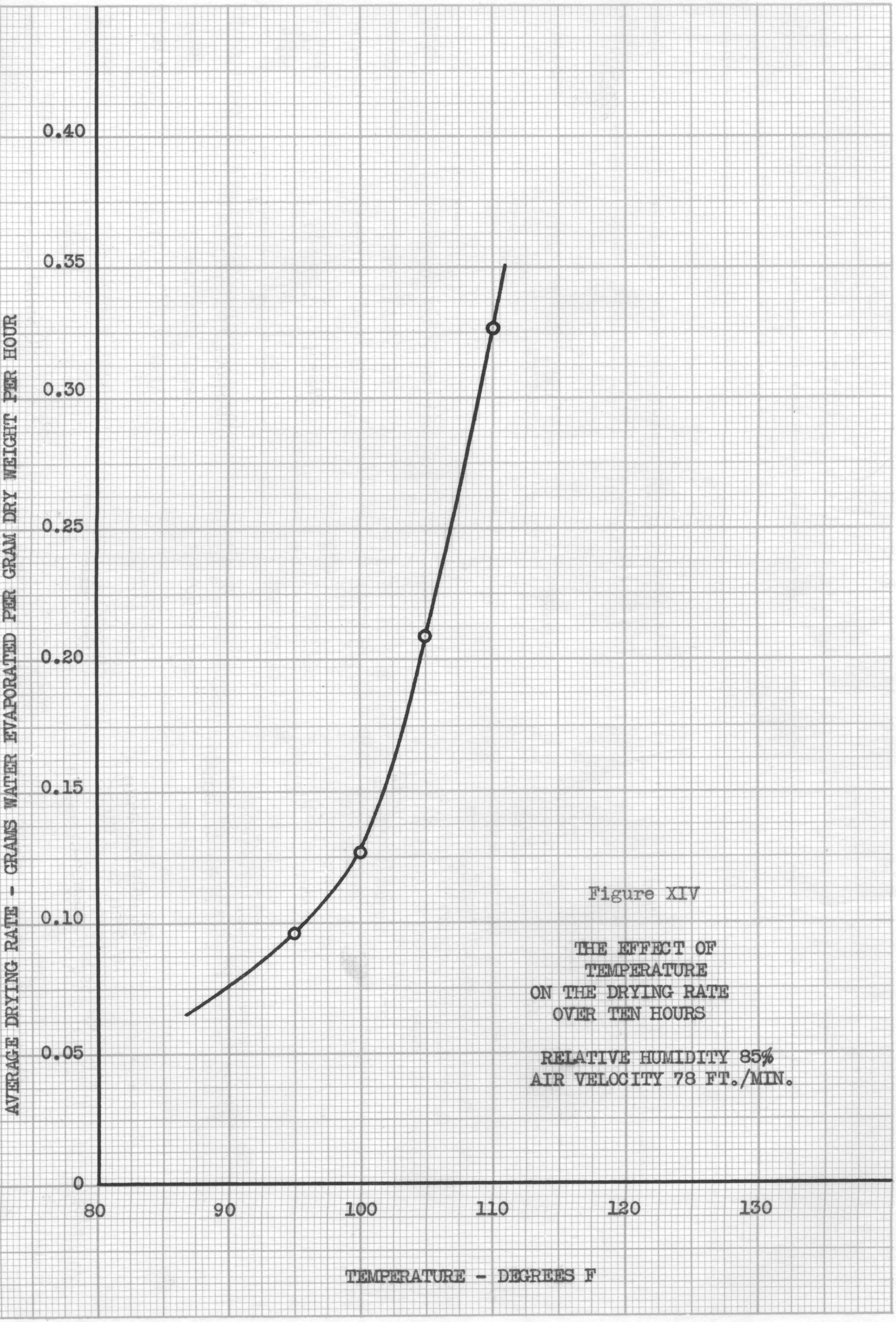

Figure XIV

THE EFFECT OF
TEMPERATURE
ON THE DRYING RATE
OVER TEN HOURS

RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

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TABLE XV

THE EFFECT OF RELATIVE HUMIDITY ON THE AVERAGE DRYING RATE OF TOBACCO

Drying Rates Averaged over 10 Hours

Time Hr.	Run Number	Relative Humidity Per Cent	Dry Bulb Deg.F	Drying *Rate G/G/Hr.
10.0	4	75	95	0.1847
10.0	9	80	95	0.1143
10.0	7	85	95	0.0907
10.0	8	90	95	0.0760

*G/G/Hr. Grams water evaporated per gram dry weight per hour, averaged over the first ten hours of the first period.

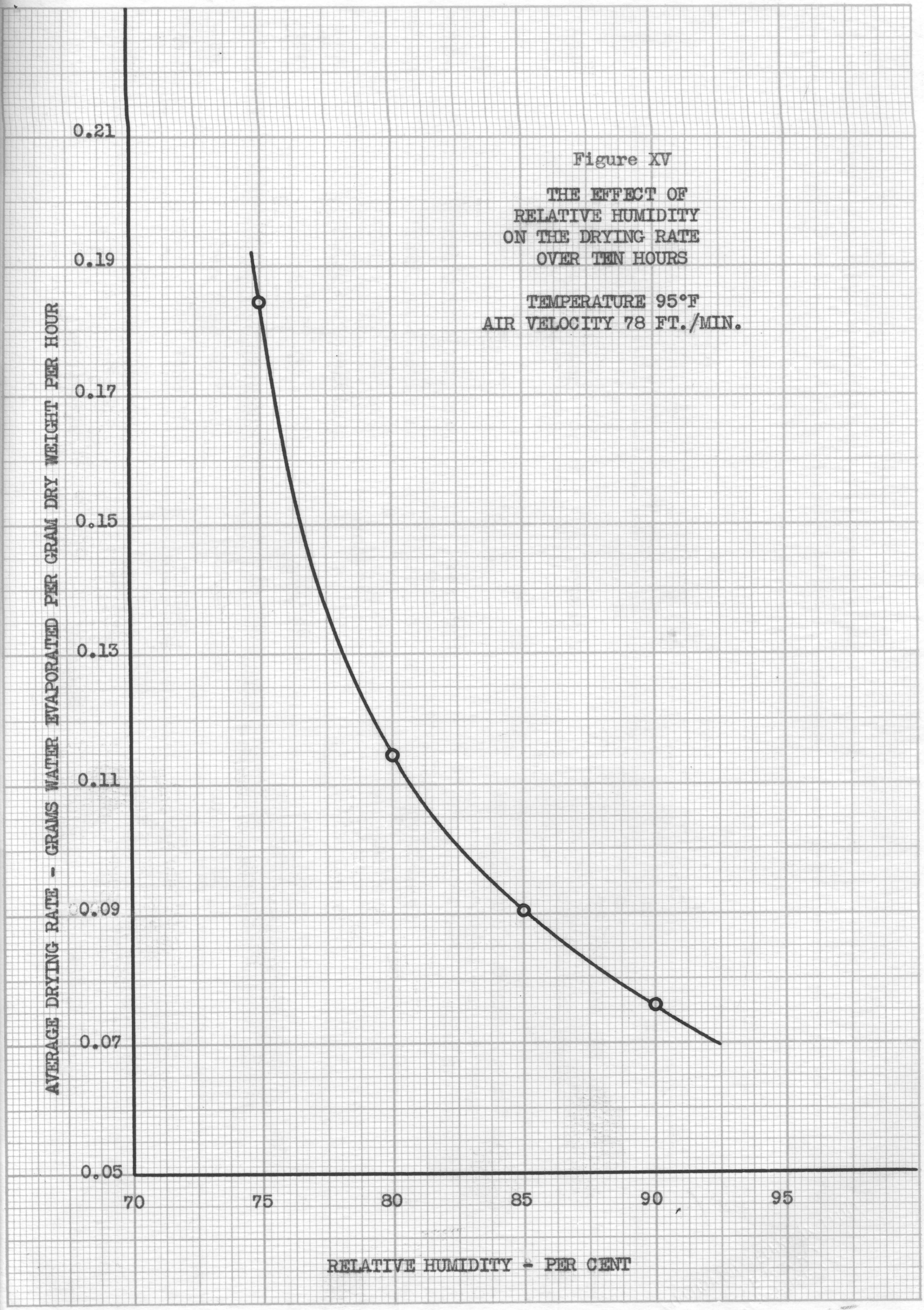

Figure XV

THE EFFECT OF
RELATIVE HUMIDITY
ON THE DRYING RATE
OVER TEN HOURS

TEMPERATURE 95°F
AIR VELOCITY 78 FT./MIN.

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TABLE XVI

THE EFFECT OF TEMPERATURE ON THE AVERAGE DRYING RATE OF TOBACCO

Drying Rates Averaged over 30 Hours

Time Hr.	Run Number	Dry Bulb Deg.F	Relative Humidity Per Cent	Drying *Rate G/G/Hr.
30.0	4	95	85	0.0413
30.0	5	100	85	0.0535
30.0	6	105	85	0.0712
30.0	3	110	85	0.0847

*G/G/Hr. Grams water evaporated per gram dry weight per hour, averaged over the first thirty hours of the first period.

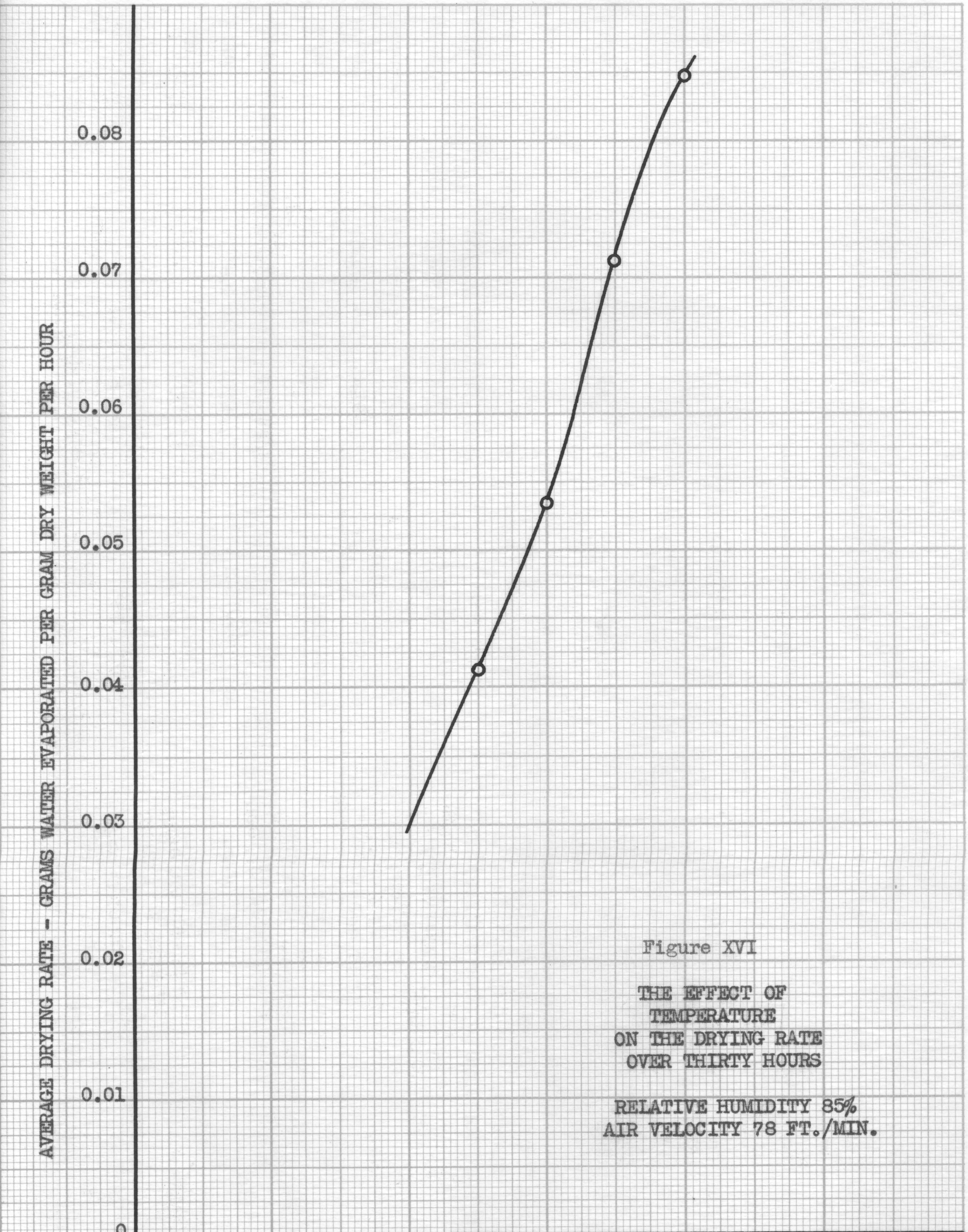

Figure XVI

THE EFFECT OF
TEMPERATURE
ON THE DRYING RATE
OVER THIRTY HOURS

RELATIVE HUMIDITY 85%
AIR VELOCITY 78 FT./MIN.

TABLE XVII

THE EFFECT OF RELATIVE HUMIDITY ON THE AVERAGE DRYING RATE OF TOBACCO

Drying Rates Averaged over 30 Hours

Time Hr.	Run Number	Relative Humidity Per Cent	Dry Bulb Deg.F	Drying *Rate G/G/Hr.
30.0	8	75	95	0.0676
30.0	7	80	95	0.0463
30.0	4	85	95	0.0413
30.0	9	90	95	0.0379

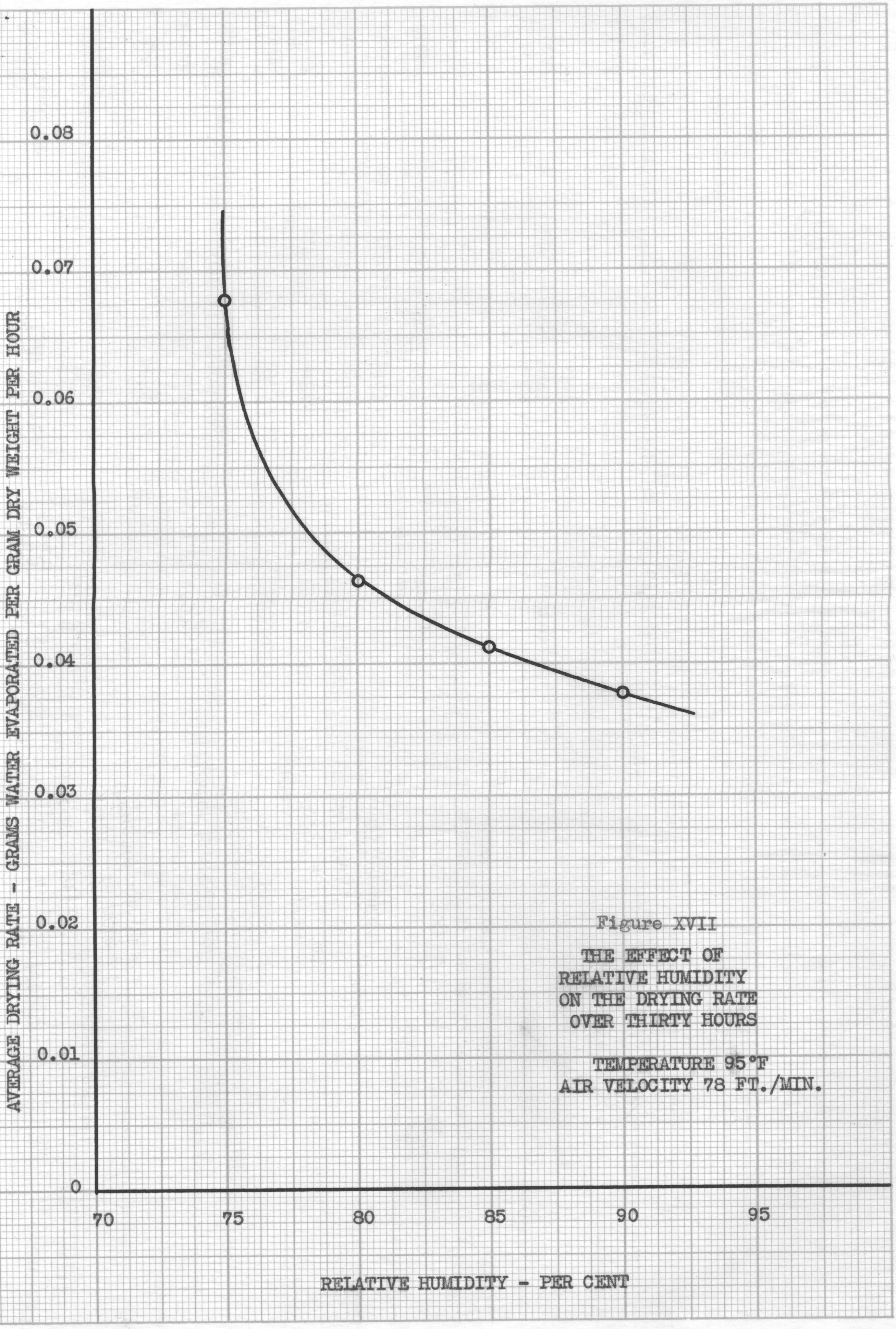

Figure XVII

THE EFFECT OF
RELATIVE HUMIDITY
ON THE DRYING RATE
OVER THIRTY HOURS

TEMPERATURE 95°F
AIR VELOCITY 78 FT./MIN.

TABLE XVIII

THE EFFECT OF AIR VELOCITY ON THE AVERAGE DRYING RATE OF TOBACCO

Rates Averaged Over The Initial 4 Hours

TEMPERATURE 100 DEG. F RELATIVE HUMIDITY 85%

Run Number	Air Velocity Ft./Min.	Weight Loss Gm.	Average Wt. Loss Gm.	Dry Weight Gm.	Drying Rate G/G/Hr.
15*	4.75	2.14	00.535	5.69	0.0940
25*	12.39	4.07	01.018	9.70	0.1050
23*	18.51	4.60	1.151	11.65	0.0990
17*	23.53	3.79	0.948	7.70	0.1230
18*	30.10	3.74	0.935	6.72	0.1390
19*	30.10	4.73	1.182	8.05	0.1470
20*	40.55	4.40	1.100	7.70	0.1430
21*	50.50	3.56	0.890	6.50	0.1370
22*	50.50	5.43	1.358	8.55	0.1590
4	50.00	133.60	33.400	230.00	0.1450
5	78.00	300.40	75.100	552.50	0.1360
3	96.00	124.40	31.100	204.00	0.1521
2	100.00	124.80	31.200	190.00	0.1643
1	115.00	120.40	30.100	192.50	0.1564

G/G/Hr. Grams water evaporated per gram dry weight per hour, averaged over four hours.

* Data interpolated from the work of Delamar

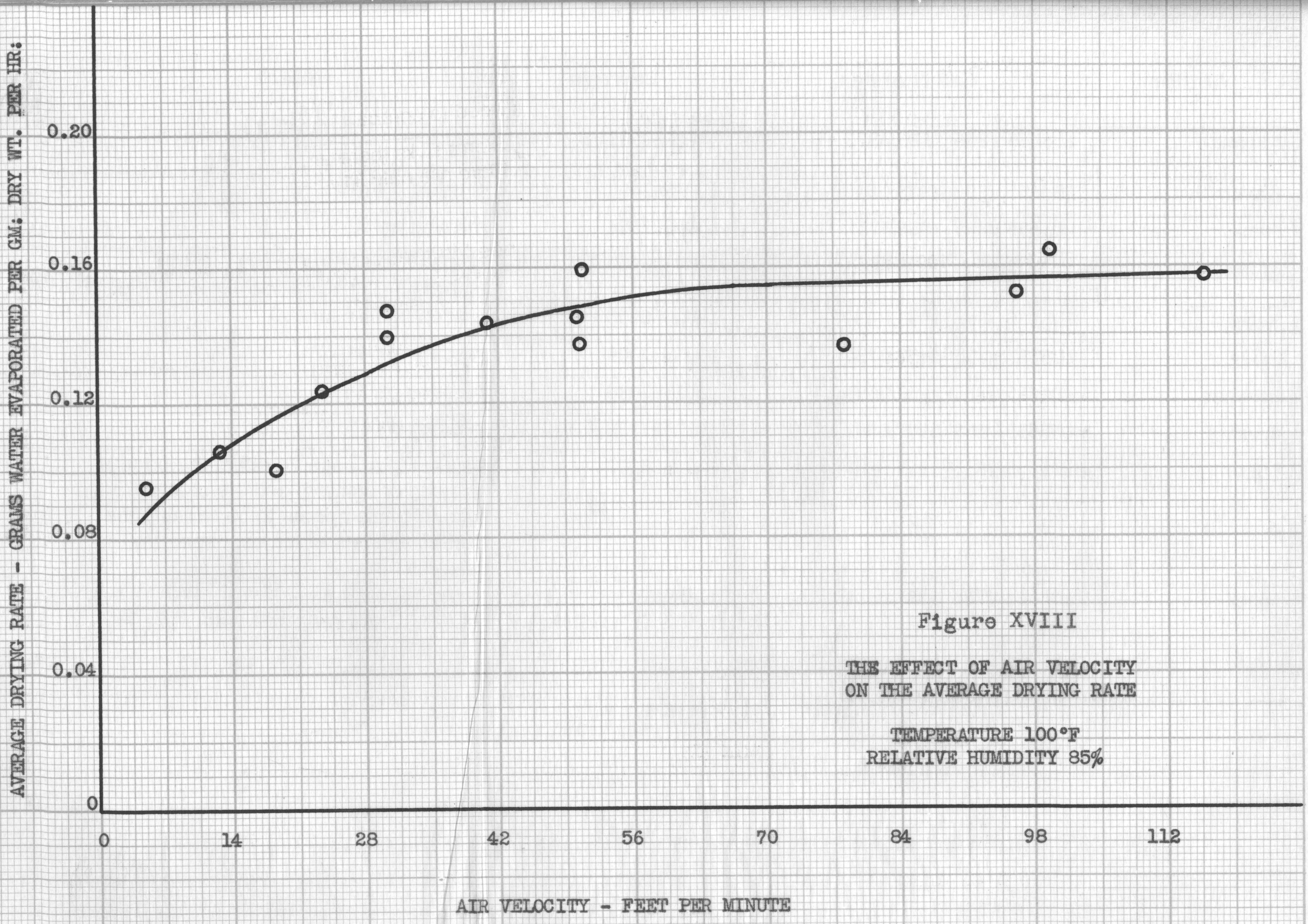

Figure XVIII

THE EFFECT OF AIR VELOCITY
ON THE AVERAGE DRYING RATE

TEMPERATURE 100°F
RELATIVE HUMIDITY 85%

TABLE XIX

AIR FRICTION PAST TOBACCO LEAVES

Data Taken During Preliminary Run Number One

Friction Determined by Weight Difference With Blower Off and Blower On

Time Hr.	Water Content *Gm/Gm	Weight Blower On Gm.	Weight Blower Off Gm.	Weight Differ. Gm.
0.000	5.070	2529	2513	16
0.500	4.442	2256	2240	16
0.500	3.930	2054	2041	13
0.500	3.600	1914	1900	14
0.500	3.342	1809	1799	10
0.500	3.115	1714	1700	14
0.500	2.917	1633	1622	11
0.500	2.358	1400	1387	13
0.500	2.190	1329	1320	9
0.500	2.022	1260	1253	7
1.000	1.895	1206	1199	7
1.000	1.782	1161	1157	4
0.500	1.745	1145	1139	6
0.500	1.320	967	958	9
0.500	0.962	817	806	11
0.500	0.756	732	721	11
0.868	0.495	623	614	9
1.132	0.324	552	539	13
1.000	0.243	518	512	6
0.500	0.248	520	514	6
0.633	0.243	529	518	11

*Gm/Gm Grams water remaining per gram dry weight

V. DISCUSSION OF RESULTS

Since it is impractical to determine the area of tobacco leaves, and the area is not of uniform thickness, it is apparent that a drying rate base on area would be erroneous and invaluable. It was found that a fairly good relation existed between dry and green tobacco weights. Therefore, all drying rates are expressed on the dry weight basis, as pounds of water evaporated per pound of dry weight per hour. It is apparent that any units used will give the same numerical value, providing time is in hours. In addition, the small weight of the sticks was not subtracted from the total weight. However, this does not affect the relative rate. This was done to insure design data as being overall values. If it is desired, a simple conversion may be made.

Drying Rate Curves: All drying rate curves consist of a plot of dry weight, versus the drying rate, as pounds of water evaporated per pound of dry weight per hour. It is evident that small errors in the data will show on the curve as magnified by the square. These curves indicate the effect of temperature, relative humidity, and air velocity on the relation between water content and the drying rate.

Curing Rate Curves: Curing curves are termed thus because they are designed to indicate the rate and degree of curing. They consist of plots of time in hours versus water content. These curves indicate the amount of water removed and the amount remaining over any period of time.

Basis of Calculation: The basis of all the calculations made was the bone dry weight of the tobacco. This is not the actual bone dry weight, but is the weight of the tobacco when its moisture content is in equilibrium with the air moisture, when this is a very low value. The values of the bone dry weight were determined by the equilibrium weight of the leaf at 180 deg. F. and 3 per cent relative humidity.

The results obtained are apparently very successful, since they explain the manner of curing, define the limits, and present a quantitative basis for the analysis and solution of tobacco curing problems. The data was correlated with that of Delamar's, taken from a different crop and season, and found to be in excellent agreement. Thus, it appears that the conditions required for curing, and their individual or collective effects do not vary greatly, regardless of the season or crop of tobacco. This may be explained by the fact that curing may be effectively executed over a range of drying conditions. While this range is rather narrow, there is apparently enough tolerance to facilitate curing regardless of slight differences in tobacco crops and stalk position.

The essential results obtained have been presented in design terms, thus facilitating the use of these results as criteria in the design and schedule of larger units.

The Dry Weight Basis: A distinct difference was observed between the ratio of green to dry weight of center leaves and that of the top leaves. The equation for the center leaf mean was found to be $W_g = 6.64E_d$, while that of the top leaves was found to be $W_g = 5.675E_d$, where W_g = green weight, and E_d = bone dry weight (see Fig. 1). Thus, it may be seen that the top leaves have a lower water content than the center leaves by $\frac{6.640 - 5.675}{6.640} \cdot 100 = 14.5$ per cent. This fact correlates the Rule of Zalensky, which states that the higher the stalk position, the more dense are the leaves.

The difference in the ratio of green to dry weight indicate that the top leaves must be finer in construction, having smaller cells, smaller vein structures, and therefore a more hindered and comples mechanism of drying than the center leaves. It must be understood, however, that this may not affect the initial rate of drying, since the stomatal pores of the smaller leaves are more numerous and effective in the transpiration of the water. This apparently was borne out by the data obtained, since no noticeable difference was observed in the curing of center and top leaves. Therefore, in view of the curing tolerance range and the accelerated drying rate of the smaller leaves, the same conditions apparently may be safely employed with center leaves and top leaves.

The relation between green and dry weight was found to be essentially a straight line function, which facilitated ease of calculation. For the purpose of a common base from which drying rates could be computed, it was decided to use the equation $W_g = 6.075E_d$, which seemed to most fairly represent the mean of all of the runs made. This value, in general, proved very satisfactory, although it does not bear out the relation between water content and the drying rate precisely. However, at the lower water contents, humidity is rather ineffective, and therefore, this basis becomes advisable, and the error diminishes to a very small per cent. Thus, a suitable datum plane was established, by which each rate of water loss could be compared.

The Preliminary Runs: Essentially, the value of the preliminary runs was in the proof of the fact that very accurate control must be employed if comparable and indicative results are to be obtained (see Figs. 2, 2a, 3, 3a). In addition, the tobacco developed brown spots in one hour, indicating that the leaves will be rapidly killed out if the drying rate is too fast, or the temperature too high.

Although the temperatures employed in these runs were not excessively high, the relative humidity was low enough to cause the leaves to dry before the process of etiolation could take place, thus fixing the green leaf color, and leaving the tobacco commercially worthless.

The intervals in which the killing occurred were marked by an excessively rapid drying rate. Immediately following this, a surface shrinkage occurred which caused the leaves to curl. This indicated that the stems of the leaves had dried much slower than the web. Therefore, the stems offer the greatest resistance to drying, and by this, specify the maximum drying conditions.

It is evident that curing cannot be executed at temperatures below atmospheric, and above 110 deg. F.;this may be explained by the fact that above this temperature killing occurred in a short time, even though an excessive quantity of water had not been vaporized from the leaf. However, the stability of the leaf apparently increased with water content.

The Effect of Humidity: The effect of humidity is shown in two manners, for the purpose of granting a clearer insight into the complex functions of this variable. The graduated effect of humidity is plotted by obtaining the average drying rate over five 3 hour periods (see Fig. 13) during the first period, and plotting these averages versus the relative humidity employed.

The curves for the 3 - 6 hour interval indicate that the relative humidity plays an important part in the initial stages of the process. A rather unexpected phenomenon occurs in that between 80 and 85 per cent relative humidity, humidity has little effect on the drying rate. This clearly indicates the importance of the vital functions of the cells of the leaves. If this may be taken as a criteria, then it may be said that practically all vital cell activity is stopped after twenty-one hours, for after this interval, the effect disappears.

At relative humidities of 75 per cent, an extremely rapid initial drying rate occurs. This excessive drying rate was accompanied by improper curing, with only about forty per cent of the leaf's surface being yellowed. Thus it is seen that an excessive drying rate in the initial stages, caused by low humidities or high temperatures, will not permit good curing. In addition, it may be clearly seen that the sensitivity to drying and therefore curing, decreases with a decrease in water content. Therefore, as the sensitivity decreases, it becomes possible to employ more extreme drying conditions, thereby increasing the drying efficiency.

At 90 per cent relative humidity, the drying rate was markedly decreased, thus indicating that an equilibrium between the air and the leaves was approached. An extrapolation of the curve indicates that at 96 per cent relative humidity, the green leaves would not lose any of their contained water, and the drying rate would become zero. The 9 - 12 hour interval curve shows similar results, but to a lesser degree.

The 15 - 18 hour interval curve is similar in effect, and indicates a further decrease in the effect of humidity, and also indicates that the effect of water content on the drying rate gradually causes humidity to become relatively less effective. The 21 - 24 and 27 - 30 hour interval curves indicate that humidity plays a negligible part in determining the rate of drying. Therefore, it may be seen that after 21 hours of curing, it is not necessary to control the relative humidity within such narrow limits as is initially required. Actually, a narrow range gradually widens as curing proceeds. This quality is of definite benefit, since it is desired to maintain a low humidity near the end of the yellowing process to prevent the formation of fungi growths.

From an overall viewpoint, it may be said that in order to insure good curing, the relative humidity of the air must be maintained within 80 - 85 per cent during the initial curing stages, and may vary as the curing proceeds over a successively broader range with little effect. The effect of humidity in the final period appears only as it determines the final equilibrium water content.

The effect of relative humidity on the average drying rate over ten hours (see Fig. 15) indicates clearly the large part played by this function in the initial stages. It may be observed that at a relative humidity just below 80 per cent, a gradual change in the normal slope of the curve takes place. Below this critical humidity poor curing resulted, while above this, excellent curing was obtained. This again indicates the effect of the vital cell processes. Apparently, the surface openings of the leaves were rapidly exhausted of their water content before stomatal action could check it. The stomatal pores were then fixed open, which resulted in an excessive drying rate that was too rapid to allow proper etiolation and food utilization to proceed normally.

Essentially, the effect of relative humidity is to increase the drying rate (see Fig. 17), and beyond certain limits, may cause the tobacco to spoil regardless of any favorable temperature. However, as curing proceeds, the effect of humidity becomes progressively smaller, and thus permits the use of broader ranges of this function.

The Effect of Temperature: The effect of temperature was indeed unusual, and was definitely affected by the vital action of the leaves and their water content. It is the action of the living cells of the leaf that give the drying characteristics of tobacco unusual properties not found in the usual drying problems. Itmay be said that in the initial stages of curing, the tobacco is hypersensitive to small changes in humidity and temperature.

Similar to the effect of relative humidity the effect of temperature is shown by a plot over three hour intervals of the average drying rate in the first period versus the temperature employed (Fig. 12), and also by a plot of the average drying rate over ten hours (Fig. 15) of the first period.

The 3 - 6 hour interval indicates an excessive drying rate at 110 deg. F., with a decrease in the 9 - 12 hour interval. This may be explained by the fact that the higher temperature gave rise to a rapid dessication of the leaf before the stomata could close. After closing, a lower drying rate was experienced. The rapid decrease in the water content may have aided in this action, although the time interval does not indicate that this may have been appreciable. In the 9 - 12 hour interval, it may be seen that between 100 and 105 deg. F., there was a very slight increase in the drying rate, with a decrease at 110 deg. F.; this is probably due to a combination of surface hardening and the lower water content. The effect of water content definitely appears in the 15 - 18 hour interval, which indicates a higher drying rate at 100 deg. F. After 15 hours, temperatures in the curing range have little effect on the drying rate, and after 27 hours, no increase is observed in the drying rate between 95 and 105 deg. F. This indicates a compensating relation between water content and temperature with regard to the drying rate. The ability of the tobacco to withstand higher temperatures as the drying proceeds is a very desirable property. If low temperatures and high humidities are employed near the end of the yellowing process, sponging of the tobacco occurs. Since the temperature may be raised about twenty per cent at this point, the tendency toward sponging may be decreased.

From the curve of the average drying rate over the first ten hours (Fig. 15), it may be seen that temperature plays an exaggerated part in the rate of drying, which is not in relation to normal vapor pressure dhanges. It may be seen that a change in the normal slope of the curve appears after a temperature of 105 deg. F. was employed. Above this temperature very poor curing resulted, and above 110 deg. F. no curing was experienced. Below 105 deg. F., excellent curing resulted in all cases where the humidity was suitable. Thus it may be seen that temperatures in the range of 105 deg. F. cause a too rapid drying to take place, while above 110 deg. F. the tobacco was killed before etiolation could be accomplished.

Essentially, the effect of temperature is to abnormally increase the drying rate in the first period (Fig. 16). The absolute upper limit for the initial stages of curing was found to be 110 deg. F., while it is not safe to exceed 105 deg. F.

The Effect of Air Velocity: Air velocity may be considered to have a practically negligible effect on the overall drying rate, over the range of velocities tested (Fig. 18). Contrary to the findings of other investigators, the data taken was not linear with the drying rate. This may be partially explained by the fact that the velocities employed in this work far exceeded that of other investigators.

After a velocity of 56 feet per minute has been exceeded, there is apparently no further effect on the drying rate by higher velocities. However, it was noted that tip dry became excessive in the neighborhood of one hundred feet per minute. In view of the fact that the average drying rate had not increased, it may be said that higher velocities set up an unusual aerofoil section which principally affects the leaf tips.

In packed tobacco, excessive leaf shaking was observed at a velocity of 90 feet per minute, which is considerably higher than the value obtained for single leaves. Therefore, it may be said that 90 feet per minute is the highest safe air velocity. In view of the small effect of air velocity, it is more efficient to use the lowest possible air velocity. This limit is determined by that velocity which does not permit an appreciable change in air conditions to take place as the air passes through the tobacco, which may be packed in depth. In addition, it is not wise to employ velocities above 90 feet per minute, thus insuring uniformity of drying.

Curing: Within the curing range, as set down in the previous paragraphs, high quality curing resulted. The most important overall result of the experiments was that the time required for curing was reduced by 100 to 150 per cent of that required by the present practice.

By the employment of air conditioning methods, a very even control is effected, and the ease with which the varying conditions required for curing could be attained was markedly increased. This is the key to the value of air conditioning.

The first period of the process was not greatly affected with regard to the time required for completion by any of the conditions that were tested. Therefore, it may be said that the time required for etiolation is practically constant, although some increase in the rate was attained by employing conditions of high temperature and very high relative humidities. The second period was reduced by about ten per cent in some cases by gradually decreasing relative humidity. However, no appreciable saving in time was observed until the third and fourth periods were entered. It was possible to completely kill, dry,and order the tobacco in five hours. This same process requires from two to four days in actual practice.

Since the third period requires the majority of fuel in practice, a reduction of time from two days to four hours will represent a large saving in the fuel required for curing. In addition, this decrease in time increases the season capacity of a tobacco barn, since a shorter time is necessary for each harvest. Also, the farmer may be required to tend his barns a much shorter time than is required at the present. By the application of suitable control instruments in connection with a clock mechanism, the labor required in the curing process may be reduced to that of fueling, loading and unloading.

Thus, it is seen that the application of conditioned air to the process of curing may result in large savings in both fuel and labor. The principal objection is that of the high initial first cost of the equipment. In addition, farmers would have to be trained in the use of such equipment.

Composite Run: The composite run failed to cure as well as it was hoped (see Fig. 11). The explanation for this lies in the fact that the temperature was increased too early.

However, it did indicate that sponging could be prevented, and that the method of changing conditions was more efficient than the application of constant conditions.

Air Friction: The friction of the air past the tobacco leaves varied in accordance with the physical condition of the leaves (see Table 19). Thus, curled leaves presented more than the normal amount of drag, while limp leaves presented the minimum. The fan horsepower, is calculated from the maximum resistance, which was found at the end of period three.

VI. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The Effect of Temperature: From the results of the experiments, the following is concluded:

(1) The initial range of temperature through which tobacco may be cured is relatively narrow. The best range was found between 95 and 105 deg. F., at 85 per cent relative humidity.

(2) Temperatures above 110 deg. F. during the first few hours of the process will rapidly kill the tobacco, and prevent curing.

(3) Temperatures between 105 and 110 deg. F. do not rapidly kill the tobacco, but cause an excessive drying rate, thus decreasing the quality of the tobacco.

(4) The tobacco becomes progressively less sensitive to temperature as drying proceeds, thus facilitating the use of higher temperatures at the end of the yellowing, thus preventing fungi formations.

(5) Temperatures above 180 deg. F. in the killing period are not advisable.

(6) In the first period, temperature exerts an abnormally high effect on the drying rate.

The Effect of Humidity: From the results of the experiments, the following is concluded:

(1) The best humidity range for curing was found to be between 80

and 85 per cent relative humidity, at 95 deg. F.

(2) In the initial stages of curing, relative humidity exerts a large influence. Below 75 per cent relative humidity, too rapid dessication of the leaf took place, thus preventing good curing.

(3) Relative humidities above 85 per cent caused excessive sponging.

(4) The effect of relative humidity becomes progressively smaller as drying proceeds. Thus, relative humidities of as low as 50 per cent may be employed at the end of the yellowing to prevent leaf sponging.

(5) The internal diffusion resistance controls the second and third periods. Therefore, relative humidity is of small importance over ranges of about twenty per cent.

(6) Relative humidity determines the final equilibrium water content.

The Effect of Velocity:

(1) Velocity of the air has little effect on the average drying rate, within the range of 40 to 125 feet per minute.

(2) Above 100 feet per minute, excessive tip drying takes place.

(3) Above 90 feet per minute, excessive leaf vibration occurs.

(4) The minimum air velocity is that which does not permit the air conditions to materially change as the air passes the tobacco.

The Composite Run: From the results of the experiment, the following is concluded:

(1) Greater drying efficiency was obtained.

(2) Sponging was eliminated.

Curing: From the results of the experiment, the following is concluded:

(1) The time required for curing by employing air, conditioned and varied between 48 and 50 hours.

(2) The time required for curing was reduced by 100 - 150 per cent of the time required by the present practice.

(3) The fuel requirements were greatly reduced.

(4) The total labor requirements were greatly reduced.

(5) A uniform grade of well cured tobacco was obtained.

(6) Small discrepances in the degree of ripeness may be overcome.

(7) Unifrom conditions for curing were obtained throughout the unit. Local over-heating was completely eliminated.

(8) Stem greenness of the cured tobacco was entirely eliminated.

(9) The process readily lends itself to the application of automatic control instruments.

(10) The conditions required to cure optimum tobacco do not vary greatly from year to year, or with stalk position. The curing range empodies the required conditions, regardless of leaf character.

Recommendations

It is the opinion of the three men who have worked on this problem that further laboratory procedure would not be nearly as effective as the commencement of a field program. During the past two years the mechanism, limits, and curing characteristics have been exhaustively investigated. In addition, the drying rates and the relations of temperature, humidity, and air velocity have been conclusively established by the data taken during these experiments. It is, therefore, logical to believe that the time is now ready to endeavor to apply air conditioning methods on a larger scale under field conditions.

Further Laboratory Procedure: If it is deemed wise to continue experimentation under laboratory conditions, the following phases of the process are recommended for investigation.

(1) Investigate the possibility of improving the yellow color
by by (a) heat treatments, (b) the admixing of quantities of gases such as carbon dioxide and ethylene.

(2) Investigate the sensitivity to killing of the tobacco in the first period, after varying time intervals.

(3) Investigate the leaf action during the second period, and correlate the limits.

(4) Experiment with the composite type run of varying conditions, and establish more conclusively the maximum curing efficiency conditions.

Field Study: The logical field study divides itself into two distinct phases. Experimentation is recommended in the case of barns, and on a community type curer. The community type is of distinct advantage in that it may have the capacity of ten to twenty barns, all operated by one man, and requiring an initial cost of roughly 50 per cent less than that for the equivalent number of barns. However, barns are constructed over the entire South, and their investment must be realized before any cooperative curing unit may be economically installed.

Barn Experimentation: In the case of barn experimentation, the following system is suggested. Withdraw air from the lower right corner of the barn; pass this through a cross equipped with a damper to facilitate partial or complete recirculation; the is then drawn through a blower, thence to a heating compartment. This heating compartment may be equipped with an oil burner, above which is mounted a small, simple boiler. The products of combustion are allowed to follow the air, since carbon dioxide has no detrimental effect upon the tobacco. From the heater, pass the air by a steam spray, and humidify as desired; pass the air through an inside duct to the top of the barn, and allow to flow against a deflecting plate, and thence downward through the tobacco.

Control is exercised by a hygrostat and thrmostat mounted in the duct after the steam spray, and by the damper setting. A clock mechanism may be employed, thus facilitating automatic operation.

Community Type Curer: It is suggested that this type operate on the principle of the ring furnace. Thus, the structure would consist of a number of compartments, which are alternatingly charged and discharged, according to the circuit. Air is supplied by two ducts, one supplying air of a high temperature and low humidity, and one supplying air of a low temperature and high humidity. The exhaust air will be reconditioned, or fed to the low temperature system, where it may be used after the addition of steam. Proper conditions are supplied to the compartments by a blending chamber, equipped with a revolving damper, and fed by two ducts.

The conditioning equipment consists of an oil burner and fan for the high temperature system, while the low temperature system employs a small oil burner and steam. Thus, a highly efficient thermal system is introduced.

Control is maintained by a thermostat in the high temperature duct, and a thermostat and hygrostat in the low temperature duct. The blending is controlled by a clock mechanism, or by a manually operated damper.

VII SUMMARY

The flue curing process for tobacco is practiced today in nearly the same manner as when tobacco first became of commercial importance, with no definite procedure being followed. A scientific study has proved that the curing process is accurately defined within narrow limits, and that control rather than art may be more definitely relied upon.

Tobacco curing differs from a true drying process in that both physical and chemical changes are involved. Since it is impractical to evaluate the chemical changes because of their complexity, the physical changes were investigated, for they govern both the chemical and physical changes which take place.

Drying rate curves for each period of the curing process were obtained over a wide range of constant conditions of temperature, relative humidity, and air velocity. Correlation of these curing curves indicate the narrow limits of the conditions required for satisfactory curing, and the critical points beyond which resulted in poorly cured tobacco.

From the results obtained, air conditioning improves the process by (1) reducing the time approximately one-half, thus doubling the capacity of the barns; (2) the production of uniform quality tobacco completely eliminating loss from improper curing; and (3) large reductions in labor and fuel requirements.

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