DRYING OF CELLULOSE NITRATE PLASTIC
BY MEANS OF CONDITIONED AIR

by

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I. INTRODUCTION

Cellulose nitrate is one of the oldest synthetic plastics. Its first application was in 1868 when John W. Hyatt produced a material for billiard balls by mixing cellulose nitrate and camphor. This product is known as celluloid. The production of cellulose nitrate plastic in the United States increased to a peak of an annual production of 18,161,000 pounds in 1946, then gradually decreased to 5,266,000 pounds in 1954. Although new plastics have largely replaced it, cellulose nitrate plastic has many excellent properties and is still needed in many applications.

In the processing of cellulose nitrate plastic a serious problem, checking and warping, is encountered during drying. In the ordinary process of drying by convection heat, the liquid content differences are set up from center to surface, and the surface tends to dry and shrink before the interior. This has two bad effects. The first is that there may be developed a hardened layer on the surface, known as case-hardening, which retards the diffusion of the remaining internal liquid. The second effect is that the shrinkage will cause the material to warp or check, or otherwise change its gross structure. To avoid these effects controlled rates of drying must be employed.

In the case of drying cellulose nitrate plastic humidification of the drying air with alcohol might be the most effective method of control, but it is not practical and involves fire hazard. It seems possible that the humidification of the drying air with water might serve the same purpose. Water from air diluting the alcohol on the surface of a solid will lower the vapor pressure of alcohol and decrease its rate of evaporation from the surface of the solid. If, in addition, radiant heat is applied, acting by penetration into the solid and increasing its temperature, it should increase the diffusion rate of liquid in the interior of the solid. If the rate of evaporation is decreased and the rate of diffusion increased, it should be possible to prevent the shrinkage and uneven drying, thereby decreasing the overall drying time and reducing warping and checking.

The purpose of this investigation was to determine the effects of relative water humidity of the air, convection heat and radiant heat for air drying cellulose nitrate plastic.

II. LITERATURE REVIEW

Cellulose Nitrate

The properties of cellulose nitrate plastic and of the solvent to be removed are reviewed in this section as their effects are closely interrelated.

Nitrogen Content of Cellulose Nitrate. The cellulose molecule(15) is a polymeric chain consisting of repeated glucose units. Each of these monomeric units contains three reactive hydroxyl groups as $C_6H_7O_2(OH)_3$. Consequently, three kinds of nitrates are expected to be formed after nitration, namely: mono-, di-, and trinitrate. It is not possible to prepare a cellulose nitrate with only one degree of substitution, a mixture of the three degrees of substitution accompanied with different nitrogen content always being formed. The nitrogen content(19,25) for cellulose nitrate used as plastic is from 10.9 to 11.2 per cent. The properties exhibited by cellulose nitrate depend mainly on the relative proportion of hydroxyl groups and nitrate groups.

Alcohol in Cellulose Nitrate. After the nitration of cellulose(12,20), fresh water is added to purify the products. Upon completion of the purification treatment, the slurry of cellulose nitrate in water is pumped to draining bins where the major portion of water drains out. Presses apply pressure which forces out more water. The remaining water is removed by displacement with alcohol which is pumped through the cellulose nitrate while held under pressure. A large part of the alcohol can be recovered. The remainder of the alcohol must be dried out carefully in order that a satisfactory finished product can be obtained.

Vapor Pressure of Ethyl Alcohol-Water Solutions. Chu(9) compiled the data of Jones(10) on the vapor equilibrium data for the binary system of ethyl alcohol and water. The data are shown in Table I for the temperature of 50 °C (122 °F). It is shown that at the same temperature the total vapor pressure decreased with decreasing mol per cent of ethyl alcohol in the liquid. The mol per cent of ethyl alcohol in the vapor decreased with that in the liquid. While these data apply to vapor in the absence of air, the partial pressure of the components in air at any pressure can be calculated.

TABLE I

Vapor-Liquid Equilibrium Data of Ethyl Alcohol and Water

Mol % of Ethyl Alcohol in Liquid	Mol % of Ethyl Alcohol in Vapor	Temperature °C	Pressure mm Hg
4.6	29.0	50.50	133
9.3	42.4	50.52	157
12.25	48.2	50.25	164
15.8	50.7	50.75	177
34.25	58.6	50.5	196
33.3	59.0	50.51	200
51.3	64.9	50.2	207
82.4	84.5	50.2	220
90.8	91.0	50.5	225

Chu, J. C., R. J. Getty, L. F. Brennecke and R. Paul: "Vapor-Liquid Equilibrium Data," p. 90. Reinhold Publishing Corp., New York, N. Y., 1950.

Jones, C. A., E. M. Schoenborn, and A. P. Colburn: Ind. Eng. Chem., 35, 666 (1943).

Properties and Applications of Cellulose Nitrate Plastic. Cellulose nitrate plastic(17,26) is the toughest of all thermoplastics and has good dimensional stability. It has excellent chemical resistance as to animal and vegetable oils, dilute acids, alkalies, and water. The water absorption is very low, 0.6 to 2.0 per cent for 24 hours immersion.

The chief disadvantages of cellulose nitrate plastic are its flammability and decomposition on continued exposure to light. This undesirable characteristic has been improved to some extent in recent years by the use of plasticizers containing chlorine and phosphate. Another disadvantage of the material is its tendency to discolor and become brittle under sunlight.

Usually, cellulose nitrate plastic is not used at temperatures above 140 °F because it softens in the region of 158 °F.

Cellulose nitrate plastic is not adapted to compression or injection molding because of its sensitivity to heat, and hence is not marketed as a molding powder. By the methods of fabrication of drawing, sawing, blowing, and blending, this plastic can be made in the form of sheets, rods, tubes, and films, which in turn are converted into many items of decorative and functional value, such as personal accessories, sports equipment, tableware, toilet articles, and industrial pieces.

Theory of Drying

The most important process for drying liquids(27,28) from solids depends upon first vaporizing the liquid after which it is carried away in the vapor form from the structure by which it was held. If air or some inert gas is used to carry away the vapor formed, the process is called air drying. If circulating water is used instead of air, the process is called water drying. If the vapor is passed to a condenser, a pump being employed to withdraw the air from the apparatus, it is spoken of as vacuum drying. The process used in this research is air drying.

Mechanism of Air Drying of Solid Materials. The general case of drying(4) may be considered as the transfer of liquid from the interior of a solid into the drying medium. It involves two steps: first, the diffusion of the liquid through the interior of the solid to the surface, and second, the evaporation from the surface of the solid into the main stream of drying medium.

Assume that over the wet solid there is flowing a stream of air of constant temperature, velocity, direction, humidity, and pressure. This process is known as drying under constant drying conditions. A typical rate of drying curve(6) under constant drying conditions is shown in Figure 1.

In the initial stage of the drying of a very wet solid(6,21) under constant drying conditions, the surface is completely wet with liquid, and the drying is similar to the evaporation of that liquid. As long as the surface is wholly wet with liquid, the rate of evaporation is independent of the solid but is essentially the same as the rate of evaporation from a free liquid surface, and under constant drying conditions the rate of drying is constant. This stage is termed the "constant rate period," as <u>ab</u> in Figure 1. However, at some definite liquid content the rate of drying begins to decrease, and the range from there to dryness is called the "falling rate period," as all portions of the curve below <u>b</u> in Figure 1. The liquid content at the point <u>b</u> is called the "critical

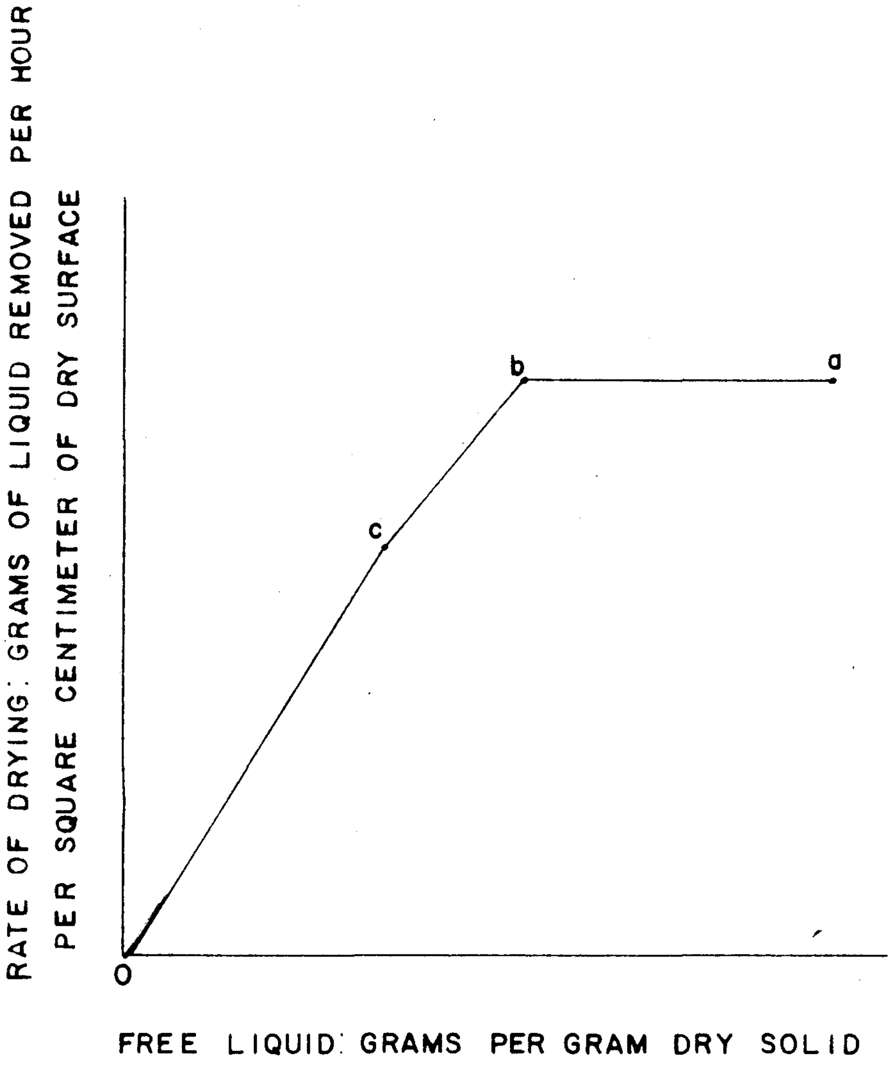


FIGURE I. TYPICAL RATE OF DRYING CURVE

BADGER, W.L. AND BANCHERO, J.T.: "INTRODUCTION TO CHEMICAL ENGINEERING," P. 492. McGRAW-HILL BOOK CO., NEW YORK, N.Y. 1955 liquid content" which indicates the end of the constant rate period and the beginning of the falling rate period. When dried for a very long time, the liquid content of the solid approaches an ultimate value which depends primarily on the relative humidity of the air and is termed the "equilibrium liquid or moisture content".

The Constant Rate Period. During the constant rate period(21), liquid is diffusing to the surface of the solid at a rate equal to that of evaporation from the surface, and the rate of drying is controlled by the latter. The solid assumes a constant equilibrium temperature, just as a free liquid surface assumes the wet-bulb temperature of the air. When the heat necessary for evaporation is supplied only by conduction through the same surface air film through which the vapor diffuses, the surface assumes the wet-bulb temperature of the air. When heat is supplied in other ways, such as by radiation or by conduction from dry surfaces in contact with the material, such as the shelves on which it rests, the surface temperature is higher than the wet-bulb temperature, and the rate of drying is increased.

The Falling Rate Period. The falling rate period(23) is in general divisible into two secondary periods or zones, which from the mechanism of drying may be called the "zone of unsaturated surface drying", or the first falling rate period, and the "zone where internal liquid diffusion controls", or the second falling rate period.

The zone of unsaturated surface drying follows immediately after the critical point, as bc in Figure 1, page 9. The decrease in the rate of drying in this zone is due to the decrease in the wetted surface of the material. The surface is no longer completely wetted, but dry portions of the solid are exposed to the air film, so that the rate of evaporation per unit of total surface is reduced. The effective wetted surface in this zone is frequently a linear function of the water content, so the curve representing the rate of drying against liquid content of the solid is straight in this region. The mechanism of drying is essentially the same as during the constant rate period. The rate is independent of the thickness of the material being dried, and the factors discussed below as influencing the rate of drying in the constant rate period have similar effects on the rate of drying in this zone.

The maximum rate of diffusion of liquid to the surface decreases with the liquid content of the material, so that a second critical point, as <u>c</u> in Figure 1, page 9, is reached beyond which the resistance to internal liquid diffusion is greater than the surface resistance to vapor removal. This is the zone as <u>co</u> in Figure 1, where internal liquid diffusion controls the rate of drying.

<u>The Possible Cases of Actual Drying</u>. As pointed out above, the constant rate(6,24) period ends at the critical liquid content. In case the critical liquid content is less than the desired final liquid content, the constant rate period constitutes the whole drying process. In case the initial liquid content is less than the critical, no constant rate period appears. Obviously, if the initial liquid content is less than the second critical point, internal liquid diffusion will control throughout the drying process.

Wenzel(29) reported that, during the constant-drying-rate period, the increased roughness of the solid surface may lead to higher rates of evaporation than from a free liquid. He also pointed out that during the falling-drying-rate period, different kinds of variation in drying rate curves may be obtained. They may be concave upward or downward. Badger(7) explained that the point of discontinuity in the falling rate period of the curve, as c in Figure 1, page 9, does not always occur, since the first falling rate period corresponds to that part where the wetted surface continually decreases, and the second falling rate period begins when the surface is completely dry. For the cases where the change of drying rate from partially wetted to completely dry surface is very gradual so that no sharp change is detectable, discontinuity between the first falling rate period and the second falling rate period will not occur.

The Factors Affecting the Rate of Drying. The major operating factors affecting the rate of drying are velocity of the air, humidity of the air, direction of the air, and the solid stock temperature.

Air Velocity. During the constant rate period(22) and the first falling rate period, the rate of drying is controlled by the rate of vapor transference through the surface air film. Factors which affect thickness of the air film influence the rate of drying in these two periods. Perhaps the most important one of these factors is the velocity of the air past the surface. It has been shown that the rate of drying could increase in proportion to the 0.8 power of the air velocity during these two periods. However, the velocity of air has little effect in the second falling rate period.

Air Humidity. Vapor from the surface of the liquid(21) on the solid must diffuse through the air film in contact with the surface. The driving force for this diffusion is the difference between the vapor pressure of this liquid at the interface and the partial pressure of vapor in the air stream. Thus, in the first two drying stages when evaporation controls, if the humidity of air is increased, the rate of drying must decrease; and the rate of drying may be accurately controlled by controlling the humidity of the air. In the second falling rate period, the humidity of the air only affects the equilibrium water content.

Air Direction. In the first two stages (2) when evaporation controls the rate of drying, if the air is flowing perpendicular to the surface, the rate of drying should be higher than if the flow is parallel to the surface, since under the former case the film is thinned down more by the air flow than in the latter. The air direction has no effect if diffusion controls.

Solid Stock Temperature. Increasing the temperature of the stock (3) by increasing the air temperature increases the rate of drying in both the evaporation and the diffusion phases. If evaporation controls, increased temperature increases the rate of evaporation, because the per cent saturation of the air at the interface decreases, and so the driving force becomes larger. If diffusion controls, the rate of diffusion is increased because of decreased viscosity. In general, increasing the temperature will increase the drying rate to a greater extent if evaporation controls than when diffusion controls.

Effects of Shrinkage. An important factor(7) in controlling the drying rate is the shrinkage of the solid as the liquid content is lowered. At the start of drying, the liquid content may be uniform through the solid, but an appreciable liquid content gradient is soon set up from center to surface. In the case of a material which shrinks as it dries, especially as colloidal and fibrous materials, the surface tends to shrink before the interior, and unless the material is sufficiently elastic to take up the resultant strains some permanent distortion, such as warp or surface cracking, results. In other cases, as the surface layer dries and shrinks it becomes relatively impervious to the diffusion of the remaining internal liquid, producing the so-called case-hardening effect.

When these effects must be avoided, controlled humidity drying is employed, using air of sufficiently high humidity to decrease the difference between the vapor pressure of liquid on the surface of the solid and the partial pressure of vapor in the air stream, thus reducing the rate of drying. This often makes it possible to keep a small liquid gradient from the inside to the outside of the solid, and so decrease the effect of shrinkage.

<u>Equilibrium Liquid Content</u>. When a wet solid(5) is brought into contact with air under constant conditions and the exposure is sufficiently long for equilibrium to be reached, the solid will reach a definite liquid content that will be unchanged by further exposure to this same air. This is known as the "equilibrium liquid or moisture content" of the material under the specified conditions. For air of zero humidity the equilibrium liquid content of all materials is zero.

For any given relative humidity, the equilibrium liquid content varies greatly with the type of material. For the same material, the equilibrium liquid content decreases with an increase in the air temperature.

Characteristics of Radiant Heat

The characteristics of radiant heat are presented as follows.

General. The radiant energy(1), not being absorbed or obstructed by the atmosphere through which it passes, can penetrate the substance being dried. As the radiant energy encounters the substance and is absorbed, it is converted into heat. Nelson and Silman(18) stated that all heating by radiation, whatever the nature of the source, is largely dependent on radiation of those wave lengths. The infrared or heat rays correspond to wave lengths from 8,000 to 4,000,000 Å which are longer than those normally visible with the human eye, but for most industrial applications the range may be narrowed down to a range from 8,000 to 2,500,000 Å.

Nelson and Silman also stated that energy must be radiated to the receiver at as high a rate as possible, so that loss by convection is limited. Also, the surrounding air should be kept at as high a temperature as possible so that the receiver will not tend to lose heat until it has reached the temperature of the air. Such considerations are important if the effects of radiant heat are to be shown with any accuracy.

Nelson and Silman further stated that in the application of radiant heat to drying one must not forget that despite the fact that radiant heat can supply the heat to evaporate the liquid, the vapor so formed must be removed from the immediate vicinity of the material. Radiant heat cannot perform the latter, so a flow of air is necessary.

Infrared Radiant Heat. Carber and Tiller(8) stated that infrared radiant heating has found application in many vaporization processes, including the drying of textiles and explosives. When using infrared radiant heat on materials having low thermal conductivities, such as plastics, unless great care is exercised the heat will not be conducted away from the surface fast enough and burning may occur. Radiant heat has been employed alone and combined with convection heat to produce heat transfer rates which are higher than those available with convection heat alone.

In the drying of sawdust, sugar, celotex, filter-cel, cloth, and calcium carbonate, Winegard and

Rozier(30) reported that infrared and steam heated air combined gave the highest drying rates and the lowest drying times. Infrared alone was next in order with respect to rates and times, and steam heated air resulted in the lowest drying rates and the longest drying times.

Other Influences. Garland(13) stated that the use of radiant heat must be applied with good sense to a drying problem. In the drying of wool felt using mild heat, the outside of the material was not damaged but the interior was badly scorched. This was not due to extreme penetration of the heat, but because the outside of the material was cooled by air currents while the interior was not so cold. During the drying of wet insulating board, a thermocouple penetrating the interior of the material showed a drop in temperature to the freezing point, while the outer surface was badly scorched and charred. Too rapid heating of the surface had caused such a rapid rate of evaporation of the liquid that the large temperature drop had resulted. The radiant heater may be placed as close as possible to the material, but the drying rate will determine the final position.

Assume that the total radiant energy(14) falling on a substance is unity, then the addition of all the fractions absorbed, reflected, and transmitted by the substance must also be unity. The majority of engineering materials are opaque substances having zero transmissivities, but there are none which completely absorb or reflect all the incident energy. If a body had a complete or unity absorptivity, it must be a perfect black body.

The quantity of radiant energy converted into heat by the substance depends on the amount of energy it absorbs.

Drying of Cellulose Nitrate Plastic

A search of the literature revealed very little work on the study of the drying of cellulose nitrate plastic. However, Johnson(11) reported that drying of cellulose nitrate plastic employing radiant heat was faster than drying employing only convection heat from air. The interior temperature of 0.045-inch thick cellulose nitrate plastic was increased by 31 °F by employing radiant heat. The source of radiant heat was from one electric hot plate whose surface temperature was 600 °F, placed five inches from the specimen. Johnson also reported that there was a cooling effect on the drying specimen due to high air velocity. Air velocity of 979 feet per minute over a drying specimen of cellulose nitrate plastic lowered its interior temperature from 103 to 78 °F.

III. EXPERIMENTAL

This section of the thesis contains the purpose of the investigation, plan of experimentation, materials and apparatus used, data and results obtained, and sample calculations.

Purpose of Investigation

The purpose of this investigation was to determine the effects of relative water humidity of the air, convection heat, and radiant heat for air drying cellulose nitrate plastic. Proper control of conditions should result in improvement in the drying of cellulose nitrate plastic and shortening the drying time.

Plan of Experimentation

The plan of experimentation used in this investigation was as follows:

Literature Review. In reviewing the literature special attention was given to the publications concerning the solvents and properties of cellulose nitrate, the theories of drying, air conditioned drying, and the effect of radiant heat in drying.

Test Material. Cellulose nitrate plastic sheet containing nitrogen from 10.9 to 11.2 per cent was used as the test material. Ten grams (for a thin sheet) or thirty grams (for a thick sheet) of the plastic was saturated with ethyl alcohol, diffused uniformly. Then the wet specimen was dried to constant weight under controlled conditions.

Preliminary Tests. Preliminary tests were conducted to determine the required diffusion time of alcohol in the plastic, the nature of the general influence of relative water humidity in the air, and the air temperature on the drying rate of cellulose nitrate plastic.

Operational Tests. After the results of the preliminary tests were obtained, operational tests were conducted, controlling the variables, as follows, all with a constant air velocity of 50 feet per minute.

Effect of Relative Water Humidity. Tests were made with relative water humidities of 30, 40, 50, and 60 per cent at a constant air temperature of 120 °F.

Effect of Convection Heat. Tests were made with air temperatures of 110, 120, 130, and 140 °F at a constant relative water humidity of 40 per cent.

Effect of Radiant Heat. Tests were made at different internal temperatures of the plastic by supplementing the convection heat with radiant heat at constant air temperature and relative water humidity.

Analysis of Results. The data obtained from the above tests were used to analyze the effects of the variable conditions and to evaluate their possible advantages in drying cellulose nitrate plastic.

Materials

The following materials were used in the experimental work.

Alcohol, Ethyl. Technical grade, 95 per cent, meets ACS specifications. Manufactured by U. S. Industrial Chemicals, Inc., Baltimore, Maryland. Used as solvent for cellulose nitrate plastic.

Desiccant. Sulfuric acid, technical grade, 96 per cent. Manufactured by J. T. Baker Chemical Co., Phillipsburg, New Jersey. Used to dehydrate the dried samples.

Plastic. Pyralin (cellulose nitrate plastic sheet containing nitrogen from 10.9 to 11.2 per cent). Gray-colored pieces, 0.18 centimeter thick; brown-colored pieces, 0.60 centimeter thick. Obtained from E. I. du Pont de Nemours and Co., Arlington, New Jersey. Used as test material.

Steam. Steam was drawn directly from the power plant main running to Davidson Hall. Used for heating and for humidification.

Thread. Six-cord, No 8 cotton thread. Obtained from Black-Logan Co., Blacksburg, Virginia. Used to suspend sample in the drying chamber from the balance.

Wire. Copper enameled, thermocouple wire, B & S gage, No 30. Obtained from Leeds and Northrup, Philadelphia, Pennsylvania. Used in thermocouples.

Wire. Constantan enameled, thermocouple wire, B & S gage, No 30. Obtained from Leeds and Northrup, Philadelphia, Pennsylvania. Used in thermocouple.

Apparatus

The following apparatus was used in the experimental work.

Anemometer. Taylor, model No 3132, fan type, diameter 4 inches, reading in feet. Obtained from Taylor Instrument Co., Rochester, New York.

Balance. Laboratory type, triple beam, division 0.1 gram, capacity 311 grams. Obtained from Fisher Scientific Co., Silver Spring, Maryland. Used to weigh specimen.

Beaker. Pyrex, capacity 600 ml. Obtained from Fisher Scientific Co., Silver Spring, Maryland. Used to hold ethyl alcohol in which the specimen was immersed.

Blower. Centrifugal type, belt drive, wheel diameter 14 inches. Obtained from Sturtevant Mill Co., Boston, Massachusetts.

Bottle. Glass bottle, with tight cover, diameter of mouth 7 cm or larger. Obtained from Fisher Scientific Company, Silver Spring, Maryland. Used to hold the wet plastic for the first three hours' diffusion of alcohol.

Desiccator. Glass, removable top, diameter 10 cm. Obtained from Fisher Scientific Co., Silver Spring, Maryland. Used to hold the plastic for thorough diffusion of alcohol, and to dehydrate the dried specimen to constant weight.

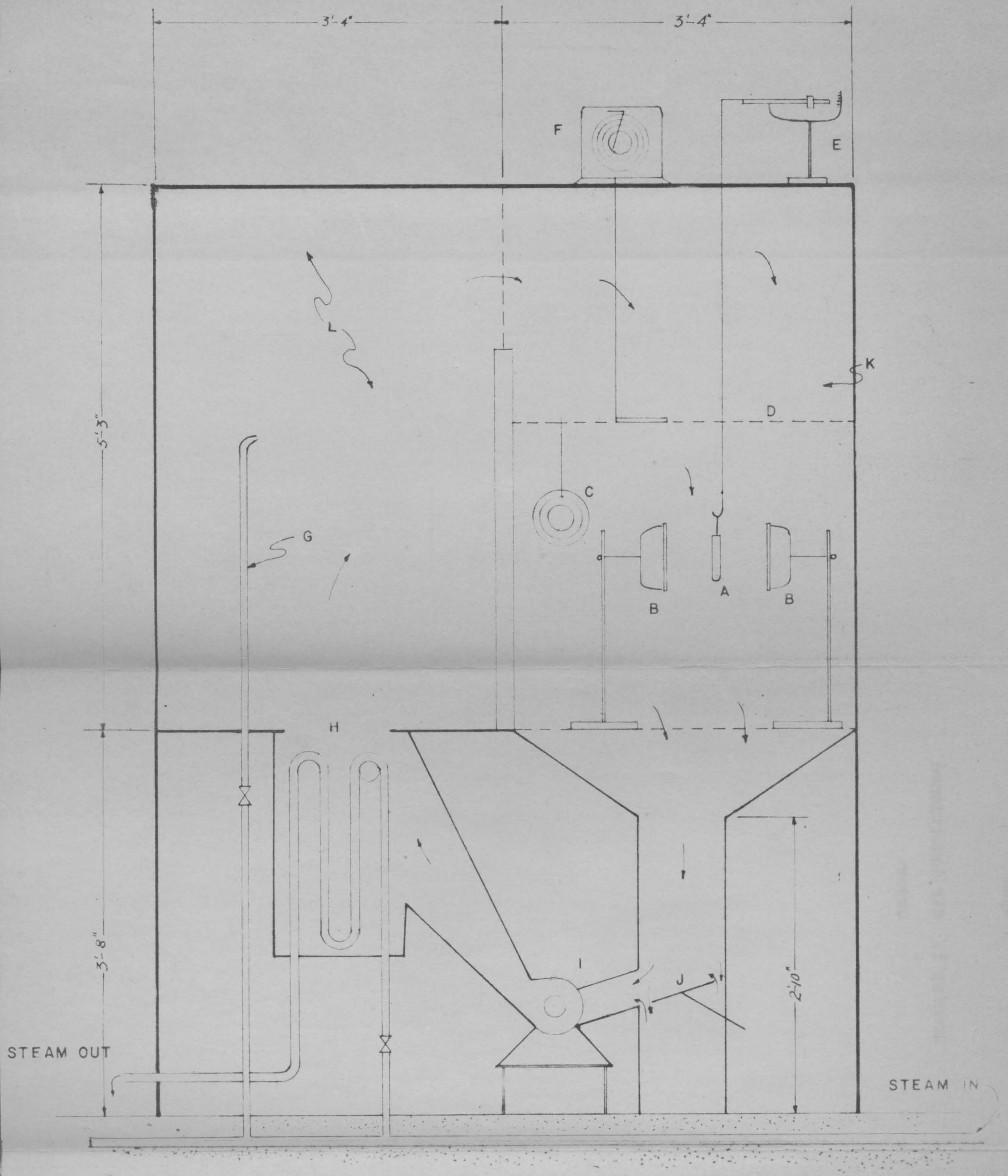
Dryer. Air conditioned. Framework of angle iron overlaid with galvanized sheet iron, and insulated with 1/2-inch cellotex. The construction is shown in Drawing 1, page 30.

Heater. Autemp, laboratory hot plate, ac, 115 v, 450 w. Obtained from Fisher Scientific Co., Silver Spring, Maryland. Used as radiant heat source.

Motor. Three hp, 1720 rpm, ac, 220 v, 60 cy. Obtained from General Electric Co., Schenectady, New York.

Potentiometer. Brown, portable, model No 126W3, range from 0 to 71 millivolts. Obtained from Minneapolis-Honeywell Regulator Co., Philadelphia, Pennsylvania. Used to measure electromotive force of the thermocouple connected to the drying specimen.

Relative Humidity Recorder. Bristol recording humidigraph, model 44, 4-inch recorder. Obtained from Bristol Co., Waterbury, Connecticut. Used to record the relative humidity of the air.



LEGEND

A - DRYING SPECIMEN
B - ELECTRIC HOT PLATES
C - RELATIVE HUMIDITY RECORDER
D - PERFORATED BAFFLE PLATE
E - BALANCE
F - AIR TEMPERATURE RECORDER
G - STEAM HUMIDIFICATION PIPE
H - STEAM HEATER
I - BLOWER
J - DAMPER
K - DRYING CHAMBER
L - HUMIDIFICATION CHAMBER

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VIRGINIA POLYTECHNIC INSTITUTE
BLACKSBURG, VIRGINIA

DRAWING 1

AIR CONDITIONED DRYER

SCALE: 1" = 1'-0"	DATE	CASE NO:
DRAWN BY: Y. K. PAN	11-19-56	FILE NO:
CHECKED BY: Y. K. PAN	11-20-56	FIGURE NO:
APPROVED BY:	11-21-56	SHEET NO:

Temperature Recorder. Bristol recording thermometer, model No 17501-18, serial No 576129, range 0 to 300 °F. Obtained from Bristol Co., Waterbury, Connecticut. Used to record the air temperature in the drying chamber.

Thermometer. Mercury, glass, range 0 to 300 °F. Obtained from Fisher Scientific Co., Silver Spring, Maryland. Used in calibration of thermocouples and the relative humidity.

Timer. Electric, ac, 115 v. Range 0 to 1000 minutes. Graduated in hundredths of a minute. Obtained from Fisher Scientific Co., Silver Spring, Maryland. Used to time drying test.

Method of Procedure

The method of procedure employed in the experimental work is described and explained in the order: preparation of specimen, control of drying conditions, operation of drying test, determination of dry weight, and operating conditions of tests.

Preparation of Specimen. The preparation of specimens consisted of three steps: cutting cellulose nitrate plastic into proper size, soaking in ethyl alcohol, and conditioning the wet specimen.

The grey plastic sheet, 0.18 centimeter thick, was cut into pieces 8.2 by 4.9 centimeters in size, while the brown plastic sheet, 0.6 centimeter thick, was cut into pieces 5.0 by 7.6 centimeters in size. The drying surfaces of the specimens were 85 and 81 square centimeters, respectively, and they were of convenient size for soaking and drying.

The specimen was suspended by a fine copper wire in 95 per cent ethyl alcohol contained in a beaker. The beaker was covered and the specimen allowed to absorb alcohol. In the preliminary tests only the grey specimen was used, and the soaking time was two hours. In the operational tests the grey specimen was soaked for two and one-half hours and the brown specimen five hours. If soaked for a longer time the plastic would swell and lose its shape.

After soaking, the specimen was conditioned by hanging it in a closed glass bottle for different periods of time, to permit uniform diffusion of alcohol through the specimen. In the preliminary tests the grey specimen was tested with different lengths of diffusion time: three and one-half hours, eight hours, and thirty-six hours. In the operational tests the diffusion time was increased to three days for the grey specimen and four or five days for the brown specimen. This was done by hanging the specimen in a closed bottle for the first two and one-half hours for the grey specimen and eight hours for the brown specimen; then the specimen was removed and laid on the plate of a desiccator containing some alcohol in the bottom. With this procedure the wet specimen neither lost its shape due to hanging too long nor due to adhering to the plate of the desiccator.

Control of Drying Conditions. The operating conditions in the dryer were controlled as follows:

The blower was started. Air was taken from outside, or mixed with recirculated air from the drying chamber when a high humidity was used. Air was heated by passing over the steam coils into the humidification chamber. The steam valve in the humidification chamber was opened and steam was mixed with the warm air. By adjusting the heat from the steam coils and the steam from the pipe, the air was adjusted to the desired temperature and humidity. The conditioned air flowed through a perforated baffle plate into the drying chamber. When radiant heat was used, a desired temperature of the specimen could be obtained by adjusting the temperatures on the electric hot plates and the distances between the specimen and the two hot plates. A piece of dry plastic was used to determine the required stock, or internal, temperature before the test began. One and one-half hours were required to set these conditions.

Operation of Drying Test. The conditioned specimen was hung in the dryer on the loop of a thread which ran from the balance through the top of the dryer. The initial weight and time were recorded.

The surface temperature and internal temperature of the specimen were recorded periodically. The surface temperature of the specimen was obtained by sticking a thermocouple directly on the surface of the specimen. The internal temperature of the specimen was measured by placing a thermocouple in a 1/16-inch diameter hole bored in the center of the specimen at the lower end. The time interval for recording the weight of the drying specimen increased as the alcohol content in the specimen decreased. When the weight of the specimen decreased no more than 0.01 gram during a one-half hour interval, the specimen was considered free from alcohol. Usually, it took two days for drying to this extent, and during the night between these two days the specimen was moved from the dryer to a closed bottle in the room.

Determination of Dry Weight. The original weight of the specimen could not be used as the dry weight in the calculation of drying rate as some plastic dissolved into the alcohol during soaking. The dry weight was determined by removing the specimen from the dryer and placing it on the plate of a desiccator containing 96 per cent sulfuric acid. The vapor pressure of water in such a concentration of sulfuric acid is practically zero; hence, the relative humidity of the air in the desiccator was considered to be zero. After the weight of the specimen had become constant during a one-day interval, it was assumed that this constant weight was the dry weight. Usually, it took seven to nine days for the grey specimen in the desiccator to reach constant weight, while the brown specimen required fifteen to eighteen days. It was shown that such a dried specimen would not decrease in weight again by more than four per cent at the room conditions even for as long a time as three and one-half months.

Operating Conditions of Tests. The conditions used for the preliminary tests are shown in Table II and the conditions used for the drying tests are shown in Table III.

TABLE II

Operating Conditions of Preliminary Test

Purpose	Run No	Diffusion Time	Air	
			Relative Water Humidity	Temperature
		hr	%	°F
A	1	3-1/2	40	120
	2	8	40	120
	3	36	40	120
B	4	3-1/2	30	120
	5	3-1/2	50	120
C	6	3-1/2	30	110

Specimen: 0.18 x 4.9 x 8.2 centimeters; grey cellulose nitrate plastic sheet; immersed in alcohol 2 hours.

A: To determine the effect of diffusion time of alcohol in specimen.

B: To determine the nature of the general influence of relative water humidity.

C: To determine the nature of the general influence of air temperature.

TABLE III

Operating Conditions of Drying Tests

Purpose	Run No	Specimen	Air: Relative Water Humidity %	Air: Temperature °F	Internal Temperature by Radiant Heat °F
A	7	grey	30	110	no radiant heat
	8	grey	50	110	no radiant heat
	9	grey	30	130	no radiant heat
	10	grey	50	130	no radiant heat
B	11	grey	30	130	154
	11a	brown	30	130	158
	12	grey	30	110	130
	12a	brown	30	110	132
	13	grey	50	110	128
	13a	brown	50	110	130
	14	grey	50	110	114
	14a	brown	50	110	119
C	15	grey	53-56	84-86	no radiant heat

Specimen: Grey; 0.18 x 4.9 x 8.2 centimeters; immersed in alcohol 2-1/2 hours; diffusion time, 3 days

Brown; 0.6 x 5.0 x 7.6 centimeters; immersed in alcohol 5 hours; diffusion time, 5 days.

A: To determine the effect of relative water humidity and air temperature.

B: To determine the effect of radiant heat.

C: To determine the drying rate under atmospheric conditions.

Data and Results

The data and results obtained from this investigation are presented in the following section.

Effect of Diffusion Time of Alcohol in the Specimen. The results of the preliminary study of the drying rates of cellulose nitrate plastic after different periods of alcohol diffusion in the specimen, 3-1/2, 8 and 36 hours, are given in Tables IV, V and VI, pages 44, 45 and 46, respectively. Figure 2, page 47, shows the corresponding curves of these drying rates. The results of the preliminary tests showed that the drying rate, versus the alcohol content of the specimen, was inversely proportional to the length of diffusion time until the alcohol content was reduced to 0.15 gram per gram dry weight. After the alcohol content was reduced to 0.15 gram per gram dry weight the difference in diffusion time had no effect on the drying rate.

General Influence of Relative Water Humidity. The results of the preliminary study of the drying rates of cellulose nitrate plastic at different relative water humidities of 30, 40 and 50 per cent are given in Tables VII, IV and VIII, pages 48, 44 and 49, respectively. Diffusion time of three and one-half hours and air temperature of 120 °F were used in all of these tests. Figure 3, page 50, shows the corresponding curves of these drying rates. The results of the preliminary tests showed that increasing the relative water humidity of the air decreased the drying rate.

General Influence of Air Temperature. The results of the preliminary study of the drying rates of cellulose nitrate plastic at different air temperatures of 110 °F and 120 °F are given in Tables IX and VIII, pages 51 and 49. Diffusion time of three and one-half hours and relative water humidity of 30 per cent were used in all of these tests. Figure 4, page 52, shows the corresponding curves of these drying rates. The results of the preliminary tests showed that increasing the air temperature increased the drying rate.

Effects of Relative Water Humidity and Air Temperature. With a soaking time of two and one-half hours and diffusion time of three days, it was believed that alcohol was diffused uniformly in the specimen. Then the operational tests were conducted under conditions of air temperatures of 110 °F and 130 °F, and relative water humidities of 30 and 50 per cent. The data and results are given in Tables X, XI, XII and XIII, pages 53, 54, 55 and 56. Figure 5, page 57, shows the corresponding curves of these drying rates. The results of the operational tests showed that both the air temperature and the relative water humidity affected the drying rate, but the air temperature had a greater effect. Figure 6, page 58, presents the time required to dry the wet plastic by convection heat. It was indicated that with these operational conditions there was no case-hardening and within these limits the higher temperature and lower relative humidity shortened the time required to dry off the same per cent alcohol from the wet specimen. Figures 7 and 8, pages 59 and 60, present the effect of the internal temperature of the specimen on the drying rate of the plastic. It was indicated that the internal temperature of the specimen was increased with the increase of drying time to a maximum value and then remained constant. The drying rate versus time was inversely proportional to the internal temperature of the specimen.

Effect of Radiant Heat. Four runs were made at different internal temperatures of the specimen by supplementing the convection heat with radiant heat. The data and results are given in Tables XIV, XV, XVI, and XVII, pages 61, 62, 63 and 64. When the internal temperatures of the plastic were 154 °F, 130 °F and 128 °F at the relative water humidities of 30 and 50 per cent, case-hardening and warping and checking occurred. When the internal temperature was lowered to 114 °F at 50 per cent relative humidity the plastic was dried uniformly without these defects. Figure 9, page 65, shows the corresponding drying curves under these conditions. Figures 10 and 11, pages 66 and 67, show the comparison of the drying rates of plastic by convection heat alone and by supplementing the convection heat with radiant heat. It was indicated that the drying rate of the former was slower than that of the latter.

Four additional specimens of brown color were also tested in the operational test. It was thought that the darker color might cause greater heat absorption and that the greater thickness might affect the operation. The data and results are given in Tables XVIII, XIX, XX and XXI, pages 68, 69, 70 and 71. Figure 12, page 72, shows the corresponding curves of these drying rates. It was shown that the brown plastic reached a higher internal temperature than did the grey plastic under the same conditions. In the first three tests, 11a, 12a and 13a, the brown specimen suffered badly from case-hardening, bubbles and checking. In test 14a very few bubbles formed in the specimen.

Drying Rate under Atmospheric Conditions. The drying rate of cellulose nitrate plastic under atmospheric conditions is shown in Table XXII, page 73. Figure 13, page 74, shows the corresponding curve of the drying rate. It was apparent that the drying rate of plastic under atmospheric conditions was very slow, compared to that at the other conditions.

TABLE IV

Preliminary Test of Drying Rate of Cellulose Nitrate Plastic after Three and One-half Hours Diffusion

Run: No 1
Air Temperature: 120 °F
Relative Water Humidity: 40 %

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
	Specimen A: Dry weight, 9.03 gm; drying surface, 85 sq cm				
0.00	13.15	4.12	0.456	--	--
0.1	12.77	3.74	0.414	0.38	0.0447
0.2	12.41	3.38	0.374	0.36	0.0424
0.4	12.07	3.04	0.336	0.34	0.0200
0.7	11.59	2.56	0.284	0.48	0.0155
1.0	11.33	2.30	0.255	0.26	0.0102
1.3	11.14	2.11	0.234	0.19	0.0075
2.3	10.75	1.72	0.191	0.39	0.00459
3.3	10.52	1.49	0.165	0.23	0.00271
5.3	10.20	1.17	0.131	0.32	0.00188
7.3	9.97	0.94	0.104	0.23	0.00136
9.3	9.80	0.77	0.0853	0.17	0.00100
Test interrupted					
0.00	9.64	0.61	0.0677	--	--
1	9.56	0.53	0.0587	0.08	0.00094
2	9.51	0.48	0.0532	0.05	0.00059
2.75	9.48	0.45	0.0498	0.03	0.00047
4.75	9.41	0.38	0.0422	0.07	0.00041
7.75	9.33	0.30	0.0333	0.08	0.00032
8.75	9.31	0.28	0.0310	0.02	0.00024
	Specimen B: Dry weight, 9.38 gm; drying surface, 85 sq cm				
0.00	13.65	4.27	0.455	--	--
0.1	13.18	3.80	0.406	0.46	0.0542
0.2	12.84	3.46	0.369	0.34	0.0400
0.5	12.23	2.85	0.304	0.61	0.0236
0.7	11.97	2.59	0.286	0.26	0.0153
1.0	11.70	2.32	0.248	0.27	0.0105
1.5	11.40	2.02	0.216	0.30	0.0070
2.5	11.05	1.67	0.178	0.35	0.00412
3.5	10.83	1.45	0.155	0.22	0.00259
5.5	10.53	1.15	0.123	0.30	0.00177
7.5	10.32	0.94	0.100	0.21	0.00124
9.5	10.16	0.78	0.0832	0.16	0.00095
Test interrupted					
0.00	10.00	0.62	0.0662	--	--
1	9.94	0.56	0.0598	0.06	0.00071
2	9.89	0.51	0.0544	0.05	0.00059
2.75	9.87	0.49	0.0523	0.02	0.00032
4.75	9.80	0.42	0.0448	0.07	0.11141
7.75	9.71	0.33	0.0352	0.09	0.00035
8.75	9.69	0.31	0.0331	0.02	0.00024

TABLE V

Preliminary Test of Drying Rate of Cellulose Nitrate Plastic after Eight Hours Diffusion Time

Run: No 2
Air Temperature: 120 °F
Relative Water Humidity: 40 %

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
Specimen A: Dry weight, 8.87 gm; drying surface, 85 sq cm					
0.00	13.15	4.28	0.488	--	--
0.10	12.80	3.93	0.433	0.25	0.0294
0.35	12.35	3.48	0.392	0.45	0.0212
0.50	12.16	3.29	0.371	0.19	0.0149
0.75	11.91	3.04	0.343	0.25	0.0118
1	11.73	2.86	0.323	0.18	0.0085
1.5	11.38	2.51	0.283	0.35	0.0082
2	11.10	2.23	0.251	0.28	0.0066
3	10.70	1.83	0.206	0.30	0.00353
Test interrupted					
0.00	9.73	0.86	0.097	--	--
1.25	9.57	0.70	0.0789	0.16	0.00151
3.25	9.42	0.55	0.0620	0.15	0.00089
5.25	9.23	0.46	0.0518	0.09	0.00053
Specimen B: Dry weight, 8.87 gm; drying surface, 85 sq cm					
0.00	12.60	3.73	0.422	--	--
0.1	12.41	3.54	0.398	0.19	0.0224
0.2	12.25	3.38	0.381	0.16	0.0189
0.5	11.90	3.03	0.351	0.35	0.0137
0.75	11.69	2.82	0.318	0.21	0.0099
1	11.42	2.65	0.299	0.17	0.0080
1.5	11.25	2.38	0.259	0.27	0.00637
2	11.02	2.15	0.243	0.23	0.00542
3	10.67	1.80	0.203	0.35	0.00412
Test interrupted					
0.00	9.80	0.93	0.105	--	--
1.25	9.65	0.78	0.088	0.15	0.00142
3.25	9.49	0.62	0.070	0.16	0.00099
5.25	9.38	0.51	0.058	0.11	0.00043

TABLE VI

Preliminary Test of Drying Rate of Cellulose Nitrate Plastic after Thirty-six Hours Diffusion Time

Run: No 3
Air Temperature: 120 °F
Relative Water Humidity: 40 %

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
Specimen A: Dry weight, 8.67 gm; drying surface, 85 sq cm					
0.00	13.28	4.61	0.532	--	--
0.13	12.96	4.29	0.494	0.32	0.0281
0.24	12.78	4.11	0.474	0.18	0.0212
0.40	12.54	3.87	0.447	0.24	0.0176
0.50	12.43	3.76	0.434	0.11	0.0130
0.75	12.18	3.51	0.405	0.25	0.0118
1.00	11.95	3.28	0.379	0.23	0.0108
1.50	11.52	2.91	0.336	0.37	0.0087
2.00	11.28	2.61	0.301	0.30	0.00707
3.00	10.79	2.12	0.245	0.49	0.00577
4.00	10.46	1.79	0.206	0.33	0.00389
6.00	9.98	1.31	0.151	0.48	0.00283
9.00	9.48	0.81	0.0934	0.50	0.00194
11.00	9.31	0.64	0.0738	0.17	0.00100
Test interrupted					
0.00	9.06	0.39	0.0450	--	--
1.25	9.03	0.36	0.0415	0.03	0.00028
3.25	8.97	0.30	0.0346	0.06	0.00035
5.25	8.93	0.26	0.0300	0.04	0.00024
Specimen B: Dry weight, 8.70 gm; drying surface, 85 sq cm					
0.00	12.77	4.07	0.468	--	--
0.13	12.45	3.75	0.432	0.32	0.0281
0.23	12.30	3.60	0.416	0.15	0.0177
0.42	12.07	3.37	0.388	0.23	0.0141
0.50	12.00	3.30	0.380	0.07	0.0103
0.75	11.80	3.10	0.356	0.20	0.00946
1.00	11.61	2.91	0.334	0.19	0.00895
1.50	11.31	2.61	0.300	0.30	0.00611
2.00	11.06	2.26	0.260	0.25	0.00588
3.00	10.66	1.96	0.224	0.40	0.00472
4.00	10.37	1.67	0.194	0.29	0.00342
6.00	9.94	1.24	0.143	0.43	0.00253
9.00	9.50	0.80	0.092	0.44	0.00173
11.00	9.33	0.63	0.0725	0.17	0.00100
Test interrupted					
0.00	9.08	0.38	0.0438	--	--
1.25	9.02	0.32	0.0364	0.06	0.00057
3.25	9.01	0.31	0.0356	0.01	0.00006
5.25	8.97	0.27	0.0310	0.04	0.00024

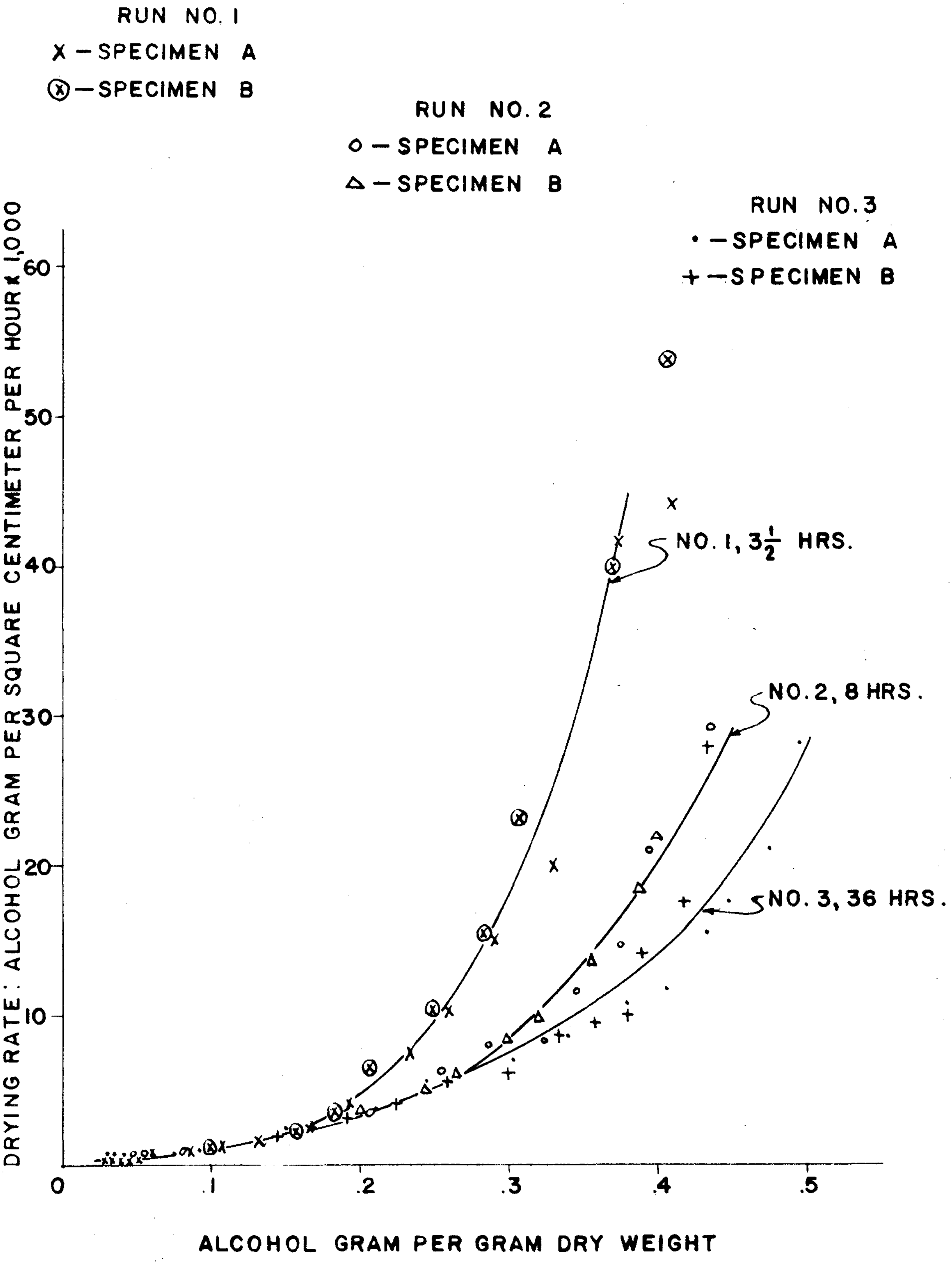


FIGURE 2. EFFECT OF DIFFUSION TIME OF ETHYL ALCOHOL ON THE DRYING RATE OF CELLULOSE NITRATE PLASTIC

TABLE VII

Preliminary Test of Drying Rate of Cellulose Nitrate Plastic in Air of 30 % Relative Humidity

Run: No 4
Air Temperature: 120 °F
Alcohol Diffusion Time: 3-1/2 Hours

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
Specimen A: Dry weight, 9.16 gm; drying surface, 85 sq cm					
0.00	13.33	4.17	0.454	--	--
0.1	12.82	3.66	0.400	0.51	0.0600
0.2	12.45	3.29	0.359	0.37	0.0436
0.5	11.77	2.61	0.285	0.68	0.0267
0.7	11.49	2.33	0.254	0.28	0.01645
1	11.20	2.04	0.223	0.29	0.01140
1.5	10.88	1.72	0.188	0.32	0.0752
2	10.70	1.54	0.168	0.18	0.0424
3	10.46	1.30	0.142	0.24	0.0282
4	10.38	1.12	0.122	0.18	0.0106
6	10.02	0.86	0.0938	0.26	0.0153
8	9.83	0.67	0.0732	0.19	0.0112
10	9.71	0.55	0.0602	0.12	0.00071
Test interrupted					
0.00	9.62	0.46	0.0503	--	--
1	9.54	0.38	0.0415	0.08	0.00094
2	9.49	0.33	0.0360	0.05	0.00059
5	9.39	0.23	0.0251	0.10	0.00004
9	9.29	0.13	0.0141	0.10	0.00003
Specimen B: Dry weight, 9.16 gm; drying surface, 85 sq cm					
0.00	13.21	4.05	0.442	--	--
0.1	12.73	3.57	0.390	0.48	0.0565
0.2	12.38	3.22	0.351	0.35	0.0412
0.5	11.69	2.53	0.276	0.69	0.0251
0.7	11.40	2.24	0.245	0.29	0.0171
1.2	10.99	1.83	0.200	0.41	0.00896
1.7	10.74	1.58	0.172	0.25	0.00546
2.2	10.58	1.42	0.155	0.16	0.00378
3.2	10.37	1.21	0.132	0.21	0.00247
4.2	10.20	1.04	0.113	0.17	0.00200
6.2	9.97	0.81	0.884	0.23	0.00136
8.2	9.79	0.63	0.0687	0.18	0.00106
10.2	9.68	0.52	0.0568	0.12	0.00071
Test interrupted					
0.00	9.60	0.44	0.0480	--	--
1	9.52	0.36	0.0393	0.08	0.00094
2	9.47	0.31	0.0338	0.05	0.00059
5	9.37	0.21	0.0229	0.10	0.00003
9	9.27	0.11	0.0200	0.10	0.00002

TABLE VIII

Preliminary Test of Drying Rate of Cellulose Nitrate Plastic in Air of 50 % Relative Humidity

Run: No 5
Air Temperature: 120 °F
Alcohol Diffusion Time: 3-1/2 Hours

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
Specimen A: Dry weight, 9.07 gm; drying surface, 85 sq cm					
0.00	13.15	4.08	0.450	--	--
0.1	12.75	3.68	0.406	0.40	0.0472
0.2	12.45	3.38	0.373	0.30	0.0353
0.45	12.00	2.93	0.323	0.45	0.0211
0.70	11.66	2.59	0.286	0.34	0.0160
1	11.45	2.38	0.263	0.21	0.00823
1.5	11.16	2.09	0.231	0.29	0.00684
2	10.99	1.92	0.212	0.17	0.00400
2.5	10.84	1.77	0.195	0.15	0.00390
4.2	10.48	1.41	0.156	0.36	0.00250
6.4	10.21	1.14	0.126	0.27	0.00155
8.2	10.04	0.97	0.107	0.17	0.00111
Test interrupted					
0.00	9.49	0.42	0.0464	--	--
1.4	9.49	0.42	0.0464	?	?
2.5	9.49	0.42	0.0464	?	?
3.9	9.46	0.39	0.0430	0.03	0.00025
10.4	9.41	0.34	0.0375	0.05	0.00009
13.4	8.35	0.28	0.0309	0.06	0.00023
14.4	8.34	0.27	0.0298	0.01	0.00012
Specimen B: Dry weight, 8.98 gm; drying surface, 85 sq cm					
0.00	12.83	3.85	0.428	--	--
0.1	12.47	3.49	0.389	0.36	0.0424
0.2	12.20	3.22	0.359	0.27	0.0318
0.45	11.77	2.79	0.311	0.43	0.0202
0.7	11.49	2.51	0.280	0.28	0.0132
1	11.25	2.27	0.253	0.24	0.0094
1.5	11.02	2.04	0.227	0.23	0.00542
1.75	10.91	1.93	0.215	0.11	0.00516
2.25	10.76	1.78	0.198	0.15	0.00390
4	10.41	1.43	0.159	0.35	0.00236
6	10.23	1.15	0.128	0.28	0.00165
8	9.96	0.98	0.109	0.17	0.00100
Test interrupted					
0.00	9.40	0.42	0.0468	--	--
1.4	9.40	0.42	0.0468	?	?
2.5	9.40	0.42	0.0468	?	?
3.9	9.38	0.40	0.0446	0.02	0.00016
10.4	9.31	0.33	0.0368	0.07	0.00013
13.4	9.27	0.29	0.0323	0.04	0.00016
14.4	9.25	0.27	0.0300	0.02	0.00024

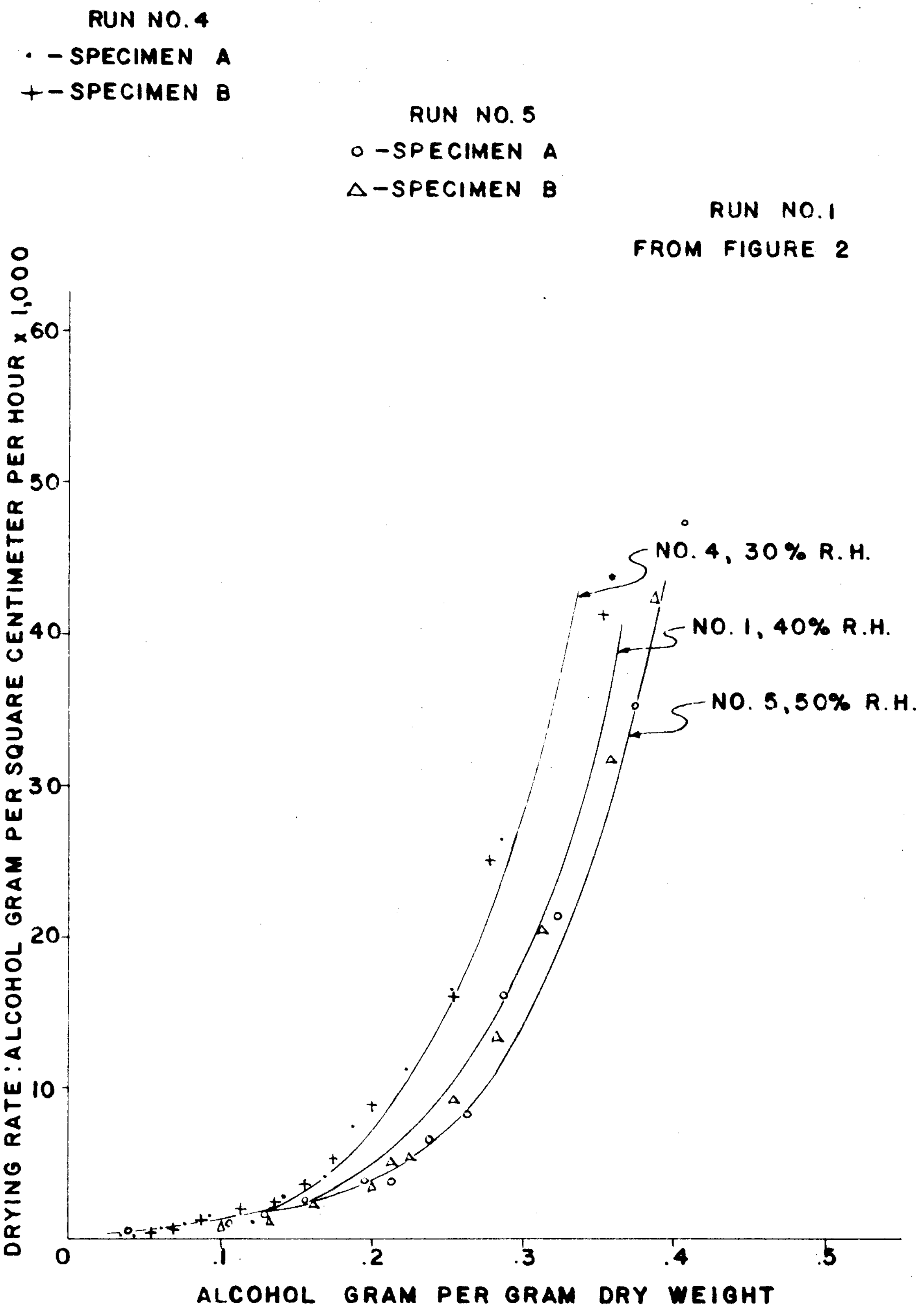


FIGURE 3. NATURE OF THE INFLUENCE OF RELATIVE WATER HUMIDITY ON THE DRYING RATE OF CELLULOSE NITRATE PLASTIC

TABLE IX

Preliminary Test of Drying Rate of Cellulose Nitrate Plastic in Air at 130 °F

Run: No 6
Relative Water Humidity: 30 %
Alcohol Diffusion Time: 3-1/2 Hours

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
Specimen A: Dry weight, 9.28 gm; drying surface, 85 sq cm					
0.00	12.81	3.53	0.381	--	--
0.1	12.45	3.17	0.342	0.36	0.0424
0.2	12.23	2.95	0.318	0.22	0.0259
0.5	11.76	2.48	0.268	0.47	0.0178
0.8	11.48	2.20	0.237	0.28	0.0110
1	11.33	2.05	0.221	0.15	0.0089
1.5	11.07	1.79	0.193	0.26	0.0061
2.3	10.81	1.53	0.165	0.26	0.00383
4.3	10.47	1.19	0.128	0.34	0.00200
6.3	10.27	0.99	0.107	0.20	0.00118
8.3	10.12	0.84	0.0906	0.15	0.00089
Test interrupted					
0.00	9.48	0.20	0.0216	--	--
1	9.46	0.18	0.0194	0.02	0.00024
2	9.45	0.17	0.0183	0.01	0.00012
4	9.43	0.15	0.0162	0.02	0.00012
5.25	9.42	0.14	0.0151	0.01	0.00010
Specimen B: Dry weight, 9.00 gm; drying surface, 85 sq cm					
0.00	12.56	3.56	0.396	--	--
0.1	12.19	3.19	0.354	0.37	0.0436
0.2	11.95	2.95	0.328	0.24	0.0282
0.45	11.52	2.52	0.280	0.43	0.0202
0.70	11.24	2.24	0.249	0.28	0.0131
1	11.01	2.01	0.224	0.23	0.0108
1.3	10.84	1.84	0.204	0.17	0.0067
1.8	10.64	1.64	0.182	0.20	0.0047
2.6	10.45	1.45	0.161	0.19	0.00255
4.6	10.13	1.13	0.126	0.32	0.00188
6.6	9.94	0.94	0.104	0.19	0.00112
8.6	9.79	0.79	0.088	0.15	0.00089
Test interrupted					
0.00	9.19	0.19	0.0211	--	--
1	9.17	0.17	0.0189	0.02	0.00024
2	9.16	0.16	0.0178	0.01	0.00012
4	9.14	0.14	0.0156	0.02	0.00012
5.25	9.13	0.13	0.0145	0.01	0.00010

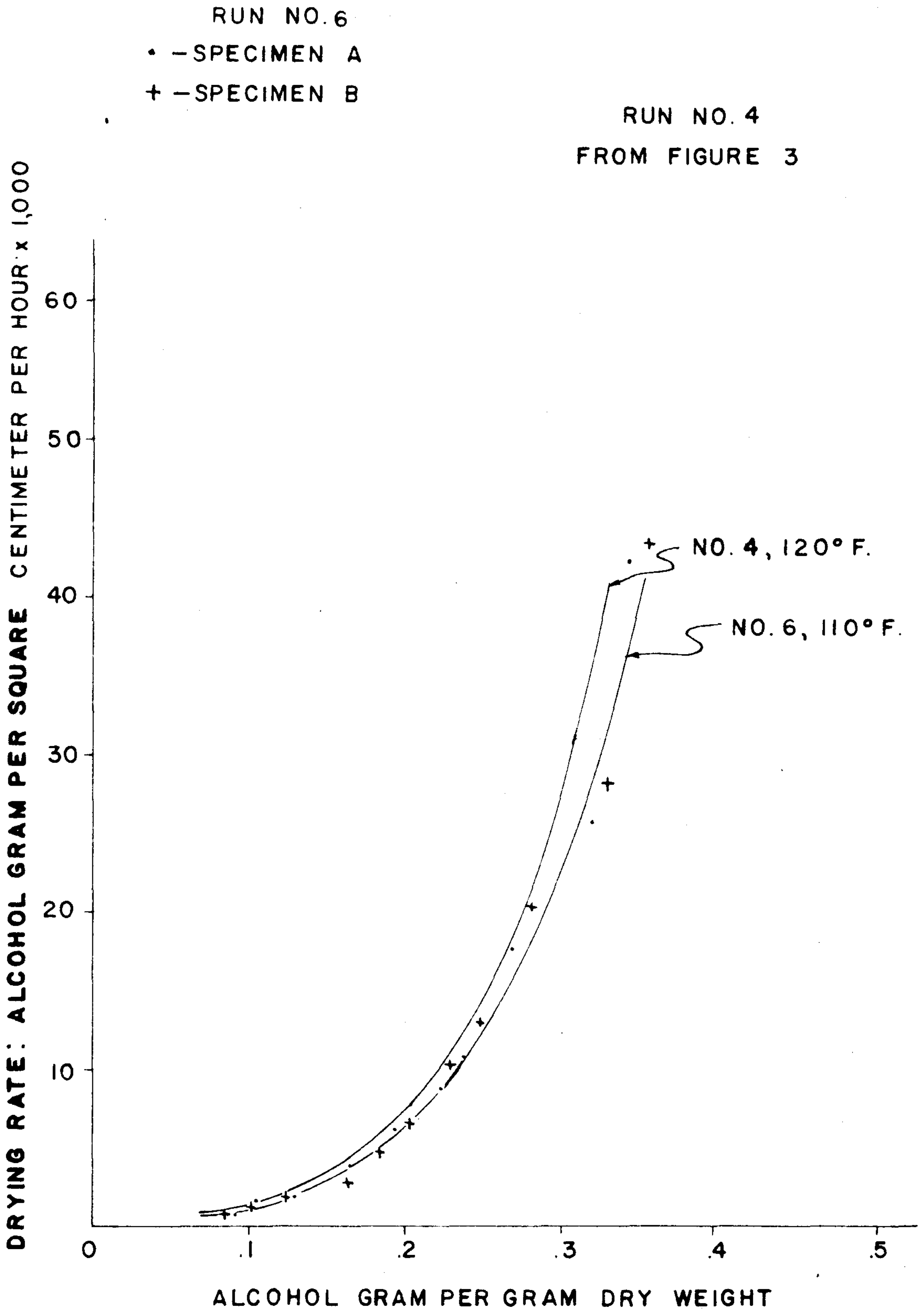


FIGURE 4. NATURE OF THE GENERAL INFLUENCE OF AIR TEMPERATURE ON THE DRYING RATE OF CELLULOSE NITRATE PLASTIC

TABLE X

Drying Rate of Cellulose Nitrate Plastic at 110 °F and 30 % Relative Humidity

Run: No 7
Specimen: Grey; dry weight, 8.81 gm
Alcohol Diffusion Time: 3 days

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Internal Temperature of Specimen
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F
0.00	11.89	3.08	0.350	--	--	--
0.1	11.78	2.97	0.334	0.11	0.0129	--
0.2	11.69	2.88	0.326	0.09	0.0106	96
0.4	11.56	2.75	0.312	0.13	0.00765	98
0.7	11.40	2.57	0.291	0.16	0.00630	99
1	11.28	2.47	0.280	0.13	0.00477	102
1.3	11.15	2.34	0.266	0.11	0.00430	104
2.3	10.86	2.05	0.233	0.30	0.00353	104
3	10.67	1.86	0.211	0.19	0.00320	104
5	10.26	1.45	0.164	0.41	0.00242	104
7.3	10.93	1.12	0.127	0.33	0.00169	104
9.3	9.68	0.87	0.099	0.25	0.00147	104
11.3	9.53	0.62	0.071	0.15	0.00089	104
13.3	9.45	0.55	0.063	0.08	0.00047	104
Test interrupted						
0.00	9.23	0.42	0.048	--	--	
3	9.13	0.32	0.036	0.10	0.00039	
5	9.09	0.28	0.032	0.04	0.00024	
7	9.04	0.23	0.027	0.05	0.00029	
10	9.00	0.19	0.021	0.04	0.00016	
13.3	8.98	0.17	0.019	0.02	0.00007	

TABLE XI

Drying Rate of Cellulose Nitrate Plastic at 110 °F and 50 % Relative Humidity

Run: No 8
Specimen: Grey; dry weight, 8.84 gm
Alcohol Diffusion Time: 3 Days
Maximum Internal Temperature: 104 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
0.00	11.95	3.11	0.352	--	--
0.1	11.86	3.02	0.342	0.09	0.0106
0.2	11.78	2.94	0.333	0.08	0.0094
0.5	11.58	2.74	0.311	0.20	0.00787
0.8	11.44	2.60	0.294	0.14	0.00550
1.2	11.26	2.42	0.274	0.18	0.00430
1.7	11.10	2.26	0.256	0.16	0.00378
2.7	10.83	1.90	0.226	0.27	0.00316
3.7	10.58	1.74	0.197	0.25	0.00273
5.7	10.23	1.39	0.157	0.35	0.00206
6.9	10.04	1.20	0.136	0.19	0.00187
9.9	9.76	0.92	0.104	0.28	0.00110
10.9	9.69	0.85	0.096	0.07	0.00083
12.9	9.50	0.66	0.075	0.09	0.00053
Test interrupted					
0.00	9.43	0.59	0.067	--	--
2	9.33	0.49	0.055	0.10	0.00059
4	9.28	0.44	0.050	0.05	0.00030
6	9.23	0.39	0.044	0.05	0.00030
11	9.13	0.27	0.031	0.10	0.00029
13	9.11	0.25	0.028	0.02	0.00012

TABLE XII

Drying Rate of Cellulose Nitrate Plastic
at 130 °F and 30 % Relative Humidity

Run: No 9
Specimen: Grey; dry weight, 8.75 gm
Alcohol Diffusion Time: 3 days

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Internal Temperature of Specimen
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F
0.00	11.53	2.78	0.318	--	--	--
0.1	11.35	2.60	0.290	0.18	0.0212	108
0.2	11.20	2.45	0.280	0.15	0.0177	115
0.3	11.10	2.35	0.269	0.10	0.0118	119
0.6	10.87	2.12	0.242	0.23	0.00904	121
1	10.64	1.89	0.216	0.23	0.00678	123
1.5	10.36	1.61	0.184	0.28	0.00658	124
2.3	10.05	1.30	0.149	0.31	0.00459	124
3.8	9.68	0.93	0.106	0.37	0.00291	124
4.8	9.53	0.78	0.089	0.15	0.00177	124
5.8	9.39	0.64	0.073	0.14	0.00165	124
6.8	9.29	0.54	0.062	0.10	0.00118	124
9.8	9.11	0.36	0.041	0.18	0.00071	124
10.8	9.05	0.30	0.034	0.06	0.00071	124
12.8	8.99	0.24	0.018	0.06	0.00035	124
Test interrupted						
0.00	9.01	0.26	0.029	--	--	
2.5	8.89	0.14	0.016	0.12	0.00057	
6.3	8.74	0.09	0.010	0.05	0.00014	

TABLE XIII

Drying Rate of Cellulose Nitrate Plastic at 130 °F and 50 % Relative Humidity

Run: No 10
Specimen: Grey; dry weight, 8.66 gm
Alcohol Diffusion Time: 3 days
Maximum Internal Temperature: 124 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
0.00	11.56	2.90	0.335	--	--
0.1	11.38	2.72	0.314	0.18	0.0212
0.2	11.26	2.60	0.300	0.12	0.0141
0.3	11.16	2.50	0.289	0.10	0.0118
0.6	10.91	2.25	0.260	0.25	0.0091
0.9	10.71	2.05	0.236	0.20	0.00787
1.2	10.56	1.90	0.219	0.15	0.00590
2.2	10.17	1.51	0.174	0.39	0.00459
3.2	9.70	1.04	0.120	0.47	0.00553
4.2	9.52	0.86	0.099	0.18	0.00212
5.2	9.40	0.74	0.085	0.12	0.00141
6.2	9.31	0.65	0.075	0.09	0.00106
8.5	9.16	0.50	0.058	0.15	0.00089
10.5	9.07	0.41	0.047	0.09	0.00053
12.5	9.01	0.35	0.041	0.06	0.00036

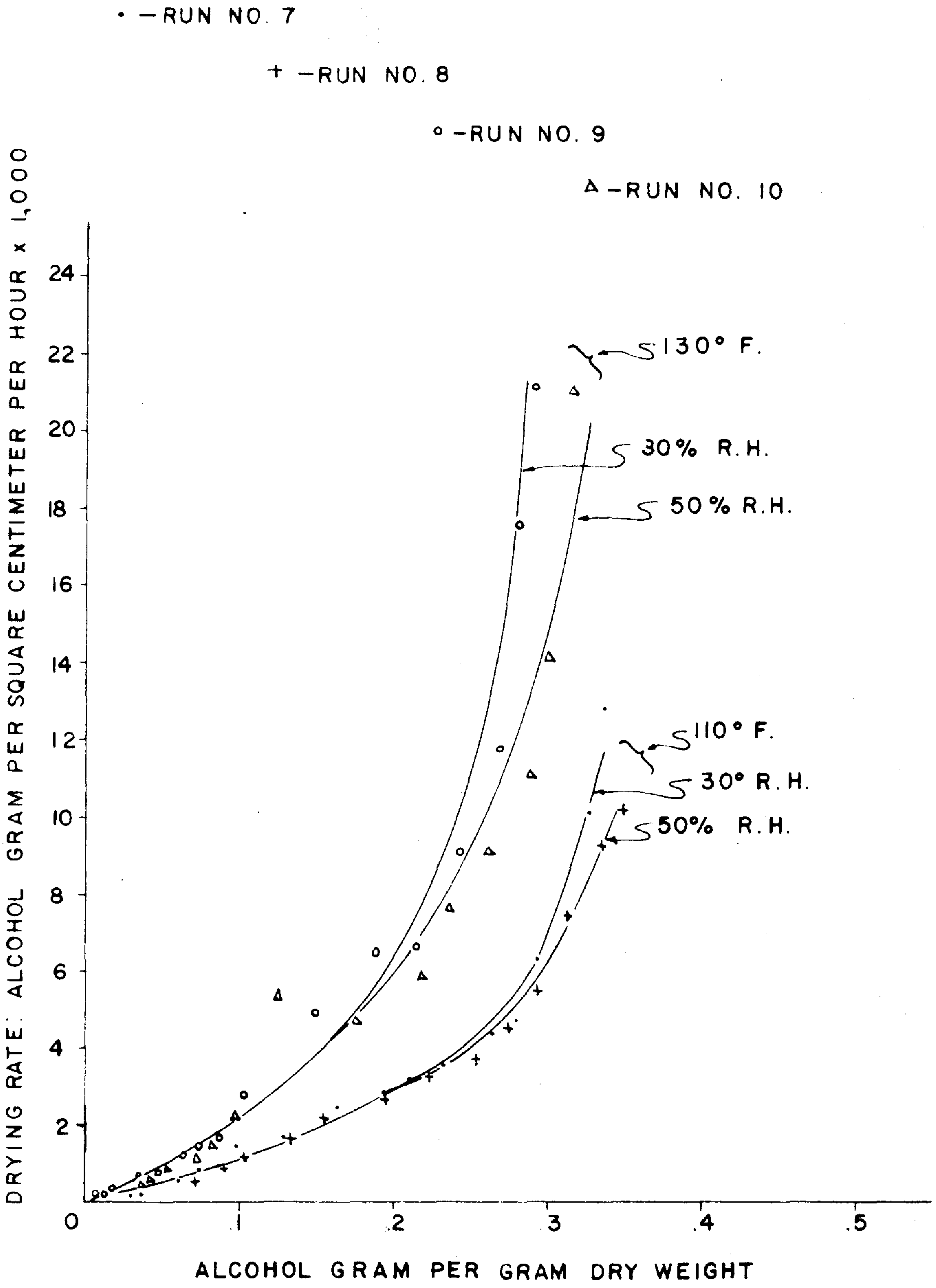


FIGURE 5. EFFECTS OF RELATIVE WATER HUMIDITY AND AIR TEMPERATURE ON THE DRYING RATE OF CELLULOSE NITRATE PLASTIC

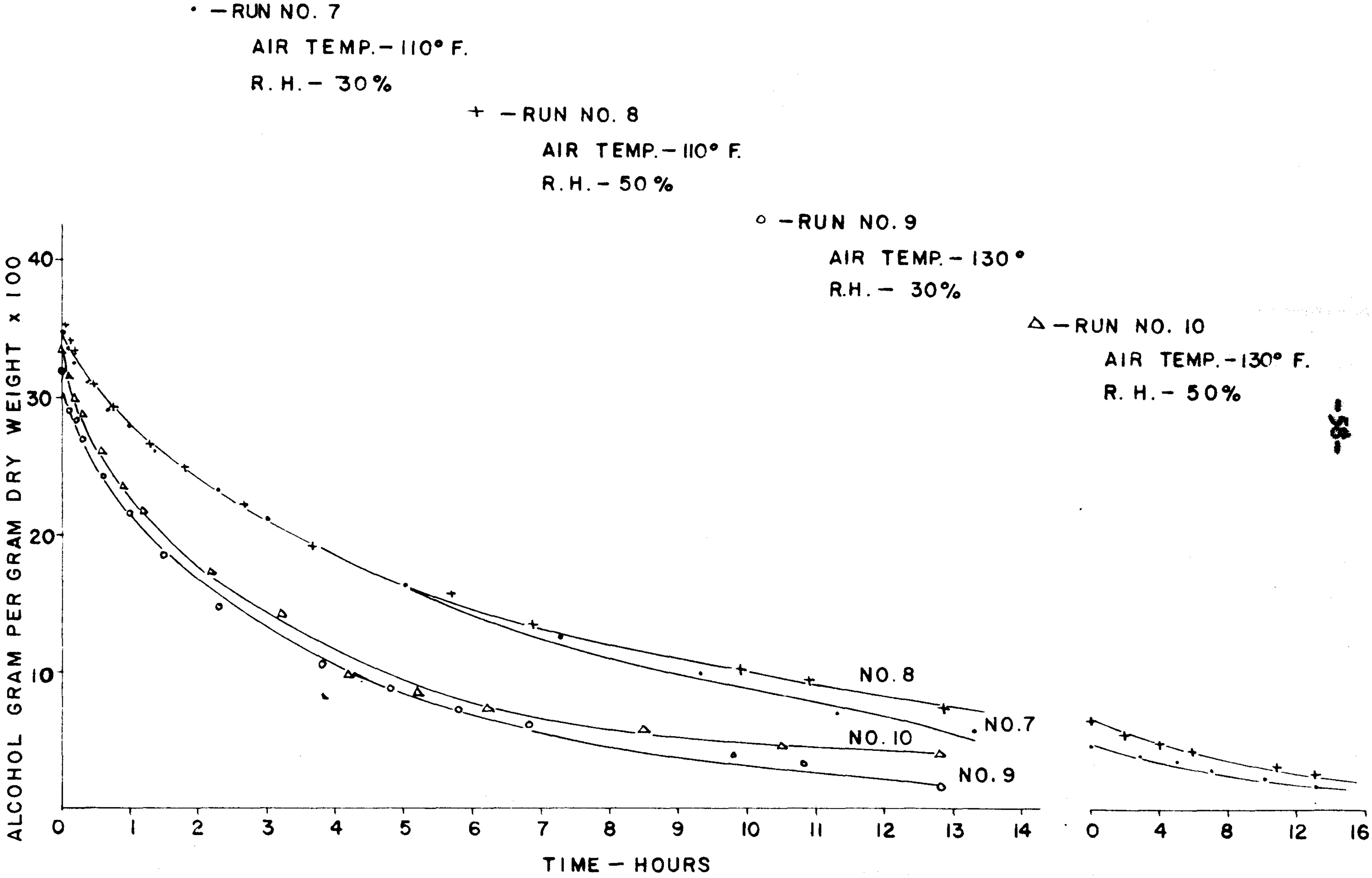


FIGURE 6. DRYING WET CELLULOSE NITRATE PLASTIC BY CONVECTION HEAT

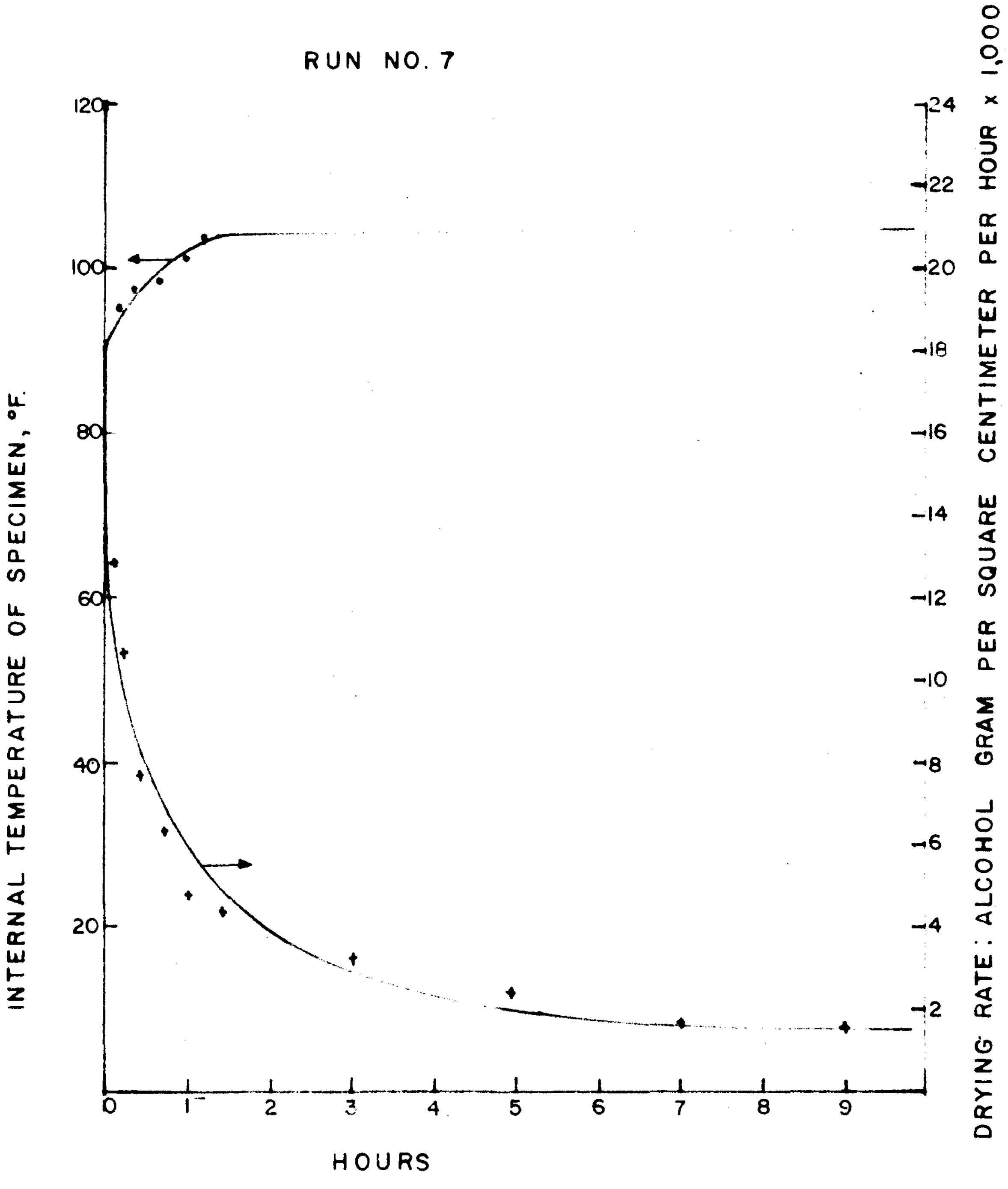


FIGURE 7. EFFECT OF THE INTERNAL TEMPERATURE OF SPECIMEN ON DRYING RATE OF CELLULOSE NITRATE PLASTIC AT AIR TEMPERATURE 110°F. AND RELATIVE HUMIDITY 30%

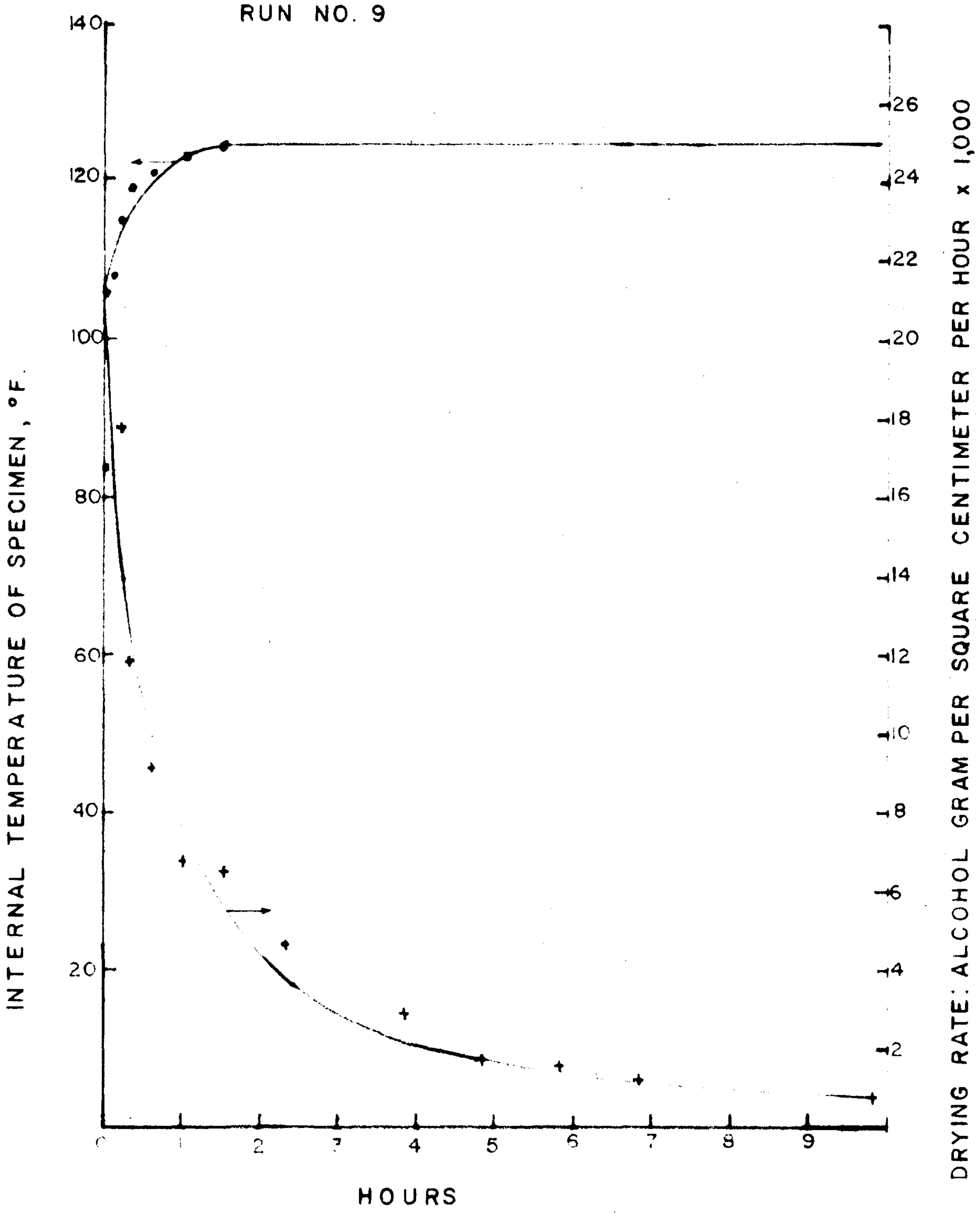


FIGURE 8. EFFECT OF THE INTERNAL TEMPERATURE OF SPECIMEN ON THE DRYING RATE OF CELLULOSE NITRATE PLASTIC WHEN AIR TEMPERATURE IS 130° AND RELATIVE HUMIDITY 30%

TABLE XIV

Drying Rate of Grey Cellulose Nitrate Plastic with Radiant Heat and 154 °F Internal Temperature

Run: No 11
Dry Weight: 8.82 gm
Air Temperature: 130 °F
Drying Surface: 85 sq cm
Relative Water Humidity: 30 %
Distance between Specimen and Hot Plates: 9 in.
Surface Temperatures of Hot Plates: 360 and 380 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Temperature of Specimen	
						Surface	Internal
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F	°F
0.00	11.37	2.55	0.290	--	--	--	--
0.1	11.15	2.33	0.265	0.22	0.0259	--	--
0.2	11.01	2.19	0.248	0.14	0.0165	147	150
0.5	10.61	1.79	0.202	0.40	0.0157	147	150
1	10.23	1.41	0.160	0.38	0.0089	147	150
1.5	9.93	1.11	0.126	0.30	0.0071	147	150
2.5	9.51	0.69	0.078	0.42	0.0050	150	154
4.5	9.14	0.32	0.036	0.37	0.0022	150	154
6.5	8.94	0.12	0.014	0.20	0.0012	150	154
8.8	8.86	0.04	0.004	0.08	0.0004	150	154

TABLE XV

Drying Rate of Grey Cellulose Nitrate Plastic with Radiant Heat and 130 °F Internal Temperature

Run: No 12
Dry Weight: 8.87 gm
Air Temperature: 110 °F
Drying Surface: 85 sq cm
Relative Water Humidity: 30 %
Distance between Specimen and Hot Plates: 9 in.
Surface Temperatures of Hot Plates: 330 and 350 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Temperature of Specimen	
						Surface	Internal
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F	°F
0.00	11.53	2.66	0.300	--	--	--	--
0.1	11.30	2.43	0.274	0.23	0.0271	118	114
0.3	11.05	2.18	0.246	0.25	0.0148	122	118
0.5	10.87	2.00	0.226	0.18	0.0106	122	120
0.8	10.68	1.81	0.204	0.19	0.0075	122	122
1.2	10.49	1.62	0.183	0.19	0.0056	124	126
1.7	10.27	1.40	0.158	0.22	0.0052	125	127
2.7	9.91	1.04	0.117	0.36	0.0042	128	130
3.7	9.67	0.80	0.090	0.24	0.0028	128	130
4.7	9.53	0.66	0.075	0.14	0.0017	128	130
6.2	9.34	0.47	0.053	0.19	0.0015	128	130
8.2	9.19	0.32	0.036	0.15	0.0009	128	130
10.2	9.10	0.23	0.026	0.09	0.0005	128	130
12.2	9.01	0.14	0.016	0.09	0.0005	128	130

TABLE XVI

Drying Rate of Grey Cellulose Nitrate Plastic with Radiant Heat and 128 °F Internal Temperature

Run: No 13
Dry Weight: 9.00 gm
Air Temperature: 110 °F
Drying Surface: 85 sq cm
Relative Water Humidity: 50 %
Distance between Specimen and Hot Plates: 9 in.
Surface Temperatures of Hot Plates: 330 and 350 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Temperature of Specimen	
						Surface	Internal
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F	°F
0.00	12.31	3.32	0.368	--	--	--	--
0.1	12.02	3.02	0.336	0.29	0.0342	--	--
0.2	11.85	2.85	0.316	0.17	0.0200	122	122
0.3	11.73	2.73	0.304	0.12	0.0142	124	124
0.6	11.45	2.45	0.272	0.28	0.0110	124	124
1	11.19	2.19	0.244	0.26	0.0077	124	126
1.5	10.93	1.93	0.215	0.26	0.0061	126	128
2	10.71	1.71	0.190	0.22	0.0052	126	128
3	10.40	1.40	0.156	0.31	0.0037	126	128
4	10.18	1.18	0.131	0.22	0.0026	126	128
6	9.92	0.93	0.103	0.25	0.0015	126	128
9	9.87	0.87	0.097	0.06	0.0003	126	128
11	9.87	0.87	0.097	0.00	0.0000	126	128
12	9.87	0.87	0.097	0.00	0.0000	126	128

TABLE XVII

Drying Rate of Grey Cellulose Nitrate Plastic with Radiant Heat and 114 °F Internal Temperature

Run: No 14
Dry Weight: 9.09 gm
Air Temperature: 110 °F
Drying Surface: 85 sq cm
Relative Water Humidity: 50 %
Distance between Specimen and Hot Plates: 8 in.
Surface Temperatures of Hot Plates: 185 and 195 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Internal Temperature of Specimen
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F
0.00	--	--	--	--	--	--
0.1	12.88	3.78	0.416	--	--	102
0.2	12.73	3.64	0.400	0.15	0.0177	105
0.3	12.71	3.52	0.388	0.12	0.0142	108
0.5	12.37	3.28	0.360	0.24	0.0142	111
1	12.00	2.91	0.320	0.37	0.0087	112
2	11.41	2.32	0.255	0.59	0.0070	114
3	10.93	1.84	0.202	0.48	0.0057	114
4	10.64	1.55	0.171	0.29	0.0034	114
6.5	10.19	1.10	0.122	0.45	0.0021	114
7.5	10.06	0.97	0.107	0.13	0.0015	114
8.5	9.96	0.87	0.096	0.10	0.0011	114
10.5	9.81	0.72	0.079	0.15	0.0009	114
11	9.76	0.67	0.074	0.05	0.0005	114

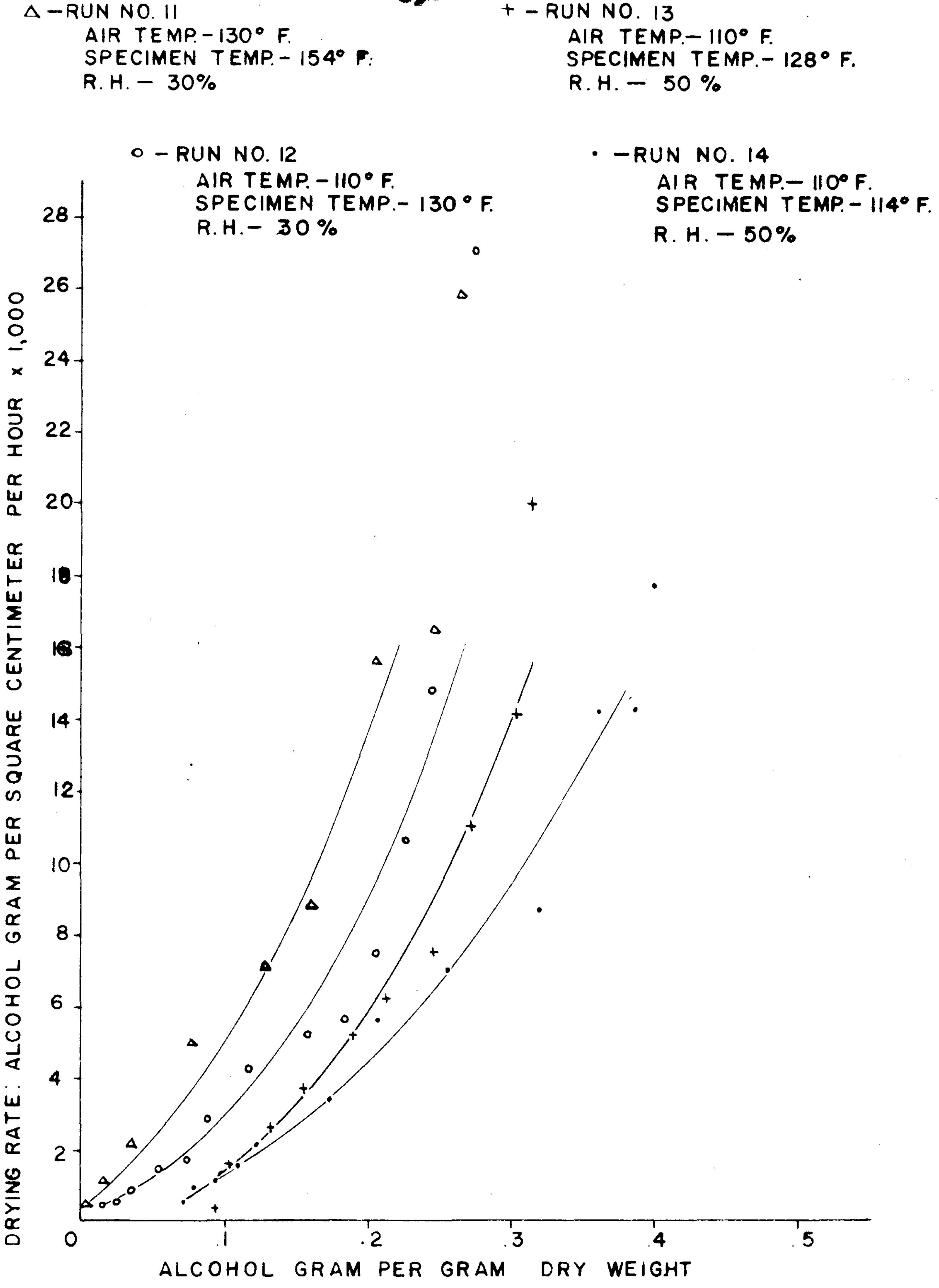
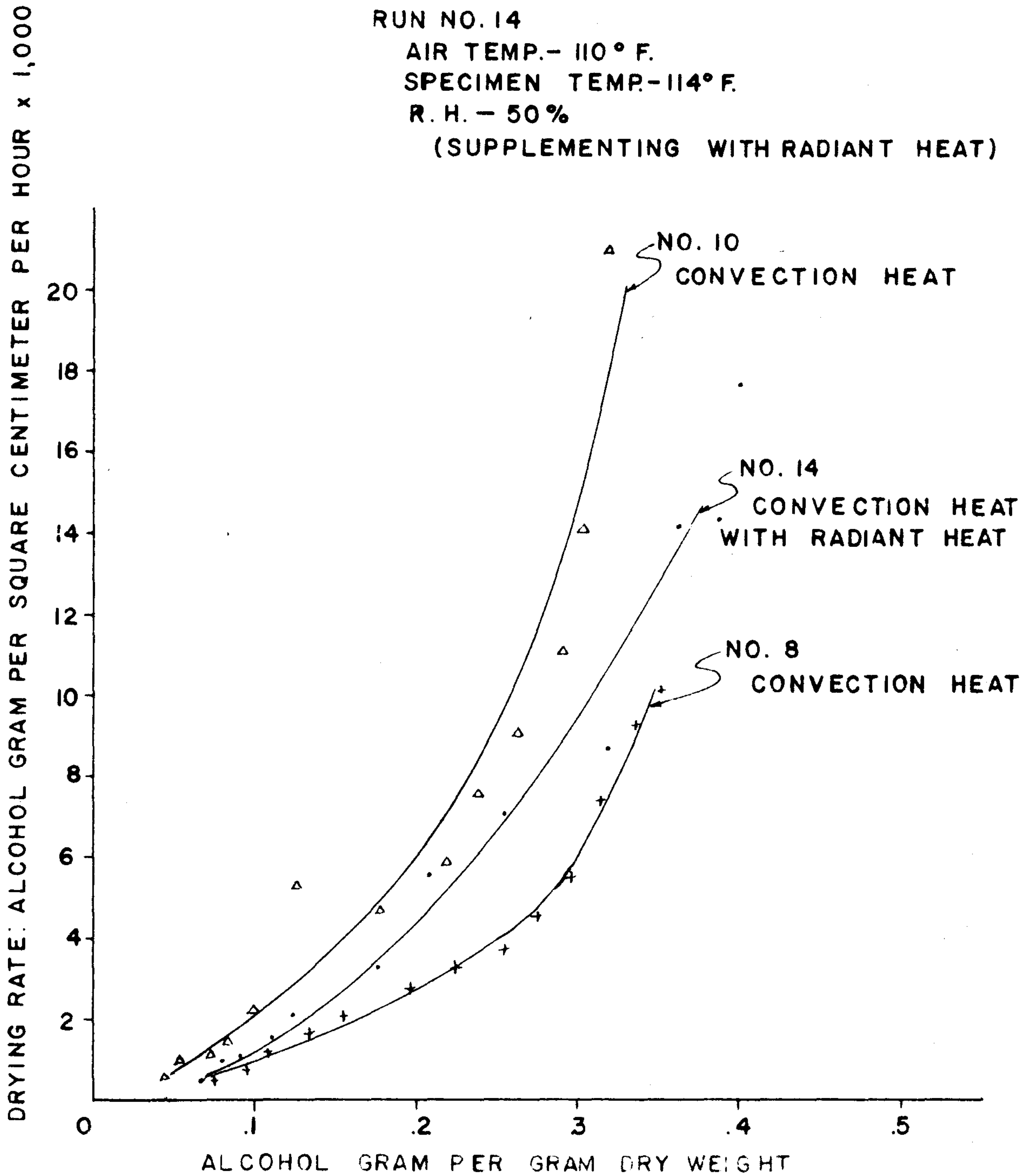


FIGURE 9. EFFECT OF RADIANT HEAT ON THE DRYING RATE OF THE GREY CELLULOSE NITRATE PLASTIC

RUN NO. 8
AIR TEMP.- 110° F.
SPECIMEN TEMP.- 104° F.
R.H.- 50%

RUN NO. 10
AIR TEMP.- 130° F.
SPECIMEN TEMP.- 124° F.
R.H.- 50%



RUN NO. 14
AIR TEMP.- 110° F.
SPECIMEN TEMP.- 114° F.
R.H. - 50%
(SUPPLEMENTING WITH RADIANT HEAT)

FIGURE 10. COMPARISON OF THE DRYING RATE OF CELLULOSE NITRATE PLASTIC BY CONVECTION HEAT AND BY SUPPLEMENTING CONVECTION HEAT WITH RADIANT HEAT

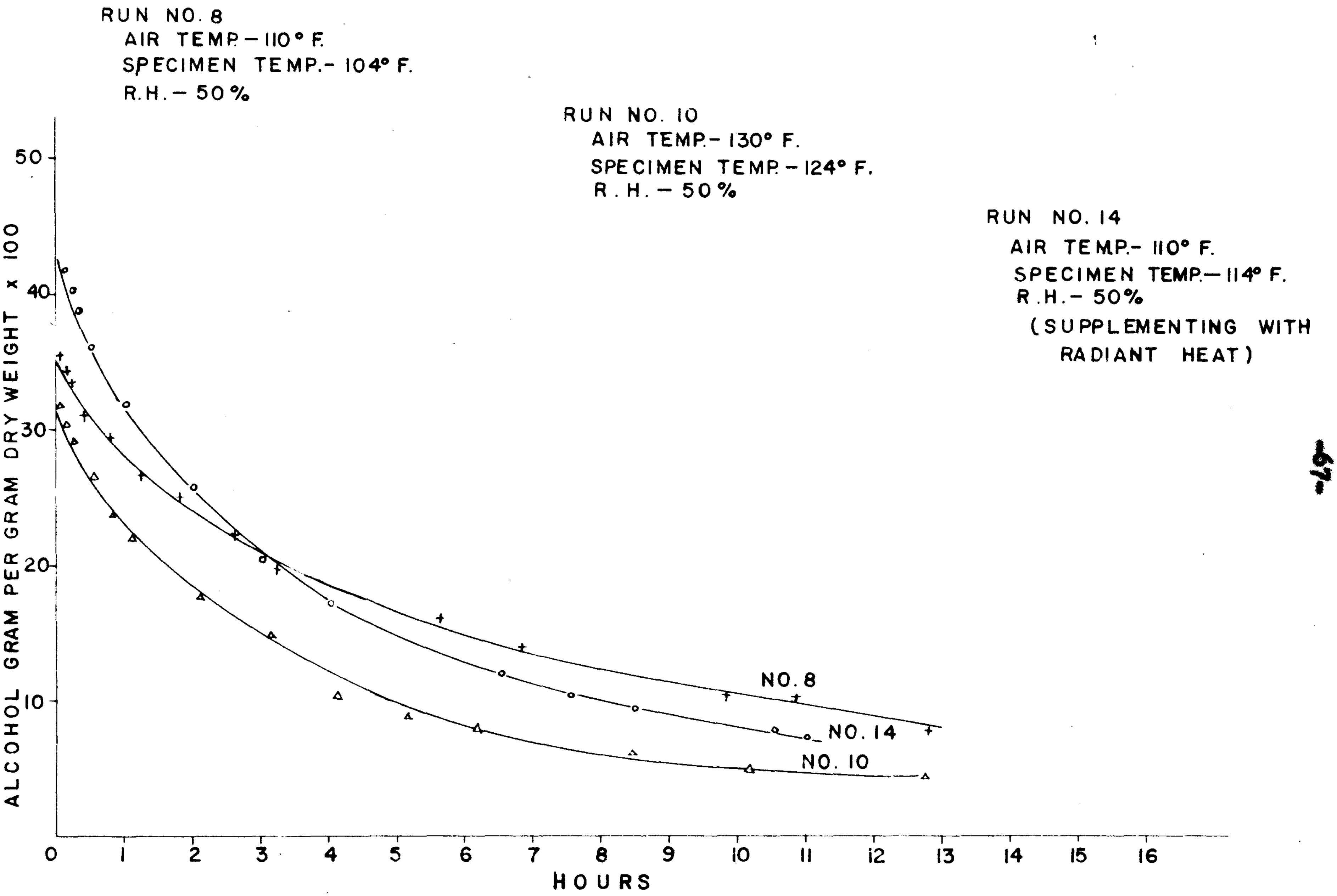


FIGURE II. COMPARISON OF THE DRYING TIME OF CELLULOSE NITRATE PLASTIC BY EMPLOYING CONVECTION HEAT AND THAT BY SUPPLEMENTING CONVECTION HEAT WITH RADIANT HEAT

TABLE XVIII

Drying Rate of Brown Cellulose Nitrate Plastic with Radiant Heat and 158 °F Internal Temperature

Run: No 11a
Dry Weight: 32.19 gm
Air Temperature: 130 °F
Drying Surface: 81 sq cm
Relative Water Humidity: 30 %
Distance between Specimen and Hot Plates: 9 in.
Surface Temperatures of Hot Plates: 360 and 380 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Temperature of Specimen	
						Surface	Internal
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F	°F
0.00	32.76	5.07	0.157	--	--	--	--
0.1	37.16	4.97	0.155	0.10	0.0124	--	128
0.2	37.08	4.89	0.152	0.08	0.0099	136	138
0.4	36.95	4.76	0.148	0.13	0.0081	139	141
0.7	36.82	4.63	0.144	0.13	0.0054	148	150
1.0	36.62	4.43	0.138	0.20	0.0082	150	153
1.4	36.45	4.26	0.133	0.17	0.0053	150	156
1.9	36.21	4.02	0.125	0.24	0.0059	152	158
2.9	35.87	3.68	0.111	0.34	0.0042	152	158
4.9	35.25	2.96	0.092	0.62	0.0038	152	158
6.9	34.80	2.61	0.081	0.45	0.0028	152	158
9.1	34.38	2.19	0.068	0.42	0.0023	152	158

TABLE XIX

Drying Rate of Brown Cellulose Nitrate Plastic with Radiant Heat and 132 °F Internal Temperature

Run: No 12a
Dry Weight: 32.67 gm
Air Temperature: 110 °F
Drying Surface: 81 sq cm
Relative Water Humidity: 30 %
Distance between Specimen and Hot Plates: 9 in.
Surface Temperatures of Hot Plates: 330 and 360 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Temperature of Specimen	
						Surface	Internal
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F	°F
0.00	39.99	7.32	0.224	--	--	--	--
0.1	39.84	7.17	0.220	0.15	0.0185	--	112
0.2	39.73	7.06	0.216	0.11	0.0136	121	122
0.3	39.62	6.95	0.212	0.11	0.0136	122	123
0.6	39.39	6.72	0.206	0.23	0.0095	123	125
1.0	39.12	6.45	0.197	0.27	0.0084	125	128
1.5	38.75	6.08	0.185	0.37	0.0091	126	132
2.0	38.50	5.83	0.178	0.25	0.0062	126	132
3.0	38.12	5.45	0.167	0.38	0.0047	126	132
4.0	37.92	5.25	0.161	0.20	0.0025	126	132
5.0	37.69	4.92	0.150	0.23	0.0028	126	132
6.5	37.35	4.68	0.143	0.34	0.0042	126	132
8.5	36.94	4.27	0.130	0.41	0.0025	126	132
10.5	36.64	3.97	0.121	0.30	0.0019	126	132
12.5	36.37	3.70	0.113	0.27	0.0016	126	132

TABLE XX

Drying Rate of Brown Cellulose Nitrate Plastic with Radiant Heat and 130 °F Internal Temperature

Run: No 13a
Dry Weight: 32.11 gm
Air Temperature: 110 °F
Drying Surface: 81 sq cm
Relative Water Humidity: 50 %
Distance between Specimen and Hot Plates: 9 in.
Surface Temperatures of Hot Plates: 330 and 360 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Temperature of Specimen	
						Surface	Internal
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F	°F
0.00	39.86	7.75	0.242	--	--	--	--
0.1	39.70	7.59	0.236	0.16	0.0198	--	--
0.3	39.48	7.38	0.230	0.21	0.0130	123	126
0.6	39.29	7.18	0.224	0.20	0.0082	124	127
1.0	39.11	7.00	0.218	0.18	0.0055	125	128
1.5	38.85	6.74	0.210	0.26	0.0064	126	130
2.5	38.52	6.41	0.199	0.33	0.0041	126	130
3.5	38.21	6.10	0.190	0.31	0.0038	126	130
5.5	37.73	5.62	0.175	0.48	0.0029	126	130
8.5	37.18	5.07	0.158	0.55	0.0024	126	130
10.5	36.83	4.72	0.147	0.35	0.0022	126	130
11.5	36.83	4.72	0.147	0.00	0.0000	126	130

TABLE XXI

Drying Rate of Brown Cellulose Nitrate Plastic with Radiant Heat and 119 °F Internal Temperature

Run: No 14a
Dry Weight: 30.18 gm
Air Temperature: 110 °F
Drying Surface: 81 sq cm
Relative Water Humidity: 50 %
Distance between Specimen and Hot Plates: 8 in.
Surface Temperature of Hot Plates: 185 and 195 °F

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate	Internal Temperature of Specimen
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr	°F
0.00	36.74	6.56	0.218	--	--	--
0.1	36.68	6.50	0.216	0.06	0.0099	--
0.3	36.56	6.38	0.211	0.12	0.0074	109
0.5	36.48	6.30	0.208	0.08	0.0050	113
1.0	36.31	6.13	0.203	0.17	0.0042	116
1.5	36.18	6.00	0.199	0.13	0.0032	119
2.5	35.99	5.81	0.194	0.21	0.0026	119
3.5	35.84	5.66	0.187	0.15	0.0019	119
6.0	35.53	5.35	0.172	0.31	0.0015	119
7.0	35.43	5.25	0.168	0.10	0.0012	119
8.0	35.35	5.17	0.165	0.08	0.0010	119
10.0	35.08	4.90	0.157	0.27	0.0016	119
10.5	35.02	4.84	0.155	0.06	0.0014	119

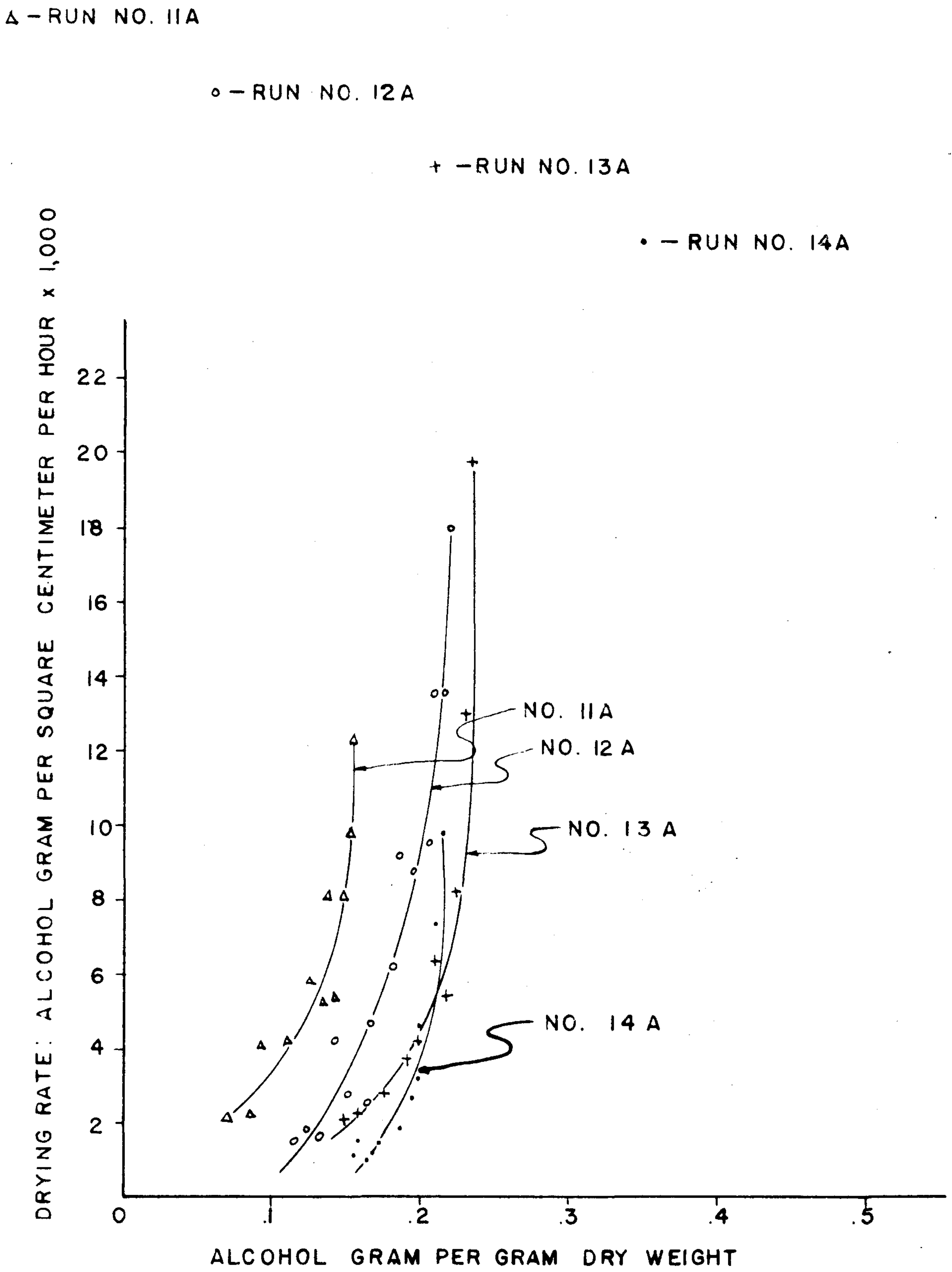


FIGURE 12. EFFECT OF RADIANT HEAT ON THE DRYING RATE OF THE BROWN CELLULOSE NITRATE PLASTIC

TABLE XXII

Drying Rate of Cellulose Nitrate Plastic Under Atmospheric Conditions

Run: No 15
Dry Weight: 8.81 gm
Drying Surface: 85 sq cm
Air Temperature: 85 °F
Relative Water Humidity: 55 %

Time	Weight of Wet Specimen	Total Alcohol in Specimen		Alcohol Evaporated	Drying Rate
hr	gm	gm	gm/gm dry wt	gm	gm/sq cm/hr
0.00	14.43	5.62	0.638	--	--
0.1	14.32	5.51	0.624	0.11	0.0130
0.2	14.22	5.41	0.615	0.10	0.0118
0.5	13.96	5.15	0.585	0.26	0.0102
1.0	13.70	4.89	0.571	0.26	0.0061
1.5	13.48	4.67	0.530	0.22	0.0052
2.5	13.16	4.35	0.494	0.32	0.0038
3.5	12.91	4.10	0.465	0.25	0.0029
4.5	12.66	3.85	0.437	0.25	0.0029
5.5	12.48	3.67	0.416	0.18	0.0021
8.0	12.05	3.24	0.368	0.43	0.0020
8.5	11.98	3.17	0.360	0.07	0.0016
9.5	11.86	3.05	0.346	0.12	0.0014
10.5	11.75	2.94	0.334	0.11	0.0013
11.5	11.65	2.84	0.322	0.10	0.0012
Test interrupted					
0.00	11.00	2.19	--	--	--
1.0	10.97	2.16	0.245	0.03	0.0004
2.0	10.89	2.08	0.236	0.08	0.0094
4.3	10.76	1.95	0.221	0.13	0.0012

RUN NO. 15

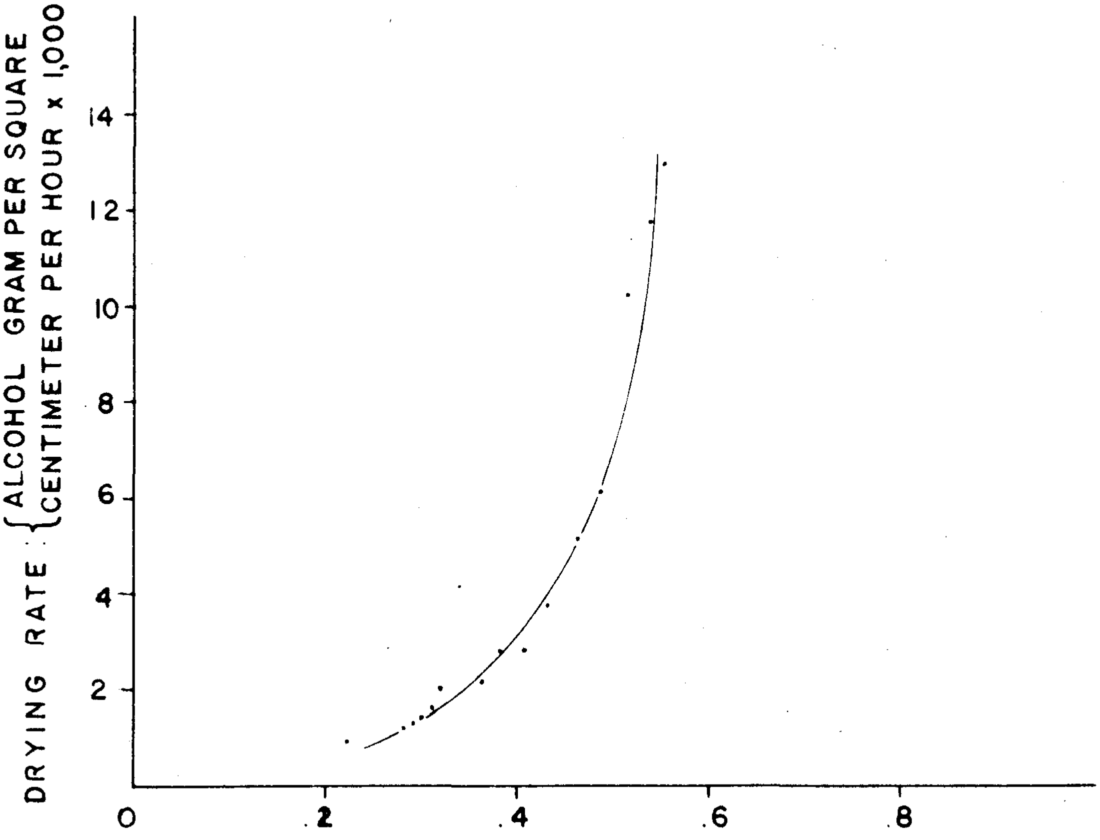


FIGURE 13. THE DRYING RATE OF CELLULOSE NITRATE PLASTIC UNDER ATMOSPHERIC CONDITIONS

Sample Calculations

The sample calculations involved in the experimental work are given in this section. All data for illustrations of the sample calculations are taken from run No 1, Table II, page 37.

Total Alcohol in Specimen. The total alcohol in the specimen was calculated as follows:

$$W_o = W - W_b$$

where:

W = weight of wet specimen during drying, gm

W_b = dry weight of dried specimen, gm

W_o = total alcohol in specimen during drying, gm.

At 0.5 hour the total alcohol in the specimen was

$$12.43 - 8.67 = 3.76 \text{ gm.}$$

Alcohol Gram per Gram Dry Weight. The alcohol gram per gram dry weight was calculated by the following expression:

$$a = \frac{W_o}{W_b}$$

where:

a = alcohol gram per gram dry weight.

At 0.5 hour the alcohol gram per gram dry weight was

$$\frac{3.76}{8.67} = 0.434 \text{ gm per gm.}$$

Alcohol Evaporated. Alcohol evaporated was calculated as follows:

$$b = W_1 - W_2$$

where:

W_1, W_2 = weights of wet specimen at two consecutive weighings, gm

b = alcohol evaporated, gm.

From 0.5 to 0.75 hour the alcohol evaporated was

$$12.43 - 12.18 = 0.25 \text{ gm}.$$

Drying Rate. The drying rate was calculated as follows:

$$p = \frac{b}{85(t_1 - t_2)}$$

$$p' = \frac{b}{81(t_1 - t_2)}$$

where:

b = alcohol evaporated, gm

85 (sq cm) = drying surface of grey specimen of dimensions 0.18 x 4.9 x 8.2 cm

81 (sq cm) = drying surface of brown specimen of dimensions 0.6 x 5.0 x 7.6 cm

t_1, t_2 = time of two consecutive weighings for W_1 and W_2, hr

p, p' = drying rate of grey specimen and brown specimen, respectively, gm/sq cm/hr.

The drying rate of the grey specimen for the interval from 0.50 to 0.75 hour was

$$\frac{0.25}{85(0.75-0.50)} = 0.0118 \text{ gm/sq cm/hr.}$$

IV. DISCUSSION

This section contains a discussion of the operations and a discussion of the results.

Discussion of Operations

Operation of the Dryer. An unsatisfactory point in the operation of the dryer was that the air temperature could not be held constant above 140 °F. Another defect in the operation was that, at a relative humidity of 60 per cent, moisture condensed on the wire by which the specimen was suspended and the weight could not be determined. These factors limited the range of test conditions.

Source of Radiant Heat. Two electric hot plates were used as a source of low temperature radiant heat to increase the internal temperature of the plastic. By adjusting the distance between the hot plates and the specimen and by regulating the surface temperature on the hot plates, any desired internal temperature could be obtained in the specimen. The maximum temperature was dependent on the susceptibility of the material to heat.

<u>Determination of Air Velocity</u>. Air velocity has little effect in the second falling rate period. In this work the majority of the drying time was in that period, and the air velocity in all tests was kept constant. The maximum air velocity obtainable with the centrifugal blower, 50 feet per minute in the drying chamber, was used.

<u>Measurement of Specimen Temperature</u>. Both the surface and internal temperatures of the specimen were determined by copper constantan thermocouples. The difference between the internal and surface temperatures of the brown specimen, 0.6 millimeter thick, was 6 to 4 °F, while that of the grey specimen, 0.18 millimeter thick, was 4 to 2 °F. A greater temperature gradient existed in the thicker and darker specimen with the same source of radiant heat.

<u>Determination of Dry Weight</u>. When cellulose nitrate plastic was soaked in alcohol some plastic and camphor plasticizer dissolved in the alcohol. An attempt was made to determine the dissolved weight. The solution was evaporated and the residue was weighed. The weight thus obtained was always negligible. This was probably because the extracted

camphor vaporized. Since the loss could not be determined, the original weight of the specimen could not be used as the dry weight for the test.

The dry weight was obtained after the specimen was removed from the dryer and dried in a zero humidity desiccator until its weight became constant for a one-day period.

It was found that such a dry specimen decreased in weight less than 4 per cent after 3-1/2 months exposure to air.

Determination of the Required Diffusion Time. It was first attempted to dry the wet cellulose nitrate plastic as soon as it was taken out of the alcohol with no time for the solvent to diffuse uniformly. It was found that the initial drying rate of such a specimen was very high, decreased very rapidly in the first half hour and became very low after two hours. It was apparent that the alcohol soaked up by the specimen did not diffuse uniformly and most of it was held on or near the surface.

The plastic to be dried in the factory is in colloidal form with the alcohol distributed uniformly.

In order to determine the requirements for uniform distribution, three preliminary tests were made with different diffusion times, 3-1/2, 8 and 36 hours. The drying rate was found to be inversely proportional to the length of diffusion time when the alcohol content was above 0.15 gram per gram dry weight. After the alcohol content fell below that value, the difference in diffusion time had no effect on the drying rate. This can be explained as follows. The shorter the diffusion time, the more alcohol remained on the surface of the specimen instead of penetrating into the interior. As long as there was alcohol at the surface the drying rate was controlled by evaporation and was rapid. It should be borne in mind that the diffusion action was not only in the so-called diffusion time, but also started at the time of soaking in alcohol and continued during the drying time. Diffusion should be good while the specimen was being dried at the elevated temperature. By the time the alcohol content was reduced to 0.15 gram per gram dry weight, all the above three tests had been running for more than four hours. It was believed that after four hours at the drying temperature diffusion was uniform in all the specimens. After that, the drying rate depended only on the conditions in the dryer, and the original diffusion time, 3-1/2, 8 and 36 hours, was no longer a factor.

Control of the Drying Rate by Relative Water Humidity. The use of alcohol humidity in the air to control the drying rate of cellulose nitrate plastic should be most effective, but it involves a fire hazard and is not economical. The use of relative water humidity of air to control the drying rate was based on the principle of the depression of alcohol vapor pressure by dilution with water.

When the relative water humidity in the air is increased, the difference between the vapor pressure of water on the surface of the wet specimen and the partial pressure of water vapor in the air stream is decreased, and the drying rate is lowered. When the partial pressure of water vapor in the air is greater than the vapor pressure of water on the surface of the wet specimen, the water in the specimen will be prevented from vaporizing and some water vapor will condense from the air stream on the surface of the specimen. The mol per cent and the vapor pressure of the pure alcohol in the specimen will be decreased and, consequently, the drying rate of the pure alcohol component is lowered. In this way it should be possible to control the drying rate and avoid shrinkage and case-hardening.

The quantitative effect can be shown by the following example. The 95 per cent alcohol by weight is 89 mol per cent of alcohol. According to Table I, page 5, such a solution is at equilibrium with 91 mol per cent of alcohol in the vapor, and at 50.5 °C (122 °F) it produces a total pressure of 225 millimeters of mercury. The vapor pressure of water in the solution must be 225 x (1 - 0.91) = 20 millimeters of mercury which corresponds to a humidity of 0.168 pound of water per pound of dry air. From the humidity chart at 122 °F this is 20 per cent of saturation. Thus, any water humidity larger than 20 per cent in the air should prevent water in this alcohol solution from vaporizing.

Another example can be used to show the composition of alcohol solution under equilibrium conditions. Suppose the conditioned air used to dry the specimen was 122 °F and 40 per cent water humidity and zero alcohol humidity. From the humidity chart the amount of water in the air is 0.03 pound per pound of dry air. The corresponding partial pressure of the water is 34.9 millimeters of mercury. From Table I, page 5, 82.4 mol per cent of alcohol in water (84.5 mol per cent in vapor) at 122 °F has almost the same vapor pressure of water calculated as follows:

220 x (1 - 0.845) = 34 mm Hg vapor pressure of water.

Thus, theoretically when 95 per cent alcohol is diluted to 82.4 mol per cent the partial pressure of the water component will be equal to the vapor pressure of water in the air stream. At that time water in the wet specimen can begin to vaporise with pure alcohol, but the composition of pure alcohol and water must remain as 82.4 and 17.6 mol per cent if equilibrium is to be maintained.

Discussion of Results

Drying Curve of Cellulose Nitrate Plastic. Since the cellulose nitrate and 95 per cent ethyl alcohol formed a colloidal system, there was no constant rate period in the drying curve. The portion of the falling rate period that was studied was between 0.4 and 0.04 gram alcohol per gram dry plastic. In this range the curve was concave upward, since the vaporization rate of the alcohol decreased very rapidly until the alcohol content was reduced to about 0.15 gram per gram dry plastic, and much more slowly below this point. The fast drying period range, above 0.15 gram alcohol per gram dry plastic, was considered to be of the greatest importance in this study. If this rate was too high, case-hardening, checking and warping resulted and the final drying rate was lowered. In this range the rate was materially affected by external drying conditions, while in the lower range humidity had no effect. This indicates that humidity control should be applied in the upper drying range, only.

Effect of Air Temperature and Relative Water Humidity. Both the air temperature and relative water humidity influenced the drying rate and drying time.

The air temperature had a greater effect than humidity. Increasing the relative humidity decreased the drying rate and this effect was greater at an air temperature of 130 °F than at 110 °F. It became less as the alcohol decreased and disappeared at 0.225 gram per gram dry weight for 110 °F and at 0.17 gram per gram dry weight for 130 °F. These effects can be explained as follows.

The increase of relative humidity resulted in a decrease in the difference of vapor pressure of water at the surface of the wet specimen and the partial pressure of water vapor in the air stream. Thus, the driving force for evaporation of water from the specimen was lowered and the drying rate decreased. At a higher air temperature the drying rate was greater than at a lower temperature. When these two rates were reduced by the same percentage by relative humidity, the actual amount of reduction in the former case was larger than in the latter.

As stated above, the drying rate affected by the relative humidity was only in the higher range where evaporation controlled. In the second falling rate period the relative humidity had no effect because the drying rate of the wet specimen was controlled by the diffusion rate of alcohol in the specimen. The points of 0.225 and 0.170 gram alcohol per gram dry weight might be regarded as two critical points. Below them the drying rate belonged to the second falling rate period where the relative humidity had no effect.

An increase of air temperature raised the internal temperature of the specimen which, in turn, increased the drying rate in both the evaporation and diffusion periods. When evaporation controlled, the vapor pressure of water at the surface of the specimen was increased and the drying rate became larger. When diffusion controlled, the increase of internal temperature decreased the viscosity and increased the rate of diffusion. Thus, the total drying time was shortened by increasing the air temperature.

The Effect of Shrinkage. When a specimen was tested at a relative humidity of 30 per cent and air temperature of 140 °F, warping and checking occurred. This indicated that the temperature was too high and relative humidity was too low, so that the surface of the wet specimen dried faster than the interior and the surface tended to shrink, following which warping and checking occurred.

When the internal temperature of the thick brown specimen was raised to 130 °F by supplemental radiant heat, many bubbles formed. The reason for this was that at high internal temperature some alcohol vaporized in the interior before diffusing to the surface of the specimen.

The Effect of Radiant Heat. Cellulose and its derivatives, as cellulose nitrate, have a long chain molecular structure. The secondary bonds between the chains can be broken by heat and the interior becomes softer. The thicker and darker the plastic, the more radiant energy is absorbed under constant radiation. The internal temperature is, therefore, the critical factor rather than the temperature of the radiating surface.

By using the same source of radiant heat the internal temperature of the brown specimen was raised 2 to 5 °F higher than the grey specimen. This was due to the darker and thicker specimen absorbing more radiant energy to increase its internal temperature.

Another factor in radiant heating was indicated in runs No 12, 13, 12a and 13a. When the air temperature was 110 °F and the relative humidity was increased from 30 to 50 per cent, the internal temperature of the specimen was decreased by 2 to 5 °F. This indicated that the water vapor in the air had absorbed some of the radiant energy. The internal temperature should have risen, as the effect of higher humidity was to slow the rate of drying and thereby decrease the rate of cooling.

The Advantage of Radiant Heat. The internal temperature of the specimen could be raised either by convection or radiant heat. However, a higher air temperature would require a higher moisture content to maintain the relative humidity. By radiant heat, the internal diffusion rate could be increased without affecting the effect of relative humidity in slowing the vaporization rate. Curves are shown in Figure 11, page 67, for tests in which the temperature was raised 10 °F by radiant heat and 20 °F by convection heat. The slope of the first curve (run No 14) was greater than that of the second (run No 10). This indicated that the total drying time, calculated by extrapolation, in the former case would be shorter.

Recommendations

The following recommendations are presented for future study of the drying of cellulose nitrate plastic.

Specimen. The specimen should be taken from commercial colloidal material instead of preparing it from dried plastic sheet. The solvent is uniformly diffused in the colloid and uniform diffusion is difficult to obtain in finished plastic.

Continuous Process. A continuous process of drying without interruption should be used, and the specimen should be dried to equilibrium moisture content. Then, a better comparison could be made of total drying time under different conditions.

Operating Conditions in Different Drying Ranges. It seems that it is worth while to vary the operating conditions for a specimen in the drying process. Low temperature and high humidity can be used in the evaporation periods to prevent case-hardening, while in the diffusion period a higher temperature can be used to increase the drying rate and the control of humidity is not necessary. In this way the optimum conditions may be obtained.

Range of Operating Conditions. Drying air of temperature higher than 130 °F and relative humidity beyond the range of 30 to 60 per cent should be used. The radiant heat should be applied in various cases.

Construction of Dryer. In order to obtain optimum conditions, a new dryer should be constructed in accordance with the following ideas. The size of the dryer should be reduced by reducing the height of the lower part and the width of the dehumidification chamber; then the time required for adjusting the air to the desired conditions can be shortened. An automatic temperature control and humidity control are necessary to maintain the exact air conditions. A set of dehumidification equipment or refrigeration coils should be installed in the humidification chamber to lower the humidification below 30 per cent. The high pressure steam can be used to raise the air above 130 °F. The internal temperature of a specimen by radiant heat should be easily raised to any degree. This may be accomplished by utilizing a rheostat control with the electric hot plates. The shape and size of the electric hot plate should be made to fit different specimens.

Study of Radiant Heat. Radiant heat has rarely been applied to the drying of cellulose nitrate plastic. This is a good field of study, not only for cellulose nitrate plastic but also for other kinds of plastics and surface coatings, and should be further investigated.

Limitations

This investigation was conducted under the following limitations.

Specimen. The cellulose nitrate used was pyralin made by E. I. du Pont de Nemours and Company, plasticized with camphor. Two types of specimens were tested; one was grey color, 0.18 millimeter thick, and the other was brown color, 0.6 millimeter thick.

Air Velocity. Air velocity was kept constant at 50 feet per minute.

Solvent. The solvent used was 95 per cent ethyl alcohol.

Alcohol Content. In most cases, the drying tests were started below an alcohol content of 0.4 gram per gram dry weight of plastic.

Relative Humidity. The relative humidities were limited to 30, 40, 50 and 60 per cent. At 60 per cent moisture condensed on the suspension wire and the data were not taken.

Air Temperature. Air temperatures in the dryer were limited to 110, 120, 130 and 140 °F. At 140 °F the difficulty of maintaining a constant temperature prevented making a complete test.

Internal Temperature of Specimen by Radiant Heat.

By supplementing convection heat with radiant heat the internal temperature of the grey specimen was increased to 114, 128, 130 and 154 °F, and of the brown specimen to 119, 130, 132 and 158 °F.

V. CONCLUSIONS

The investigation of the effects of relative water humidity, convection heat and radiant heat on the drying of cellulose nitrate plastic led to the following conclusions. Unless otherwise stated all plastic mentioned below is 0.18 millimeter thick grey cellulose nitrate plastic with the commercial name of pyralin.

1. When the internal temperature of the wet plastic was raised from 104 to 114 °F by supplementary radiant heat, with drying air at 110 °F and 50 per cent relative humidity, the drying rate of plastic was increased without causing case-hardening or warping. The drying time was reduced from 12.9 hours to 10.2 hours for drying the plastic from 0.352 to 0.075 gram alcohol per gram dry weight.

2. When the internal temperature of the wet plastic was raised to 128 and 130 °F by supplementary radiant heat, with drying air at 110 °F and 50 and 30 per cent relative humidity, respectively, the drying rate of the plastic was increased, but physical damage to the plastic resulted.

3. The maximum safe air temperature for drying cellulose nitrate plastic without radiant heat was between 130 and 140 °F, physical damage to the plastic occurring at 140 °F.

4. The effect of increasing the relative humidity was to decrease the drying rate at higher alcohol content of the plastic, and the effect increased with increase of air temperature. It became less as the alcohol content decreased and disappeared when the plastic had been dried to 0.225 gram alcohol per gram dry weight at 110 °F, and 0.17 gram alcohol per gram dry weight at 130 °F.

5. An increase in humidity caused only a slight increase in drying time to alcohol content of 0.10 gram per gram dry weight and an increase in air temperature shortened the drying time much. To dry the plastic without physical damage from 0.315 to 0.100 gram alcohol per gram dry weight required 9.85 hours at 110 °F and 50 per cent relative humidity, 9.5 hours at 110 °F and 30 per cent relative humidity, 4.8 hours at 130 °F and 50 per cent relative humidity and 4.3 hours at 130 °F and 30 per cent relative humidity.

6. Radiant heat was effective in raising the internal temperature of the wet plastic without damage to the material, and the effect was slightly greater with a thicker specimen of dark color than with a thin specimen of light color.

VI. SUMMARY

In the manufacture of cellulose nitrate plastic some physical damage of the finished product always results during drying. The drying conditions should be studied and improved.

The purpose of this investigation was to determine the effects of relative water humidity, convection heat and radiant heat on the drying of cellulose nitrate plastic. The conditions causing case-hardening and physical damage were observed, drying rate was determined and drying time compared.

Specimens of cellulose nitrate plastic sheet, plasticized with camphor, were soaked in 95 per cent ethyl alcohol. They were first dried in a compartment dryer by conditioned air, with or without radiant heat. Then, they were removed to a zero relative humidity desiccator to be dried until the weight became constant within a one-day period.

The values of relative humidity studied were 30, 40, 50 and 60 per cent. The air temperatures studied were 110, 120, 130 and 140 °F. The detailed data were not obtained at 60 per cent relative humidity and at

140 °F because these conditions could not be controlled. The radiant heat was supplied from two electric hot plates and used to increase the internal temperature of the plastic.

The effect of increasing the relative humidity was to reduce or avoid damage to the plastic and to reduce the drying rate at higher alcohol content. This effect increased with the increase of air temperature and became less as the alcohol content decreased. It disappeared at 0.225 gram alcohol per gram dry weight as dried at 110 °F and temperature, and at 0.17 gram per gram dry weight as dried at 130 °F.

Increasing the air temperature increased the drying rate and shortened the drying time. The maximum safe air temperature for drying cellulose nitrate plastic without radiant heat was between 130 and 140 °F, physical damage occurring at 140 °F.

Radiant heat could be applied to raise the internal temperature of the wet plastic and to increase the drying rate without causing case-hardening, the effect being slightly greater with a thick plastic of darker color than with a thin plastic of light color.

When the internal temperature of the wet plastic was raised to 128 and 130 °F by supplementary radiant heat, with drying air of 110 °F and 50 and 30 per cent relative humidity, respectively, the drying rate was increased, but physical damage to the plastic resulted.

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