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UNIVERSITY OF LOUISVILLE

Practical Vacuum Drying Theory

A Dissertation

Submitted to the Faculty

Of the Graduate School of the University of Louisville

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Department of Chemistry

By

John W. Ridgway

1934

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Chapter I
INTRODUCTION

Chapter I

INTRODUCTION

'Coincident with the tremendous development of the chemical industries in the United States in the period between 1914 and 1920, there came a realization that certain engineering operations were common to many processes that had previously been thought to occupy separate water-tight compartments. At the same time there also came a realization that many of these operations were little understood and that they all needed examination, development, and elaboration.

As soon as this intensive research began, the fact that a given operation involved the same principles no matter in what industries it might be used became more apparent. Gradually, as it was recognized that a knowledge of these operations was the real key to an understanding of manufacturing processes, the field of the chemical engineer was recognized as covering these unit operations.'(1).

One of the most important of these operations of chemical engineering is drying. There are many types of dryers including both intermittent and continuous. Whether intermittent or continuous the dryer may be of an atmospheric or reduced pressure type. This reduced

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Pressure or vacuum type is becoming more and more important in industry.

Certain materials are greatly improved or their rate of drying increased by the use of vacuum drying. Some materials that are dried under vacuum with good results are; milk, oils, electrodes, barley, wood, sugar, textile fabrics, yeast cakes, medical plants, gels, malt extract, vegetables, fruits, cork, grain, paper, colors, food products, fine chemicals, nitro-compounds, starch, rubber, clay, explosives, and wood pulp.

'The first small experimental vacuum dryer was erected in a Petersburg sugar refinery in 1881 by Emil Passburg. This led to the erection of a larger vacuum dryer which showed that the drying of sugar could be carried out in about one-tenth of the time taken in the other dryers used up to this time. Emil Passburg then obtained a Russian patent on the drying of sugar under vacuum. In a short time all the Russian sugar refineries used vacuum drying apparatus with cars on which the products was loaded. Soon afterward vacuum dryers were used in Germany, France, and America.

Vacuum dryers were at first used only for sugar and then log-wood liquor. In time it was used with good results for viscous liquors, pastlike masses, crystalline foods, and vegetables. Around 1900 it was used by the dye and color industries and then later by chemical industries for drying their raw, intermediate, and final products.' (2).

A continuous belt type vacuum dryer was used as early as 1906 (3).

The use of vacuum dryers for the last stage of the drying period only, was studied in 1912 (4).

The applications and limitations of different types of vacuum dryers with comparative data on drying costs were studied as early as 1921 by Lavett and Van Harle (5).

The mathematics of vacuum drying was studied in 1925 by Armand Martin (6).

This investigation will include the determination, upon a semi-plant scale; of the effect of varying conditions, as temperature and vacuum, upon the rate of drying; and of the temperatures in the cake and in different parts of the vacuum chamber during the drying period.

The purpose of this investigation is also to point out the application of the results obtained to different drying problems in industry.

Chapter II

THEORY

Chapter II

THEORY

As this investigation is to study vacuum drying and to point out some of the differences between vacuum drying and air drying, it is necessary to understand clearly the theory of air drying.

In the drying of porous solids by the evaporation of the liquid from the surfaces of the solids, using air currents to effect the evaporation, Sherwood (7) has developed a theory, with experimental confirmation, showing three possible distinct stages in the drying process.

"(1) A constant drying rate period, during which the surface remains completely wet, the rate of evaporation being the same as that from a liquid surface of constant area. Constant air velocity, direction, humidity, and temperature are assumed.

(2) A falling rate period, during which there is a falling off of wetted surface, the rate being directly proportional to the fraction of surface which is wet. This rate has been shown to decrease linearly with the average liquid concentration until the liquid concentration at the surface has reached equilibrium with that of the air, and further decrease of concentration in the surface layer is not possible.

(3) A second falling rate period, during which the liquid evaporates from the surface as fast as it can get there by diffusion from the interior of the solid. During this period, the liquid concentration of the surface layer remains constant."

Rapid evaporation at low temperatures is of great advantage in the drying of materials sensitive to injury at high or moderate temperatures, and vacuum drying is commonly employed for such materials. No air circulation is used, so that the sensible heat lost in the waste air is negligible. Some materials are dried under vacuum to prevent oxidation, decomposition, or discoloration which would occur in atmospheric drying (8).

Some erroneous views in regard to vacuum drying are that no boiling occurs, but only evaporation as in air drying, that the heat efficiency is low because in the absence of air it is applied by radiation, and that owing to direct contact with the heating surfaces there is danger of overheating.

Berthold Black (9) asserts that actual boiling occurs during the early stages of vacuum drying; that the drying takes place throughout the entire material, and not on the surface, as in air drying; that the heat

efficiency is actually higher on account of the absence of the insulating effect of air; that overheating is impossible on account of the low temperature at which the water evaporates under vacuum; that a greater temperature range is possible, and a better control; and that vacuum drying eliminates the danger of poisonous gases, dust, and danger of oxidation. It also reduces the danger with explosives and makes possible a more complete recovery of volatile solvents.

Berthold Bloek gives experimental results to show that there is not only drying from the surface but from the interior as well.

'In drying in air the outside becomes dry when the substance is non-porous, and the moisture, due to capillarity flows from the inside to the outside in order to create an equilibrium. It is this small amount of water, for example kernel water, that contains different salts and minerals in solution that flows to the surface and is dried up. The interior becomes emptier and the surface becomes encrusted and completely closed. The drying then becomes more difficult and finally impossible. Such a method of drying takes out only with extreme difficulty the native water of fruits or vegetables.

This can be proved by drying sweet-bread in air. In air drying it is shown that the sugar solution flows to the surface and is then evaporated, by the outside of the sweet-bread becoming covered with a glazed crust of sugar. In comparison by drying sweet-bread under vacuum the water is removed from the entire body and not only from the surface. This process leaves the sugar where it originally was and eliminates the accumulations at the surface.

In drying slices of potatoes the air dried ones are shrunk up and absorb water with difficulty while the vacuum dried ones are porous and easily absorb water.

Glue slabs remain whole in air drying and are still moist inside while in vacuum drying they dry throughout and come out of the dryer as a powder. Air drying can only with difficulty take out the native water of fruits or vegetables and then the finished product is inferior. Vacuum drying does away with accumulations of internal juices and liquors at the surface of products. '(9).

A mathematical discussion of the theory of vacuum drying is presented by Armand Martin (6). He gives complicated equations for heating and cooling under vacuum. They are approximate and the coefficients are hard to determine. The equations are worked out for hot water as the heating medium.

Some of the advantages and disadvantages of vacuum drying are given in a complete review of vacuum drying presented before the Institute of Chemical Engineers in 1938 by G. W. Riley (10).

The advantages given were:

'(1) Freedom from contamination or spoilage of delicate products. In air drying large volumes of air are used and must be purified to prevent contamination. The oxygen in the air is liable to cause chemical change; destruction of the vitamin content of foodstuffs such as milk, increase rancidity and acidity, accelerate fermentation and otherwise depreciate in value the material. In vacuum drying there is almost sterile and inert atmosphere and the chamber is easily sterilized by filling with steam.

(2) Smaller loss of powdery product. The vapor withdrawn from a vacuum dryer being necessarily much

less dense than the air-vapor withdrawn from an atmospheric dryer insures less loss of very powdery products in the case of the former.

(3) More compact design. For corresponding duties the condensing and drying equipment is more compact in the case of the vacuum dryer.

(4) Direct heating with no overheating. The heating is direct as it is not necessary to heat air first and then use the heated air to heat the product. The heat loss is consequently less and due to the constant temperature of the steam at a given pressure there is no overheating.

(5) Quicker drying and drier products. Where the material to be dried is in trays or of large dimensions the drying is quicker under vacuum. As the moisture is withdrawn as soon as it is formed the product is obtained drier.

(6) More complete control of drying conditions. The vapor temperatures are more uniform and due to the constant temperature of steam in a jacket at constant pressure the heating can be controlled easier.'

The disadvantages given were:

(1) High cost of equipment. Due to large chamber that must be cast as one piece or in some other

way made to withstand approximately 15 pounds per square inch pressure and also due to the condensing system and the vacuum pump the initial cost of the equipment is high.

(2) In some cases atmospheric dryers have advantages due to peculiarities of the material being dried.

(3) Inspection during drying is more difficult. This is particularly the case with stationary shelf dryers, since to open up the dryer it is necessary to break the vacuum and so stop the drying process.'

As vacuum drying is so important it is thought that the variation of the rate of drying with changing conditions and the actual conditions in the dryer during the drying process should be more completely studied.

Chapter III
APPARATUS

Chapter III

APPARATUS

The apparatus consisted of the vacuum shelf dryer and its accessories, and other apparatus necessary in order to make the experimental runs.

The vacuum shelf dryer and its accessories are shown in Diagram I.

The vacuum shelf dryer consisted of a cast-iron shell (F) rectangular in cross-section, and this shell contained three shelves (B, Diagram III). These shelves were hollow and during operation were filled with steam. In the front of the dryer at either side were vertical manifolds (D and L), and a short connection (K, Diagram III) extended from either manifold to each shelf. One of the manifolds (L) was for the introduction of steam, and the other (D) was for the removal of condensate and non-condensed gases.

The material to be dried was placed on trays which were placed on these shelves. The door (F) was closed, the handles (E) screwed tight, and the interior of the dryer placed under vacuum by means of a vacuum pump. The steam in the shelves gradually heated the material in the trays to a temperature such that the

DIAGRAM I

APPARATUS

water evaporated under the pressure that existed in the dryer.

The water was condensed in a condenser (T) placed between the dryer and the vacuum pump (V) driven by the motor (S, Diagram II). The condenser was designed to cool the condensate, which was discharged through a special drip pipe arranged between inspection glasses (I) in the receiver, so that the operator could form some idea of the progress of drying from the rate of drip.

With high vacuum a special condenser must be used. Water vapor under .2 inch total pressure condenses at approximately 1.4° C. and so an ordinary water-cooled condenser would not be of service. Several methods of dealing with the vapor are available (10).

As the lowest total pressure used in this investigation was about 4 inches no special condenser equipment was necessary, for water condenses at approximately 52° C. under this total pressure.

The steam entered the dryer shelves through a pipe (M) and a manifold (L) and was regulated by a valve (L). The pressure of the steam was read on a gage (G) before it passed out of the manifold (D) through a trap

(B) into the condensate line (A).

The vacuum was drawn by the vacuum pump (10, Diagram II) through the condenser and pipes N and K. The valve at U was closed when tested for leaks. The vacuum was changed by bleeding in air at valve O. Valve O and valve L were needle valves. This enabled the operator to maintain constant vacuum and steam pressure with as little trouble as possible.

The vacuum was measured on a mercury U-tube (I) the reading being made by means of the yardstick (J). The vacuum was broken by opening valve H at the front of the dryer.

The inspection glasses G were used to observe as much as possible the conditions in the dryer.

The data table and its instruments are shown in Diagram II.

The copper-constantan thermocouples were inserted through pipe 11 from the vacuum chamber. They then pass through the vacuum bottle (5), which serves as a cold end junction, to the switch panel (9). The millivolts were read on the Leeds Northrup Potentiometer Indicator (W), with hand operated cold junction compensator,

DIAGRAM II

DATA TABLE

and converted to degrees centigrade by means of the "Copper Vs. Constantan Thermocouple Conversion Table" with the reference junction taken as zero degrees centigrade (11).

Cooling water was supplied to the condenser through pipe P and left the condenser at R. The cooling water to the vacuum pump entered through pipe 1 and left through pipe 4. The barometer Y was used to measure the atmospheric pressure during each run in order that the total pressure in the dryer could be calculated.

Copper-constantan thermocouples were used to measure the temperature in the cakes and in the vacuum chamber. These thermocouples were placed as shown in Diagram III.

The ends of the thermocouples were placed as indicated by the numbers 1 through 10 in the diagram. This is a front view of the dryer showing the cast-iron shell (A) and the three steam shelves (B). Pipe I leads to the condenser and pipe J carries the thermocouples over to pipe 11 of Diagram II.

In order to place the thermocouples in the vacuum chamber an air-tight seal was necessary. This

DIAGRAM III
 SKETCH OF DRYER END
 OF THERMOCOUPLES

seal is shown in Diagram III.

The thermocouples after leaving the vacuum chamber were taped together (C) and passed up through the reducing coupling E and then over to the vacuum bottle.

The seal was formed by a rubber stopper (F) being placed in the pipe (L) before the reducing coupling was screwed on. This stopper had a large hole fitted with a short length of glass tubing (H). This tubing was held in place by means of Kotinsky cement (G) placed on the top and bottom of the stopper around the tubing. The friction tape around the ten thermocouples was taped so as to form a wedge (D) to keep the thermocouples from being pulled downward and make the seal perfectly tight. This seal is at Z in Diagram I.

The thermocouples after leaving the seal passed through pipe to the vacuum bottle (5). This bottle contained a large one inch test tube with a stopper (8) and a thermometer (7) that read the temperature in degrees centigrade inside the test tube. This thermometer was constructed with the zero point at the middle of the stem. This permitted the bulb to be about two inches from the bottom of the large test tube.

Each of the two wires of each thermocouple was soldered to a fine copper wire and a single thickness of friction tape pinched over the junction to insulate them one from the others. These junctions were placed inside the large test tube and then the tube placed in the vacuum bottle held in place by the tin brace (12). The vacuum bottle was full of water during all the runs. This was done in order to prevent fluctuations of the cold end temperature. As the potentiometer had a hand operated cold end compensator there was no need of using ice. With the thermometer in place the cold end temperature could be observed from time to time and the compensation changed if necessary.

The copper wires to the cold end junctions were then connected to the switch (9). The wires from the copper cold ends were connected to the side marked Cu and the wires from the constantan cold ends to the side marked K. To the central turning arms of the switches were soldered copper wires that led to the thermocouple connections of the potentiometer indicator (W).

Besides the dryer and its accessories other apparatus was necessary. The samples were taken from

the filter cake with a cork borer with a slit in the end to prevent packing. They were then placed in a desiccator and weighed as soon as cool on a chainomatic balance. They were then dried in a resistance type electric oven.

As the university steam was turned off late in the afternoon steam from a small gas fired boiler was used in making all of the final runs.

The filter cakes were made in a small plate and frame filter press, the sludge being mixed in a large wood tank fitted with an electric stirrer.

The sludge was forced into the press under air pressure from a small montejus.

Chapter IV
PRELIMINARY EXPERIMENTAL

Chapter IV

PRELIMINARY EXPERIMENTAL

The preliminary experimental work consisted primarily of acquiring technique in controlling the temperature, the vacuum, and the uniformity of the filter cakes.

A. Filter Cakes.

The filter cakes were made in a plate and frame filter press. The sludge was made up by stirring sil-o-cel powder into water. The sludge contained approximately 25 cubic inches of wet filter cake per gallon. This concentration was used so that one monteju full would fill up the three frames that were used in making the cakes for each run.

Only two filter cakes were used, but three were made in order that the best two might be used. The filter cake nearest the end of the press was always the largest due to a slightly sunken frame head. This cake was used only three times during the eight runs. It was necessary to use this larger cake each of these three times because one of the other cakes was too wet. However this did show how the rate of drying varied with the thickness of the cake. This proved very

important in explaining the theory of the last stage of the drying process.

The filter cakes were formed slowly in order to keep the sil-o-cel sludge from coming through cloudy. It was found that the best cakes were formed when the starting pressure on the sludge was about five pounds per square inch. This pressure was maintained until approximately one gallon of the filtrate had been collected or until the spigots began to discharge clear liquid. The pressure was then gradually increased to thirty-five pounds. The filtering was continued at thirty-five pounds until the water no longer came from the spigots. At this point the pressure was increased to about one hundred pounds and allowed to remain there until the water again no longer came from the spigots. At this point the filtering was stopped and the cakes were then blown with air for about five minutes. The frames were then removed from the press and the cakes taken from the frames by sliding a knife blade between the cake and the frame to prevent breaking the cakes.

This procedure after a few practice runs gave uniform filter cakes dry enough to prevent "flowing" in the dryer. This was very important for

if the cakes "flowed" the zone temperatures could not be measured.

Sil-o-cel was chosen as the filter cake material for the following reasons:

- (1) It forms a noncompressible sludge.
- (2) It can hold a large amount of water and still remain consistant.
- (3) It does not combine with water or undergo chemical changes during drying.
- (4) It gives a cake that is filled with very fine pores.
- (5) It has a different color when wet, therefore one can tell when the surface of the cake becomes dry.

B. Calibration of Thermocouples.

The ten copper-constantan thermocouples were calibrated against a tenth of a degree standard thermometer with the results shown in Curves I and II.

As the temperature readings on the potentiometer indicator could only be reproduced to the nearest $.5^{\circ}$ C. the thermometer was also read only to the nearest $.5^{\circ}$ C.

The thermometer was corrected for stem emergence by the following formula (12).

CURVE I

CALIBRATION CURVES OF THERMOCOUPLES

No. 1 THROUGH No. 5

CURVE II

CALIBRATION CURVES OF THERMOCOUPLES

No. 6 THROUGH No. 10

$$C = .000154 (T_1 - T_2) N$$

C is the stem emergent correction,

T_1 is the temperature read on the thermometer,

T_2 is the average temperature of the emergent stem, and

N is the number of degrees of emergent stem.

The correction "C" was added to the thermometer reading to give the correct temperature.

The thermocouples were calibrated by placing them in a beaker of hot water along with the thermometer. Readings were taken as the water cooled down. The thermometer was read directly after each thermocouple reading.

The curves show that by shifting the zero axis separately for each curve all the thermocouples can be made to read to $\pm .5^\circ$ C. This shift is accomplished by making the following corrections directly to the temperatures read by the thermocouples:

No.1- No correction.

No.2- No correction.

No.3- Subtract .5 degree.

No.4- Subtract 1 degree.

No.5- Subtract 1 degree.

No. 6- Subtract 1.5 degrees.

No. 7- Subtract 1.5 degrees.

No. 8- Subtract .5 degree.

No. 9- Add .5 degree.

No. 10- Subtract 1.5 degrees.

These corrections were made before the temperatures were recorded in the tables. Therefore all temperatures recorded in this investigation are correct to within $\pm .5^{\circ}$ C.

C. Test Runs.

A number of test runs were made in order to eliminate all minor difficulties before the actual final experimental runs were made. These runs were made to determine the duration of the run, to determine the best time interval for the different readings, and to obtain experimental technique.

Three preliminary runs were made. The first was a four hour run with the moisture content samples being taken every half hour and the cake temperatures also being taken every half hour. It was noted that it was unnecessary to take moisture samples every half hour. It was also rather difficult to maintain constant

conditions when the cabinet was opened so often. The moisture content was too high at the end therefore the run was too short.

The second was a seven hour run with moisture content samples taken every hour and cake temperatures taken every quarter hour except on the hour, when the cake samples were taken. The conditions of this run seemed satisfactory except that the cakes were not dry enough at the end of the run.

The third was a nine hour run with the readings being taken at the same intervals as those in the second run. The cake was still slightly wet at the end of the run.

Twelve hour runs were then decided upon. Temperatures were to be taken at the top, middle, and bottom of each cake; in the space between the shelves; in the vacuum pipe outlet; and of the upper cabinet wall.

The control temperature was taken as the temperature between the steam shelf and tray number two.

The moisture content curves for these preliminary runs were not smooth curves due to bad filter cakes and variations in control conditions.

D. Difficulties Encountered.

The principal difficulties encountered were:

- (1) Variation in steam pressure. This made it necessary to adjust the steam inlet valve very often.
- (2) Steam valve did not give good control.
- (3) Filter cakes were too soft.

These difficulties were easily overcome in the following manner:

- (1) Water was injected in the boiler more often and the pressure thereby maintained between 50 and 55 pounds per square inch.
- (2) The globe valve used for steam control was replaced by a needle valve. This made possible finer adjustment. With this fine adjustment and constant steam pressure the valve required very infrequent readjustment.

(3) After the filter cakes were made as described in section A no more difficulties were experienced.

The vacuum required very little attention from the beginning.. This was due to the fact that a needle valve was used to bleed in air. Sometimes it required no readjustment during the first seven hours.

Chapter V
FINAL EXPERIMENTAL

Chapter V

FINAL EXPERIMENTAL

A. Runs Made.

The final experimental work consisted of eight runs with different temperatures and total pressures in the drying chamber. The temperatures and vacuum of each run is given in Table I.

The temperature used as a control was the temperature measured by placing a thermocouple between the steam shelf and tray number two as shown in Diagram III.

All runs were made over a twelve hour period and the control temperature maintained to within $\pm .5^{\circ}$ C. of the temperature indicated in Table I. The vacuum indicated in Table I was maintained to within $\pm 1/16$ inch of mercury during the entire run except for the three to five minutes at the end of each hour. It was necessary at these times to break the vacuum in order to obtain a small sample of each of the two filter cakes. Adjustments were changed when the dryer was closed in order to bring the cabinet up to control temperature and pressure as rapidly as possible. The conditions in the dryer never varied from the control

TABLE I

Temperature-Vacuum Conditions of Runs.

Run Number	Temperature in °C.	Vacuum in inches of Mercury
1	100	26
2	110	26
3	120	26
4	130	26
5	120	22
6	130	22
7	120	18
8	130	18

conditions at this time more than three to five minutes. The samples were taken with a half inch diameter cork borer.

The samples taken were placed in a desiccator and weighed as soon as cool. This was done in order to prevent an increase or decrease in moisture content. After the weights of the wet samples were recorded the samples were immediately placed in a small resistance oven where they were dried at about 130° C. for from twelve to twenty-four hours or until dry. The last samples taken were approximately dry and were allowed to remain in the oven at least twelve hours. The first samples of the run were wet and were allowed to remain in the oven at least twenty-four hours. They were, of course, all taken out together as the wettest samples were placed in the oven twelve hours before the dryest ones.

These samples after this drying period were reweighed and the weights recorded. All samples were weighed and dried on weighed watch glasses. The moisture content of each sample was obtained by difference and the pounds of water per hundred pounds of dry solid obtained by multiplying, the moisture content in grams divided by the weight of the dry sample in grams, by one hundred. All moisture content curves were plotted.

with pounds of water per hundred pounds of dry solid as the abscissae and time in hours as the ordinate. This enabled the investigator to determine the effect of change of temperature and vacuum on the rate of drying.

The low temperatures were investigated only at twenty-six inches of vacuum, merely for comparison. They are lower than most steam temperatures used in industry.

Zone temperatures in the filter cakes were taken only during the preliminary and the first two final runs. It seemed unnecessary to take them during all the runs after the general variation had been determined, for it only increased the experimental data and gave less time for maintaining the vacuum and control temperature constant. The middle of cake temperature and the zone temperatures in the vacuum cabinet were taken during all of the runs. This was done in order to be sure that the conditions of the dryer were varying as predicted from the results of the first runs.

The barometer reading was taken during the constant rate period in order to obtain the total

pressure in the dryer and in order to determine whether or not the water in the cake actually boiled out.

The original water content of the filter cakes in each of the final runs was almost constant.

B. Results Obtained in Runs.

The results obtained in the final experimental runs are given in Tables II through XVII. The moisture content data is plotted in Curves III through X.

The filter cakes used in the runs were square and measured 8.5 inches on a side. They were all $1\frac{1}{8}$ inch thick except No. 1 of runs three and four, and No. 2 of run six which were $1\frac{1}{4}$ inch in thickness.

The controlling conditions of each run is given at the beginning of each cabinet and cake temperature table. The runs were regulated by maintaining the inches of vacuum constant. For different runs on different days this made a slight difference in total pressure. This difference, however, was within the limits of error in maintaining constant vacuum. These total pressures are given at the beginning of the tables. They were obtained by subtracting the vacuum from the barometer readings.

TABLE II

Run No.1

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 100° C.

Vacuum = 26 inches of Mercury

Barometer = 758 mm. of Mercury

Total Pressure in Dryer = 97.6 mm. of Mercury

Boiling Point of Water at Total Pressure = 51.2° C.

Copper-Constantan Thermocouple

Time In Hours	#2 Top Cake No. 1 °C.	#3 Middle Cake No. 1 °C.	#4 Bottom Cake No. 1 °C.	#5 Top Cake No. 2 °C.	#6 Middle Cake No. 2 °C.	#7 Bottom Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
0									
.25	24.5	21.5	26.5	29.0	24.5	28.0	69.5	48.0	46.0
.50	43.0	41.0	43.0	42.0	40.5	42.5	78.0	52.0	53.0
.75	48.5	48.5	48.5	45.5	46.0	47.0	77.5	48.0	41.0
1.00									
1.25	49.5	49.5	50.0	48.0	48.0	48.5	78.5	50.0	47.5
1.50	50.0	49.5	50.0	48.5	48.5	48.5	78.5	50.5	48.0
1.75	50.5	50.5	50.5	49.0	49.0	49.5	78.5	50.5	50.0
2.00									
2.25	50.5	50.5	50.5	49.5	49.5	49.5	79.5	52.5	63.0
2.50	51.0	51.0	51.0	50.5	50.0	50.0	80.5	57.0	65.5
2.75	51.0	51.0	50.5	50.5	50.0	50.0	80.5	59.0	66.0
3.00									
3.25	51.0	51.0	50.5	50.5	50.0	50.0	80.0	63.5	66.0
3.50	51.0	51.0	51.0	50.0	50.0	50.0	79.5	68.0	66.5
3.75	51.0	51.0	51.0	50.5	50.5	50.5	80.0	59.0	68.0
4.00									
4.25	51.0	51.0	51.0	50.5	50.5	50.5	81.0	70.5	69.0
4.50	51.0	51.0	51.0	50.5	50.5	50.5	80.0	69.5	69.5
4.75	51.0	51.0	51.0	51.0	50.5	50.5	81.5	70.0	69.5

TABLE III

Run No.1

Moisture Content Data

Control Temperature = 100° C. Vacuum = 26 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	5.0033	1.5817	3.4216	216.0
	2	5.0476	1.6008	3.4468	215.0
1	1	4.6626	1.6206	3.0421	188.0
	2	4.8292	1.6596	3.1696	191.0
2	1	4.3414	1.6484	2.6930	163.0
	2	4.4626	1.7058	2.7568	162.0
3	1	3.9033	1.6505	2.2528	136.5
	2	3.8893	1.6737	2.2156	132.0
4	1	3.4256	1.6684	1.7572	105.2
	2	3.3824	1.6745	1.7079	102.0
5	1	3.0562	1.6605	1.3957	84.0
	2	3.0650	1.6392	1.4258	87.0
6	1	2.8357	1.6334	1.2023	73.6
	2	2.9034	1.6849	1.2185	72.2
7	1	2.3965	1.5246	.8719	57.2
	2	2.6261	1.6569	.9692	58.5
8	1	2.3515	1.6293	.7222	44.4
	2	2.3033	1.6378	.6655	40.7
9	1	2.0944	1.5927	.5017	31.5
	2	2.1987	1.6322	.5665	34.6
10	1	2.1490	1.7023	.4467	26.2
	2	2.1923	1.6989	.4934	29.0
11	1	2.0693	1.7097	.3596	21.0
	2	1.9957	1.6187	.3770	23.3
12	1	1.8898	1.6717	.2181	13.0
	2	1.7758	1.5966	.1792	11.2

CURVE III
RUN No. 1
MOISTURE CONTENT CURVES

VACUUM = 26"

TEMP. = 100°C.

○—○ TRAY No. 1

— TRAY No. 2

TABLE IV

Run No. 2

Cabinet and Cake Temperatures

"Control Temperatures" Between Shelf and Tray = 110° C.

Vacuum = 26 inches of Mercury

Barometer = 759 mm. of Mercury

Total Pressure in Dryer = 98.6 mm. of Mercury

Boiling Point of Water at Total Pressure = 51.4° C.

Copper-Constantan Thermocouples

Time In Hours	#2 Top Cake No. 1 °C.	#3 Middle Cake No. 1 °C.	#4 Bottom Cake No. 1 °C.	#5 Top Cake No. 2 °C.	#6 Middle Cake No. 2 °C.	#7 Bottom Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
0									
.25	41.0	37.0	41.0	41.5	38.5	45.0	75.5	58.0	45.0
.50	48.5	47.5	48.0	46.5	46.0	50.0	74.5	54.0	47.5
.75	49.0	49.0	49.0	48.0	47.5	50.0	77.0	50.0	51.5
1.00									
1.25	49.5	49.5	49.0	49.0	48.5	49.5	79.0	52.0	67.5
1.50	50.0	49.5	49.5	49.0	48.5	49.0	81.0	55.5	68.5
1.75	50.0	49.5	49.5	49.0	49.0	50.0	81.0	55.5	70.0
2.00									
2.25	51.0	50.5	49.0	49.0	49.0	50.0	81.5	75.5	73.5
2.50	50.0	50.0	49.5	49.5	49.0	49.5	81.0	74.0	73.5
2.75	50.0	50.0	50.0	50.0	49.5	49.5	81.5	77.0	74.5
3.00									
3.25	50.5	50.5	50.0	50.0	50.0	50.0	81.5	79.5	75.5
3.50	51.0	51.0	50.5	50.5	50.5	50.5	82.0	78.5	75.5
3.75	51.0	51.0	50.5	50.5	50.5	50.5	81.5	80.0	76.0
4.00									
4.25	51.0	51.0	50.5	50.5	50.5	50.5	82.5	81.5	77.0
4.50	51.5	51.0	51.0	51.0	50.5	50.5	82.5	81.0	77.0
4.75	51.5	51.5	51.0	51.0	50.5	50.5	82.0	79.5	76.5

TABLE V

Run No. 2

Moisture Content Data

Control Temperature = 110° C. Vacuum = 26 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	4.8571	1.5385	3.3176	215.5
	2	4.9698	1.5790	3.3908	215.0
1	1	4.3505	1.5138	2.8367	187.0
	2	4.5963	1.6243	2.9720	183.0
2	1	4.1374	1.6884	2.4490	145.0
	2	4.0474	1.6405	2.4069	147.0
3	1	3.4627	1.6394	1.8323	112.3
	2	3.4697	1.6337	1.8360	112.2
4	1	3.0149	1.6480	1.3669	82.9
	2	3.1091	1.6672	1.4419	86.6
5	1	2.7457	1.6502	1.0955	66.4
	2	2.6408	1.5241	1.1167	73.1
6	1	2.4570	1.5825	.8745	55.2
	2	2.4758	1.5461	.9297	60.1
7	1	2.3021	1.6660	.6361	38.2
	2	2.3488	1.6211	.7277	44.9
8	1	2.1462	1.7156	.4306	25.1
	2	2.1541	1.6780	.4761	28.4
9	1	2.1324	1.8142	.3182	17.6
	2	2.0209	1.6874	.3335	19.8
10	1	1.9106	1.6880	.2226	13.2
	2	1.9870	1.7021	.2849	16.7
11	1	1.8691	1.7585	.1106	6.3
	2	1.8837	1.7159	.1678	9.8
12	1	1.8133	1.7560	.0573	3.3
	2	1.7945	1.7200	.0745	4.3

CURVE IV
RUN No.2
MOISTURE CONTENT CURVES

VACUUM = 26"

TEMP = 110°C.

○ — ○ TRAY No.1

* — * TRAY No.2

TABLE VI

Run No. 3

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 120° C.

Vacuum = 26 inches of Mercury

Barometer = 743.5 mm. of Mercury

Total Pressure in Dryer = 88.6 mm. of Mercury

Boiling Point of Water at Total Pressure = 49.2° C.

Copper-Constantan Thermocouples

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
0					
.25	38.0	38.5	84.0	80.0	43.0
.50	42.0	42.5	88.0	70.5	45.5
.75	46.5	45.0	92.0	56.5	45.0
1.00					
1.25	47.0	46.0	94.5	84.0	50.0
1.50	46.5	47.0	93.0	87.5	69.5
1.75	47.0	46.0	93.5	92.5	72.5
2.00					
2.25	48.5	47.0	97.0	100.0	78.5
2.50	47.5	47.0	94.5	98.0	77.0
2.75	47.5	46.5	95.0	98.5	78.5
3.00					
3.25	48.0	47.5	95.0	97.0	79.0
3.50	47.5	47.0	95.0	97.5	79.5
3.75	47.5	47.0	95.5	97.5	80.5
4.00					
4.25	47.5	46.5	95.0	97.5	80.5
4.50	47.5	46.5	95.0	99.0	81.5
4.75	47.5	46.5	95.0	98.5	82.0

TABLE VI (Continued)

Run No. 3

Cabinet and Case Temperatures

Control Temperature = 120° C. Vacuum = 26 inches of Mercury

Copper-Constantan Thermocouples

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
5.00					
5.25	47.5	46.0	95.5	97.5	82.5
5.50	48.0	47.0	97.0	98.5	82.5
5.75	47.0	46.0	97.5	99.0	83.0
6.00					
6.25	48.5	47.5	98.5	98.0	83.5
6.50	48.5	47.5	99.0	96.5	83.0
6.75	47.0	47.0	99.5	95.5	82.5
7.00					
7.25	47.5	47.0	99.0	96.5	84.5
7.50	48.5	47.5	105.0	95.5	82.5
7.75	49.0	47.5	105.0	94.0	82.5
8.00					
8.25	61.0	49.0	109.0	95.5	84.0
8.50	64.0	51.5	109.5	93.0	82.5
8.75	70.0	55.5	111.0	91.5	82.5
9.00					
9.25	89.0	67.0	116.5	93.5	85.0
9.50	102.5	81.5	116.5	91.0	83.0
9.75	105.5	88.5	116.0	91.5	84.5
10.00					
10.25	110.5	102.5	116.5	85.5	84.0
10.50	113.5	106.5	116.5	85.5	84.5
10.75	113.5	106.5	115.0	91.0	84.0
11.00					
11.25	114.5	112.5	116.5	83.5	84.0
11.50	117.0	114.0	118.0	81.5	84.0
11.75	117.0	115.0	118.0	82.0	84.0
12.00					

TABLE VII

Run No.3

Moisture Content Data

Control Temperature = 120° C. Vacuum = 26 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100% Dry Solid
0	1	5.1832	1.6500	3.5332	214.0
	2	4.8566	1.5556	3.3010	212.0
1	1	4.7735	1.6389	3.1346	191.0
	2	4.4834	1.5837	2.8997	183.0
2	1	4.1368	1.6060	2.5308	157.5
	2	4.1709	1.6052	2.5657	160.0
3	1	3.5167	1.6093	1.9074	118.5
	2	3.5419	1.5291	2.0128	131.5
4	1	2.8835	1.5655	1.3180	84.0
	2	3.0006	1.5148	1.4858	98.0
5	1	2.5293	1.5778	.9515	60.4
	2	2.6784	1.5172	1.1612	76.6
6	1	2.1128	1.5083	.6045	40.0
	2	2.3335	1.4099	.8336	55.5
7	1	1.7279	1.3731	.3548	25.8
	2	1.9610	1.4778	.4832	32.7
8	1	1.7710	1.5534	.2176	14.0
	2	1.9368	1.5485	.3883	25.1
9	1	1.7968	1.6290	.1678	10.3
	2	1.8061	1.5620	.2441	15.6
10	1	1.6812	1.6124	.0688	4.3
	2	1.6862	1.6103	.0759	4.7
11	1	1.6766	1.6291	.0475	2.9
	2	1.6760	1.6127	.0633	3.9
12	1	1.5948	1.5642	.0306	1.9
	2	1.6413	1.6015	.0398	2.5

CURVE V

RUN No. 3

MOISTURE CONTENT CURVES

VACUUM = 26"

TEMP = 120°C

○—○ TRAY No. 1

x—x TRAY No. 2

TABLE VIII

Run No. 4

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 130° C.

Vacuum = 26 inches of Mercury

Barometer = 748 mm. of Mercury

Total Pressure in Dryer = 87.6 mm. of Mercury

Boiling Point of Water at Total Pressure = 49° C.

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 °C.	#4 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
0					
.25	37.5	36.0	94.5	80.5	67.0
.50	49.0	46.0	96.5	73.5	71.0
.75	49.0	47.5	99.5	74.5	73.0
1.00					
1.25	49.0	48.0	101.5	101.5	75.5
1.50	49.0	47.5	102.0	102.5	76.5
1.75	48.0	47.0	101.5	106.0	79.5
2.00					
2.25	48.5	47.0	100.5	106.5	82.0
2.50	48.0	47.0	101.5	108.5	84.0
2.75	47.5	46.5	101.5	108.5	84.0
3.00					
3.25	47.5	46.5	101.0	109.0	85.5
3.50	47.5	46.5	101.5	108.5	86.0
3.75	47.0	46.0	101.5	108.5	86.5
4.00					
4.25	47.0	46.0	100.5	108.0	87.0
4.50	47.0	46.0	102.0	108.5	87.5
4.75	47.0	46.0	101.5	107.5	87.0

TABLE VIII (Continued)

Run No. 4

Cabinet and Cake Temperatures

Control Temperature = 130°C . Vacuum = 26 inches of Mercury

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
5.00					
5.25	47.5	46.5	103.0	106.0	89.0
5.50	47.5	46.5	107.0	106.5	87.5
5.75	47.5	46.5	108.5	106.0	87.5
6.00					
6.25	48.5	47.0	111.5	104.5	87.5
6.50	48.5	47.0	112.5	104.5	87.5
6.75	49.5	47.0	114.0	105.0	88.0
7.00					
7.25	51.5	47.5	116.0	104.5	88.0
7.50	55.0	50.0	117.0	104.5	88.5
7.75	59.5	53.5	119.0	103.0	88.0
8.00					
8.25	72.0	63.5	121.0	101.0	87.5
8.50	78.5	70.0	123.0	99.5	87.5
8.75	87.5	73.5	124.5	98.0	87.5
9.00					
9.25	110.5	93.5	125.5	95.5	87.5
9.50	116.5	105.5	126.5	93.0	87.5
9.75	120.0	112.5	127.0	91.0	87.5
10.00					
10.25	123.0	115.5	127.5	88.5	87.5
10.50	126.0	121.5	128.0	87.5	87.5
10.75	127.5	124.0	129.0	87.0	89.0
11.00					
11.25	127.0	122.0	127.0	87.0	89.5
11.50	128.5	127.0	129.0	87.0	89.0
11.75	129.0	127.5	129.5	87.0	89.0
12.00					

TABLE IX

Run No.4

Moisture Content Data

Control Temperature = 130° C. Vacuum = 26 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	5.0800	1.6320	3.4480	211.0
	2	5.3376	1.6746	3.6630	219.0
1	1	4.0996	1.5312	2.5684	167.7
	2	4.6210	1.7044	2.9166	171.0
2	1	3.9362	1.5892	2.3470	148.0
	2	4.1262	1.6048	2.5234	157.0
3	1	3.1558	1.5197	1.6361	107.5
	2	3.8869	1.7039	2.1830	128.0
4	1	2.7849	1.5969	1.1880	74.5
	2	3.2382	1.7296	1.5086	87.2
5	1	2.0993	1.3736	.7257	52.8
	2	2.8116	1.6596	1.1520	69.5
6	1	1.8877	1.4236	.4641	32.6
	2	2.6772	1.6356	.9416	57.5
7	1	1.8177	1.4494	.3683	25.4
	2	2.2506	1.6450	.6056	36.8
8	1	1.6809	1.4752	.2057	13.9
	2	1.9980	1.7002	.2978	17.5
9	1	1.5531	1.4963	.0568	3.8
	2	1.9488	1.7598	.1890	10.73
10	1	1.6483	1.6190	.0293	1.8
	2	1.8590	1.7119	.1471	8.59
11	1	1.6404	1.6132	.0272	1.7
	2	1.8130	1.7403	.0727	4.2
12	1	1.5428	1.5200	.0228	1.5
	2	1.9078	1.8707	.0371	1.9

CURVE VI
RUN NO. 4

MOISTURE CONTENT CURVES

VACUUM = 26"

TEMP. = 130°C.

○ — ○ TRAY NO. 1

* — * TRAY NO. 2

TABLE X

Run No. 5

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 120° C.

Vacuum = 32 inches of Mercury

Barometer = 756 mm. of Mercury

Total Pressure in Dryer = 197.2 mm. of Mercury

Boiling Point of Water at Total Pressure = 66.2° C.

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
0					
.25	28.0	27.5	90.0	67.0	74.0
.50	46.5	45.0	91.5	70.5	68.0
.75	58.0	57.0	93.5	72.0	50.5
1.00					
1.25	63.0	60.0	96.5	74.5	56.5
1.50	64.5	62.0	98.5	71.5	58.5
1.75	64.5	62.5	98.5	77.0	59.5
2.00					
2.25	65.0	62.5	98.5	83.5	62.5
2.50	65.0	63.0	98.5	75.5	63.5
2.75	65.0	63.0	98.5	74.5	63.5
3.00					
3.25	65.0	63.0	99.5	83.0	64.5
3.50	65.0	63.5	100.5	81.5	65.5
3.75	65.0	63.5	101.0	77.5	67.5
4.00					
4.25	65.0	64.0	102.0	84.5	82.5
4.50	65.0	64.0	102.5	82.5	82.5
4.75	65.0	64.0	102.5	72.5	83.0

TABLE X (Continued)

Run No. 5

Cabinet and Cake Temperatures

Control Temperature = 120° C. Vacuum = 22 inches of Mercury

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
5.00					
5.25	65.0	64.0	103.0	66.0	84.0
5.50	65.0	64.0	103.0	70.0	84.5
5.75	65.0	64.0	104.0	72.0	84.5
6.00					
6.25	65.0	64.0	104.0	85.0	84.5
6.50	65.0	64.0	104.0	85.0	84.5
6.75	65.0	64.0	104.0	83.5	84.5
7.00					
7.25	65.0	64.5	105.0	85.0	86.5
7.50	65.0	64.0	106.0	85.0	86.5
7.75	65.0	64.0	107.0	75.0	87.0
8.00					
8.25	65.0	64.0	107.5	85.5	86.5
8.50	65.0	64.5	109.5	82.5	82.5
8.75	65.0	64.0	110.0	80.5	83.0
9.00					
9.25	65.5	64.5	112.5	89.0	84.5
9.50	67.0	66.5	112.5	88.5	85.0
9.75	69.5	71.5	113.5	80.5	85.5
10.00					
10.25	73.0	88.5	114.5	86.0	85.5
10.50	78.5	98.5	116.0	85.5	85.5
10.75	86.5	104.0	116.5	84.0	84.5
11.00					
11.25	103.0	109.0	117.0	86.0	84.5
11.50	110.0	113.5	118.5	82.0	82.5
11.75	112.0	115.0	119.0	82.0	82.5
12.00					

TABLE XI

Run No. 5

Moisture Content Data

Control Temperature = 120° C. Vacuum = 22 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	4.9616	1.5900	3.3716	212.0
	2	5.0775	1.6138	3.4637	214.5
1	1	4.7402	1.6417	3.0985	188.0
	2	4.4312	1.5987	2.8325	177.0
2	1	4.3169	1.6531	2.6638	161.0
	2	4.3803	1.6874	2.6929	159.5
3	1	3.8049	1.6079	2.1970	136.5
	2	3.6893	1.6039	2.0854	130.0
4	1	3.2632	1.5879	1.6753	105.5
	2	3.3322	1.6626	1.6696	100.2
5	1	2.9520	1.6242	1.3278	81.5
	2	2.9151	1.6121	1.3030	80.9
6	1	2.7458	1.6296	1.1162	68.5
	2	2.7056	1.6414	1.0642	64.9
7	1	2.4548	1.6567	.7981	48.2
	2	2.4129	1.6198	.7931	49.0
8	1	2.1228	1.5857	.5371	33.9
	2	2.2033	1.6696	.5337	31.9
9	1	2.0546	1.6967	.3579	21.1
	2	1.9939	1.6458	.3581	21.8
10	1	2.0735	1.7687	.3048	17.3
	2	1.8994	1.6160	.2834	17.5
11	1	1.9298	1.7494	.1804	10.3
	2	1.8942	1.7110	.1832	10.7
12	1	1.7784	1.7078	.0706	4.1
	2	1.8273	1.7526	.0747	4.2

CURVE VII

RUN No.5

MOISTURE CONTENT CURVES

VACUUM = 22"

TEMP. = 120°C.

○ — ○ TRAY No. 1

* — * TRAY No. 2

TABLE XII

Run No. 6

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 130° C.

Vacuum = 22 inches of Mercury

Barometer = 754.5 mm. of Mercury

Total Pressure in Dryer = 195.7 mm. of Mercury

Boiling Point of Water at Total Pressure = 66° C.

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 C.	#6 Middle Cake No. 2 C.	#8 Space Between Shelves C.	#9 Vacuum Pipe C.	#10 Upper Case Wall C.
0					
.25	27.5	29.0	96.5	69.0	73.5
.50	46.5	47.5	97.5	77.5	72.0
.75	58.5	57.5	99.5	82.0	55.5
1.00					
1.25	63.0	61.5	100.0	75.5	59.0
1.50	63.5	63.5	102.5	71.5	64.5
1.75	64.5	64.0	102.5	73.0	66.5
2.00					
2.25	64.5	64.0	103.5	80.5	86.5
2.50	65.0	64.0	105.0	74.0	85.0
2.75	65.0	64.0	105.0	79.5	86.5
3.00					
3.25	65.5	64.5	105.5	83.0	88.5
3.50	65.0	64.0	105.5	89.5	89.0
3.75	65.0	64.0	105.5	90.5	89.0
4.00					
4.25	65.0	64.0	105.5	86.0	87.0
4.50	65.0	64.0	106.5	90.5	86.0
4.75	65.0	64.0	107.0	84.0	86.5

TABLE XII (Continued)

Run No. 6

Cabinet and Cake Temperatures

Control Temperature = 130° C. Vacuum = 22 inches of Mercury

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
5.00					
5.25	65.0	64.0	108.0	93.5	92.5
5.50	65.0	64.0	108.5	93.0	92.5
5.75	65.0	64.0	109.5	89.0	92.0
6.00					
6.25	65.0	64.0	111.0	93.0	89.0
6.50	65.0	64.0	114.0	80.0	90.0
6.75	65.0	64.0	114.5	87.5	89.5
7.00					
7.25	65.0	64.0	116.0	93.0	93.5
7.50	65.0	64.0	116.5	83.5	92.5
7.75	65.0	64.0	118.0	73.0	92.5
8.00					
8.25	66.0	66.5	118.5	97.0	91.0
8.50	70.5	77.5	121.5	91.0	92.0
8.75	74.0	89.5	122.5	89.0	91.0
9.00					
9.25	77.5	105.0	123.5	96.5	88.0
9.50	84.5	115.0	125.5	92.0	91.5
9.75	96.5	119.0	126.5	91.5	91.5
10.00					
10.25	116.5	120.0	126.5	92.0	91.0
10.50	119.0	125.5	128.5	91.5	90.0
10.75	122.0	126.0	128.5	92.0	89.5
11.00					
11.25	125.5	126.0	129.0	98.0	89.5
11.50	126.5	128.5	128.5	88.5	87.5
11.75	128.0	129.0	129.0	90.0	87.5
12.00					

TABLE XIII

Run No. 6

Moisture Content Data

Control Temperature = 130° C. Vacuum = 22 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	5.2023	1.6640	3.5383	212.0
	2	5.0811	1.6132	3.4679	215.0
1	1	5.1317	1.8512	3.2805	177.0
	2	4.4196	1.5580	2.8616	184.0
2	1	4.5452	1.7878	2.8574	160.0
	2	4.0458	1.6068	2.4390	152.0
3	1	3.8409	1.7383	2.1026	121.0
	2	3.7082	1.6580	2.0502	124.0
4	1	3.0802	1.7058	1.3744	80.5
	2	3.1006	1.6579	1.4427	87.1
5	1	3.0720	1.8689	1.2031	64.5
	2	2.5083	1.5748	.9335	59.2
6	1	2.6408	1.7616	.8792	49.9
	2	2.2504	1.5669	.6835	43.5
7	1	2.5418	1.8217	.7201	39.5
	2	2.0786	1.5897	.4889	30.8
8	1	2.1311	1.7731	.3580	20.2
	2	1.8260	1.5713	.2547	16.2
9	1	2.2237	1.9813	.2424	12.2
	2	1.7369	1.5900	.1469	9.2
10	1	2.1205	1.9271	.1934	10.1
	2	1.7059	1.6386	.0673	4.1
11	1	2.0165	1.9206	.0959	5.0
	2	1.7126	1.6717	.0409	2.4
12	1	1.8942	1.8563	.0379	2.0
	2	1.6285	1.6014	.0271	1.7

CURVE VIII

RUN No. 6

MOISTURE CONTENT CURVES

VACUUM = 22"

TEMP. = 130°C.

○—○ TRAY No. 1

— TRAY No. 2

TABLE XIV

Run No. 7

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 120° C.

Vacuum = 18 inches of Mercury

Barometer = 746 mm. of Mercury

Total Pressure in Dryer = 288.8 mm. of Mercury

Boiling Point of Water at Total Pressure = 75° C.

Copper-Constantan Thermocouples

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
0					
.25	31.5	30.5	83.5	56.5	64.5
.50	53.5	50.5	85.5	61.0	70.5
.75	68.0	63.0	90.0	66.0	57.5
1.00					
1.25	71.5	66.5	93.0	64.0	78.5
1.50	72.0	68.5	93.5	62.5	65.0
1.75	72.5	69.5	94.0	64.5	67.0
2.00					
2.25	72.5	70.5	95.5	65.5	84.0
2.50	72.5	70.5	95.5	66.0	84.5
2.75	73.5	71.5	95.5	67.0	85.0
3.00					
3.25	74.0	71.5	95.5	68.0	84.5
3.50	74.0	73.0	98.5	73.5	87.0
3.75	74.5	73.0	98.0	73.5	86.5
4.00					
4.25	74.5	73.0	99.5	77.5	89.0
4.50	74.5	73.0	98.5	75.5	88.5
4.75	74.5	73.0	99.0	75.0	89.0

TABLE XIV (Continued)

Run No. 7

Cabinet and Cake Temperatures

Control Temperature = 120° C. Vacuum = 18 inches of Mercury

Copper-Constantan Thermocouple

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
5.00					
5.25	74.5	73.0	99.5	75.5	88.0
5.50	74.0	73.0	99.0	82.5	88.5
5.75	74.5	73.0	100.5	86.0	88.5
6.00					
6.25	74.5	74.0	103.0	84.0	88.0
6.50	74.5	74.0	101.0	73.5	88.0
6.75	74.5	74.0	102.5	73.5	87.0
7.00					
7.25	75.0	74.5	104.0	69.0	89.0
7.50	74.5	74.0	106.0	85.0	88.0
7.75	74.5	74.0	107.5	85.5	87.0
8.00					
8.25	75.0	74.5	108.0	87.0	90.5
8.50	75.5	75.0	110.0	87.5	90.5
8.75	75.0	74.5	110.5	86.5	90.5
9.00					
9.25	75.0	77.0	110.5	86.0	87.5
9.50	75.0	81.0	115.0	83.5	87.5
9.75	76.0	88.5	116.0	84.0	89.0
10.00					
10.25	88.0	102.0	116.0	86.5	88.0
10.50	99.0	107.0	117.0	85.0	85.5
10.75	104.5	109.0	117.5	83.0	85.5
11.00					
11.25	109.0	111.5	117.5	83.0	85.5
11.50	112.0	113.5	118.0	80.5	87.0
11.75	114.0	115.5	118.5	80.0	87.5
12.00					

TABLE XV

Run No.7

Moisture Content Data

Control Temperature = 120° C. Vacuum = 18 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	4.9870	1.5852	3.4018	214.5
	2	5.0022	1.5778	3.4244	217.5
1	1	4.5516	1.5980	2.9536	185.0
	2	4.6326	1.6248	3.0078	185.0
2	1	4.2848	1.6306	2.6542	163.0
	2	4.3092	1.6068	2.6124	154.0
3	1	3.6526	1.6949	2.0577	129.0
	2	3.7193	1.6654	2.0539	123.2
4	1	3.2814	1.6351	1.6463	100.6
	2	3.2507	1.6746	1.5761	94.0
5	1	3.1232	1.7137	1.4095	82.1
	2	2.8955	1.6210	1.2745	78.5
6	1	2.9005	1.7106	1.1899	69.5
	2	2.7341	1.7005	1.0336	60.9
7	1	2.4626	1.6427	.8198	49.9
	2	2.4290	1.6389	.7901	48.2
8	1	2.1973	1.6518	.5455	33.0
	2	2.1536	1.6559	.4977	30.1
9	1	2.2084	1.7743	.4341	24.4
	2	2.1476	1.7452	.4024	23.1
10	1	2.1755	1.7845	.3910	21.9
	2	2.0987	1.7560	.3427	19.5
11	1	2.0463	1.7930	.2533	14.1
	2	2.0092	1.7767	.2325	13.1
12	1	1.7962	1.6976	.0986	5.8
	2	1.8078	1.7300	.0778	4.5

CURVE IX

RUN No. 7

MOISTURE CONTENT CURVES

VACUUM = 18"

TEMP = 120°C.

—○— TRAY No. 1

—*— TRAY No. 2

TABLE XVI

Run No. 8

Cabinet and Cake Temperatures

"Control Temperature" Between Shelf and Tray = 130°C .

Vacuum = 18 inches of Mercury

Barometer = 753.4 mm. of Mercury

Total Pressure in Dryer = 298.2 mm. of Mercury

Boiling Point of Water at Total Pressure = 75.6°C .

Copper-Constantan Thermocouples

Time In Hours	#3 Middle Cake No. 1 $^{\circ}\text{C}$.	#6 Middle Cake No. 2 $^{\circ}\text{C}$.	#8 Space Between Shelves $^{\circ}\text{C}$.	#9 Vacuum Pipe $^{\circ}\text{C}$.	#10 Upper Case Wall $^{\circ}\text{C}$.
0					
.25	41.0	41.5	87.5	72.0	73.5
.50	56.5	57.0	92.5	79.5	55.5
.75	67.5	64.5	97.5	78.0	61.5
1.00					
1.25	70.5	67.5	97.0	66.0	67.0
1.50	71.0	69.0	97.5	65.5	70.0
1.75	71.5	70.0	99.0	69.0	73.0
2.00					
2.25	71.5	70.0	99.0	70.0	88.5
2.50	71.5	70.5	99.5	72.5	87.5
2.75	72.5	71.5	101.0	73.5	89.5
3.00					
3.25	72.5	71.5	103.0	79.5	90.5
3.50	73.0	72.0	103.0	83.5	89.5
3.75	72.5	71.5	103.0	77.0	90.5
4.00					
4.25	72.5	71.5	104.5	75.5	92.5
4.50	73.0	71.5	105.0	75.5	93.5
4.75	75.5	75.5	107.5	78.5	96.5

TABLE XVI (Continued)

Run No. 8

Cabinet and Cake Temperatures

Control Temperature = 130° C. Vacuum = 18 inches of Mercury

Copper-Constantan Thermocouples

Time In Hours	#3 Middle Cake No. 1 °C.	#6 Middle Cake No. 2 °C.	#8 Space Between Shelves °C.	#9 Vacuum Pipe °C.	#10 Upper Case Wall °C.
5.00					
5.25	76.0	75.0	107.5	89.0	96.5
5.50	76.0	75.0	109.0	90.0	97.5
5.75	76.0	75.0	106.0	89.5	97.0
6.00					
6.25	76.0	75.0	110.0	92.5	97.5
6.50	76.0	75.0	112.0	90.5	97.5
6.75	76.0	75.0	112.5	90.0	97.5
7.00					
7.25	76.0	75.0	114.0	92.5	96.0
7.50	76.0	75.0	118.0	92.5	94.5
7.75	76.0	75.0	118.0	92.0	93.5
8.00					
8.25	77.0	75.0	118.0	93.0	95.0
8.50	81.0	79.0	121.0	92.0	95.5
8.75	85.5	82.0	122.0	90.5	96.0
9.00					
9.25	109.5	103.5	126.5	95.5	92.5
9.50	114.5	111.5	126.5"	92.0	91.5
9.75	119.0	116.5	127.5	93.0	93.0
10.00					
10.25	122.0	120.0	127.5	92.5	95.0
10.50	127.5	124.5	129.0	92.0	94.5
10.75	129.0	126.0	129.5"	91.0	95.5
11.00					
11.25	126.0	123.0	127.5	90.5	96.5
11.50	129.0	126.5	129.5	91.0	96.5
11.75	129.5	129.5	129.5	90.0	96.5
12.00					

TABLE XVII

Run No. 8

Moisture Content Data

Control Temperature = 130° C. Vacuum = 18 inches of Mercury

Hour No.	Tray No.	Wet Sample In Gms.	Dry Sample In Gms.	Moisture Lost In Gms.	Lbs. Water Per 100# Dry Solid
0	1	5.0226	1.5725	3.4501	219.0
	2	5.0785	1.5890	3.4895	220.0
1	1	4.5706	1.6428	2.9278	178.0
	2	4.6532	1.6607	2.9925	180.0
2	1	4.1480	1.6830	2.4650	146.5
	2	4.1239	1.6793	2.4446	146.0
3	1	3.4282	1.6520	1.7762	107.3
	2	3.4899	1.6740	1.8159	108.2
4	1	2.6288	1.5475	1.0813	70.0
	2	2.9306	1.6588	1.2718	76.6
5	1	2.5210	1.6151	.9059	56.1
	2	2.6774	1.6486	1.0288	62.4
6	1	2.3588	1.6236	.7352	45.3
	2	2.5005	1.6919	.8086	47.7
7	1	2.1085	1.6134	.4951	30.8
	2	2.0812	1.5588	.5224	33.5
8	1	1.9370	1.6502	.2868	17.4
	2	2.0091	1.6735	.3356	20.0
9	1	1.8056	1.6888	.1168	6.9
	2	1.8858	1.7011	.1847	10.8
10	1	1.8333	1.7524	.0809	4.6
	2	1.7119	1.5862	.1257	7.9
11	1	1.7421	1.6902	.0519	3.1
	2	1.8106	1.7451	.0655	3.7
12	1	1.7376	1.7073	.0303	1.8
	2	1.7726	1.7297	.0429	2.5

CURVE X

RUN NO. 8

MOISTURE CONTENT CURVES

VACUUM = 18"

TEMP. = 130°C.

○—○ TRAY NO. 1

— TRAY NO. 2

The moisture content curves show that each run has a constant rate period which is followed by a decreasing rate period. The constant rate period at the first part of each run is indicated by this part of the curves being approximately a straight line. This period ends in all runs when the moisture content is approximately eighty pounds of water per hundred pounds of dry solid. From this moisture content the decreasing rate period begins as is shown by the slope of the curve increasing. The smaller the moisture content the smaller was the amount of moisture removed per hour. This decreasing rate begins when the surface of the cake begins to become dry. This was shown during the runs by the top of the filter cakes turning from brown to light tan.

Berthold Block (9) states as was indicated in Chapter II, that there is no diffusion of liquid through the cake in vacuum drying but that the cake dries over its entire cross-section. According to the results of this investigation there actually was a decreasing rate period and the surface was drier during this period than the middle or bottom as shown by the difference in the zone temperatures. This can be explained by the diffusion of the water from the

middle and bottom of the cake to the surface during this last stage of the drying period. This explanation does not seem practical as in the case of sugar-bread, described in Chapter II, the sugar would be carried to the surface with the water and this would leave a sugar crust on the bread. Experiment shows that this does not happen in the vacuum drying of sugar-bread (9).

This decreasing rate period can be explained satisfactorily by assuming that the water actually does evaporate at the middle and bottom as well as at the surface of the cake, but that there is a diffusion of the vapor itself rather than the liquid from the inside of the cake to the surface.

As cakes No.1 of runs three and four, and No.2 of run six were thicker their drying rate was slower as is shown by the curves.

C. Temperatures in Drier.

The temperatures in the cakes and in the cabinet varied in approximately the same manner during each of the runs. For this reason only the temperatures in run No.2 were plotted. All temperatures, however, are given in the tables.

The general variation of the cake temperatures is shown in Curve XI. This curve shows that for the first half hour the cake was being heated up to a point where the water would boil out. The top and bottom, as would be expected, was heated slightly faster than the middle of the cake. After the cake reached the temperature corresponding to the boiling point of water at the total pressure in the dryer, the temperature remained approximately constant until the water content had decreased to about fifty pounds per hundred pounds of dry solid. From then on the temperature at the top of the cake increased rapidly. The temperature of the middle and bottom of the cake remained constant until the water content was about thirty pounds per hundred pounds of dry solid. That then began to increase rapidly. All temperatures in the cake approached the shelf temperature in the dryer toward the end of the run.

The variation of the temperature in the vacuum space between the steam shelves is shown in Curve XII. The variation of the temperature was the same in all the runs. The temperature increased until the moisture content was about one hundred pounds per hundred pounds of dry solid. The temperature then remained constant until the water content was about

CURVE XI

VARIATION OF CAKE TEMPERATURES DURING RUN

RUN No. 2

TRAY No. 1

VACUUM = 26"

TEMP. = 110°C.

#1-TOP

#2-MIDDLE

#3-BOTTOM

CURVE XII
VARIATION OF TEMPERATURE
IN VACUUM SPACE BETWEEN SHELVES
DURING RUN
RUN No. 2

sixty pounds per hundred pounds of dry solid. This was due to a constant amount of water being removed. The temperature then increased gradually to the temperature of the steam shelf due to the higher temperature of the water vapor given off.

The vacuum outlet temperature, Curve XIII, increased until water began to be evaporated then the temperature decreased to the temperature of the water. From this point the temperature increased rapidly to the temperature of the vapor passing through the pipe and then decreased again when the water given off had decreased a large amount. The temperature in the vacuum outlet pipe was controlled by the temperature of the water vapor going through it.

The variation of the temperature of the upper wall of the vacuum cabinet is shown in Curve XIV. The temperature gradually increased to the temperature of the water vapor given off and then remained constant until the water vapor given off had greatly decreased or practically ceased. The temperature then began to decrease due to less heat being carried to the wall. The temperature of the wall remained constant even after the temperature of the vapor had increased due to a smaller amount of vapor being given off. This

CURVE XIII
VARIATION OF TEMPERATURE
IN VACUUM OUTLET PIPE
DURING RUN
RUN NO.2

CURVE XIV
VARIATION OF TEMPERATURE
OF UPPER WALL OF VACUUM CABINET
DURING RUN

RUN NO. 2

was also the cause of the constant part of the vacuum outlet pipe temperature curve.

D. Effect of Shelf Temperature on Rate of Drying; Vacuum Constant.

The effect of the shelf temperature on the rate of drying is shown in Curves XV, XVI, and XVII. The average of the two curves of each run was used in plotting the curves for comparison in this and the next section of this investigation, except in runs three, four, and six. In these three runs the curves for the smaller cakes were used as the larger cakes gave slower rate curves and could not be used in the comparison.

These comparison curves were plotted from points read directly from the other curves and not from the actual experimental data.

The abscissae was shifted upward in each case in order that the original moisture content would be 210 pounds per hundred pounds of dry solid, before the points were read from the curves and replotted as Curves XV, XVI, and XVII. This was done in order to better compare the curves.

At all the different total pressures a ten degree increase in shelf temperature caused about the

CURVE XV

EFFECT OF SHELF TEMPERATURE ON RATE OF DRYING

VACUUM = 26 INCHES OF HG.

#1-TEMP. = 100°C.

#2-TEMP. = 110°C.

#3-TEMP. = 120°C.

#4-TEMP. = 130°C.

CURVE XVI
EFFECT OF SHELF TEMPERATURE
ON RATE OF DRYING
VACUUM = 22 INCHES OF HG.

*1- TEMP = 120°C.

*2- TEMP = 130°C.

CURVE XVII

EFFECT OF SHELF TEMPERATURE
ON RATE OF DRYING

VACUUM = 18 INCHES OF HG.

#1 - TEMP = 120°C.

#2 - TEMP = 130°C.

same increase in the rate of drying except in the increase from 120 to 130° C. at 26 inches of mercury. This was probably due to the fact that the pump exerted such a pull that the vapor was taken away as soon as it was formed even at this lower driving force caused by the lower temperature difference, that is the difference in shelf and cake temperature. The lower temperatures, however, did not give the same rate curves due to the fact that vapor was not formed as fast as it could be taken away.

E. Effect of Vacuum on Rate of Drying;
Shelf Temperature Constant.

The effect of a change in vacuum on the rate of drying is shown in Curves XVIII and XIX. The curves show that at constant temperature there is very little change in the rate of drying when the vacuum is changed. Of course this will hold only for relatively high vacuum where there is quite a large difference between the boiling point of water at the total pressure in the dryer, and the steam shelf temperature.

Curve No. 3 of Curve XVIII has a faster rate of drying due again to the greater pulling force at high vacuum.

CURVE XVIII

EFFECT OF VACUUM

ON RATE OF DRYING

SHELF TEMPERATURE = 120°C.

#1 - VACUUM = 18"

#2 - VACUUM = 22"

#3 - VACUUM = 26"

CURVE XIX

EFFECT OF VACUUM
ON RATE OF DRYING

SHELF TEMPERATURE = 130°C.

#1 - VACUUM = 18"

#2 - VACUUM = 22"

#3 - VACUUM = 26"

Chapter VI

SUMMARY

Chapter VI

SUMMARY

In this investigation the following experimental results were obtained. The conclusions given are based on experimental results and indications.

✓(1) At constant temperature there is very little increase in the rate of drying when the vacuum is increased. This holds for temperatures near 130° C. and for from 18 to 26 inches of vacuum.

(2) At constant vacuum the duration of the drying period is decreased about one-sixth for each 10 degree rise in steam shelf temperature. One would not expect the decrease in drying time to be as great for 10 degree increases at much higher temperatures. At extremely high vacuum the decrease will probably also be somewhat less.

✓(3) In vacuum drying as shown by this investigation approximately 80% of the water is removed from the material in about one-half the entire drying period.

✓(4) The steam in the shelves of the dryer gradually heats the material in the trays to a

temperature such that the water actually boils out under the pressure that exists in the dryer.

✓ (5) The moisture content curves show that there is a constant rate period until the moisture content reaches about 80 pounds per hundred pounds of dry solid. From then on there is a decreasing rate period.

✓ (6) The decreasing rate period can be explained by assuming that during this period there is a diffusion of water vapor through the cake while the surface of the cake remains practically dry.

✓ (7) The bottom and top of the cakes are probably dryer than the middle from the time that the decreasing rate period begins until the drying is finished. The bottom and top, however, were not actually proved dryer until the temperatures began to rise and the color of the cake changed. This was after the decreasing rate part of the period had already existed for a few hours.

✓ (8) Thicker cakes take longer to dry due to the fact that the diffusion of the water vapor from the bottom to the top of the cake is slower. There is also

more pounds of water per square foot of exposed surface.

✓(9) The cake temperatures rise to a temperature corresponding to the boiling point of water at the total pressure in the dryer. They then remain approximately constant until the decreasing rate period is reached. After this period is reached the temperatures begin to rise until they reach the temperature of the steam shelf. The temperature of the top of the cake begins to rise first and rises the fastest. This is due to the surface of the cake being dryer than the interior.

✓(10) The temperature in the vacuum space between the shelves increases to the temperature of the water vapor passing through this space and is then constant until the decreasing rate period is reached. The temperature then gradually approaches the steam shelf temperature.

(11) The temperature in the vacuum outlet pipe increases at first then decreases to the temperature of the water vapor that condenses in it during the first part of the run. The temperature then increases to the temperature of the water vapor passing through it and

then remains constant until almost the end of the run. It then decreases due to the small amount of water vapor being carried through it.

✓ (12) The temperature of the upper wall of the vacuum cabinet increases until it reaches the temperature of the water vapor given off. It then remains constant until almost the end of the run when it begins to decrease due to the small amount water vapor given off.

✓ (13) Low temperatures at low vacuum are practically useless as the temperature given to the vapor in the dryer is such a small amount higher than the condensation temperature of the vapor, corresponding to the total pressure in the dryer, that the cabinet walls are not heated high enough to prevent condensation on them.

(14) In order to tell how long the drying period for any solid of the type used in this investigation will be it is merely necessary to select the drying conditions to be used and then to raise the abscissae of the corresponding curve to the point where the curve crosses on the abscissae at the original water content

of the solid, and then read the remaining hours on the ordinate.

✓ (15) In drying substances that decompose or change in color or some other physical property above a certain temperature, the drying can be controlled by placing a thermocouple in the top of the substance. The drying can be carried on at a vacuum high enough to give a total pressure corresponding to a boiling point of water below the decomposition temperature. Any steam temperature can be used. A high steam temperature will speed up the drying. When the temperature of the top of the cake begins to rise it is necessary to cut off the steam. From this point on the drying must be completed by bleeding in steam or better still by the use of hot water in place of steam. As the temperature of the cake at the end of the drying process is approximately the same as the shelf temperature, water can be used at a temperature equal to the maximum allowable cake temperature.

✓ (16) For drying materials not affected by temperature any vacuum above 18 inches will give a

good rate of drying. The steam temperature should be as high as is available. If only low pressure steam is available it is best to use a high vacuum in order to speed up the process as much as possible.

✓ (17) If slow drying at first is essential the steam pressure should be as near zero as possible with as low a vacuum as can be used; the limit being one that is just low enough to give the cake the maximum allowable temperature; assuming that the cake will be heated to a temperature corresponding to the boiling point of water at the total pressure in the dryer. The low steam pressure is the most important.

✓ (18) In vacuum drying the temperature and vacuum can be maintained constant with ease by using needle valves.

Chapter VII
BIBLIOGRAPHY

Chapter VII

BIBLIOGRAPHY

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