THESIS

on

A STUDY OF

CONSTANT HUMIDITY AND TEMPERATURE

SCHEDULES IN THE DRYING OF

DOUGLAS FIR

Submitted to the

OREGON STATE AGRICULTURAL COLLEGE

In partial fulfillment of
the requirements for the
Degree of

MASTER OF SCIENCE

by

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May 16, 1932

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24 Oct. 1952

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WATER IN WOOD

Water may exist in wood in four forms: (1) as free water in the cell cavity, (2) as bound water in the cell walls, (3) as vapor in the cell cavities, and (4) as part of the protoplasmic content of the living cell. The latter may be disregarded in the consideration of water present in wood after it has been cut from the tree, because there are only a few living cells in the outer sapwood. The rest have lost their protoplasmic contents.

In any study of the drying of wood these forms in which water is present are naturally of prime importance. In very wet wood, water exists as free water in the cell cavities and also as bound water in the cell walls. As some of the water leaves the cell cavities in drying, water vapor will replace it until all the free water is gone. This point at which water no longer exists as free water in the cell cavities is known as the fibre saturation point. From that point until all moisture has left the wood structure, water exists as bound water and vapor.

The removal of water from the surface layers of wood is a comparatively simple process of evaporation, but to keep this process in operation the water must be made to transfuse from the interior to replace that which is evaporated. In this process of transfusion, the properties of the absorbed liquid become important. The most important of these properties and those with which this paper will be most concerned are capillarity, viscosity, and vapor pressure.

DRYING

Following the outline of the principles of drying in "Elements of Chemical Engineering" by Badger and McCabe, two steps occur in the transfer of moisture from the interior of a solid to the drying medium. These steps are: (1) diffusion through the solid and (2) evaporation or passage into the drying medium.

These steps allow the authors to classify drying processes into three general types as follows:

(1). "Evaporation takes place at the interface (junction of the solid and the drying medium) and the main resistance is to this evaporation. Resistance to internal transfusion is small in comparison with the evaporation resistance."

(2). "Evaporation at the interface with diffusion resistance greater than that of evaporation."

(3). "Evaporation taking place before reaching the interface. Water diffuses partly as a liquid and partly as vapor. Resistance to transfusion as a liquid controls this type of drying."

In this classification the drying of wood falls in types (2) and (3), though perhaps only in the latter at temperatures over 212 degrees Fahrenheit and at moisture contents below the fibre saturation point. The fact that internal diffusion of water in wood controls the drying rate rather than evaporation resistance more definitely places the drying of wood in type (2).

This characteristic of the drying of wood brings attention to the properties of the absorbed water which must be responsible for this internal transfusion. Capillarity might be termed a positive factor in this process, since this property is responsible for the movement of liquids in tubes. Viscosity, on the other hand, would be a negative factor as this property tends to resist motion or a change of shape. The vapor pressure of a liquid should aid to some extent in the transfusion of a liquid and, therefore, can be classed as a positive factor.

Thus, under any one set of conditions these three factors are in operation, two of them tending to cause movement of moisture against the action of the third. As all of these properties or forces vary in different amounts with temperature, it is reasonable to believe that at one point, either a certain temperature or combination of temperature and humidity, a maximum resultant in the form of moisture movement in wood would be obtained.

CAPILLARITY

The rise of liquids in capillary tubes is a phenomenon of surface tension. Basically, it depends on the relative values of cohesion of the molecules of the liquid for each other and of their adhesion for the molecules of the solid of the walls of the tube. It is this relation which determines the shape of the meniscus of the surface of the liquid in the tube and consequently the pressure and the direction of the flow. If the liquid wets the walls of the tube, the meniscus will be concave and the flow will be in the upward direction. The converse is true, if the water molecules cohere to each other with a greater force than that with which they adhere to the walls of the tube. The former case is true of the capillary movement of water in the cells of wood structure, and the movement is upward into the cell cavities.

Capillary pressure varies inversely with the curvature of the meniscus of the surface of the liquid. The radius of curvature of menisci of the same liquid in tubes of different diameters will vary directly with the diameter of the tube due to the decrease in the ratio between the circumference and the area of the surface of liquid with the increase in diameter. Considering water in the cells of wood structure, L. F. Hawley of the Forest Products Laboratory estimates that this capillary pressure will amount to about one-half an atmosphere at ordinary atmospheric conditions. Also, he suggests that in the small apertures of the pits in the cell walls this pressure may rise as high as fifty atmospheres, but that it acts for so short a distance its effect is probably negligible in the movement of the absorbed moisture.

A rise in the temperature effects a decrease in capillary movement. This is due to the increased movement of the molecules of the liquid and a consequent lessening of their powers of cohesion and adhesion. In water this decrease varies from the value at 32 degrees Fahrenheit, taken as 100%, to 82% at this value at 212 degrees. This decrease follows the curve of a linear equation as is shown in the diagram on page 58.

VISCOSITY

The friction between adjacent layers of a fluid having different velocities has been termed the viscosity of the fluid. It arises from a friction between molecules as capillarity depends on the cohesion and adhesion of these molecules. While water is considered a mobile rather than a viscous liquid, it has viscosity. The viscosity of a liquid decreases with an increase in temperature. The table below shows the coefficient of viscosity for a few liquids in centimeter-gram-second units at different temperatures.

Substance	32° F.	59°	68°	100°	212°
Glycerine		14.5	8.3		
Mercury	0.0166		0.0155	0.0146	0.0126
Water	0.0179	0.114	0.01	0.0068	0.0028

The decrease in the viscosity of water is quite rapid from 32 degrees Fahrenheit to around 100 degrees, after which the decrease is slower, and at 212 degrees the curve remains almost constant at approximately 18% of the value for the viscosity at 32 degrees. (See chart on page 58)

While viscosity in itself is a retardant to the movement of water, drying practice, in the use of higher temperatures than those occurring under ordinary atmospheric conditions, takes advantage of the marked decrease in the viscosity and the resultant freer movement of the water.

VAPOR PRESSURE

The pressure exerted by the molecules of a liquid in its vapor state is termed the "vapor pressure" of that liquid. The liquid itself may have a vapor pressure due to the molecules which are passing off into the surrounding air from the surface of the liquid.

"Other things being equal, the rate of evaporation from the surface of moist wood is proportional to the difference between the vapor pressure of the water at the surface of the wood and that of the vapor in the surrounding air." This difference has been called the "saturation deficit".

At one temperature and humidity a certain part of the unconfined air surrounding a moist surface is displaced by water vapor, and, while no increase over the atmospheric pressure occurs, a proportion of the pressure existing is then due to the vapor which is present. This proportion increases up to the boiling point of water at which point all the air adjacent to the surface of the water is displaced by vapor, and the total pressure on the surface of the liquid is due to the pressure of that vapor.

DESCRIPTION OF EQUIPMENT

The adaptation of experimental data to commercial practice in any line of research is simplified if conditions during the study and equipment used are as near to those found in the industrial field as is possible. The ideal equipment in a research project of this nature would be the entire plant or factory itself, equipped with added facilities and refinements and entirely at the command of the student. Perhaps more desirable and surely more within the possibilities of educational institutions are miniatures of commercial installations, complete in detail though reduced in size.

The writer feels fortunate in having had the opportunity to carry on this study with the aid of standard dry kiln equipment, supplemented with instruments which make it an experimental as well as a practical installation.

DRY KILN

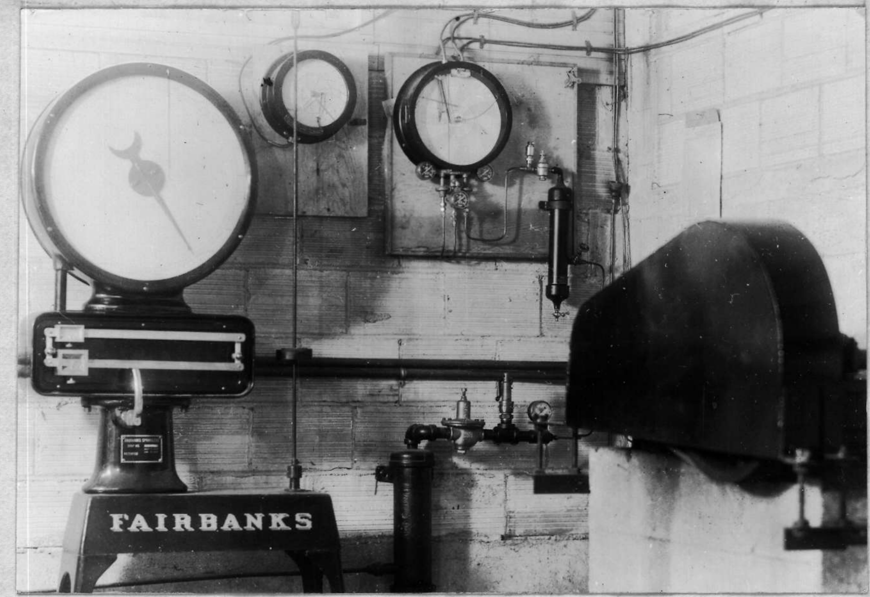
The kiln used in these experiments is of the internal-fan reversible circulation type. It is full size in every detail and dimension, with the exception of length which is only sufficient to accommodate lumber up to 20 feet long. The inside dimensions of the drying chamber, exclusive of the lower part which houses the coils, fans, etc., are approximately 12 by 12 by 22 feet. The lower part mentioned above is about five feet deep.

The drying chamber is of tile and concrete construction covered on the inside with moisture and heat resisting paint. Double-hinged doors of a patented fireproof construction close the open end of the kiln.

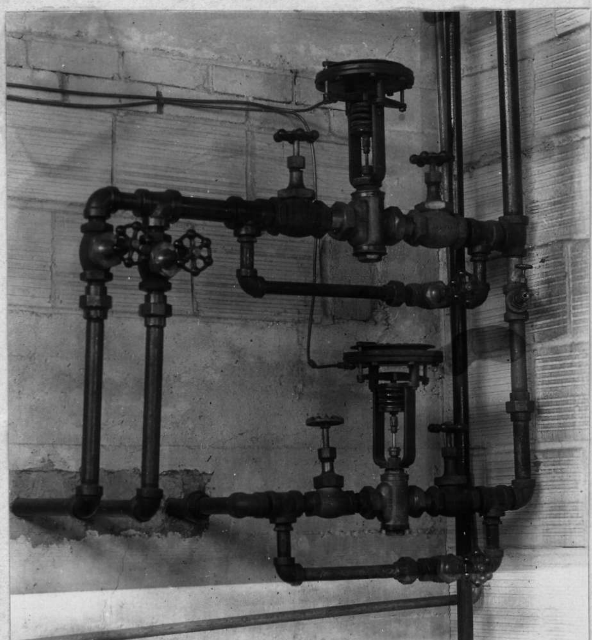
Adjacent to the closed end of the drying chamber is the operating room or "pit". This room contains all the instruments for recording and regulating conditions within the kiln. Next to the operating room is a room which contains a small boiler and a band saw. Glimpses of the operating room may be had in the included photographs. In the first photograph on page 10 may be seen the controlling and recording thermometers. The vapor-filled bulbs of these instruments are within the drying chamber and are connected to the controller by means of armored copper tubes.

CONTROLLING AND RECORDING INSTRUMENTS

The recording, controlling instrument which is the one seen furthest on the right, regulates the temperature and the humidity within the kiln. Its operation depends on two bulbs, one of which measures the temperature, while the other is completely covered with a wick,



THE SCALES, RECORDING AND CONTROLLING THERMOMETERS
AND FAN DRIVE



CONTROL VALVES FOR THE HEATING COILS (ABOVE)
AND VAPOR LINE (BELOW)

which is kept wet from a water-box or reservoir receiving water from the operating room by means of a small copper tube. The difference between the readings of these two bulbs determines the relative humidity within the drying chamber. (The relative humidity of the air is the amount of water which it contains expressed in the per cent of the amount of water it could hold if saturated at the same temperature and pressure.)

This controlling thermometer may be set for any desired temperature and humidity, and its mechanism causes compressed air to operate the diaphragm valves shown in the picture below. Air entering these valves opens them, and they are closed again by means of springs on the release of the air pressure. The top valve in the photo controls the steam entering the two heating coils, while the lower one is connected with the vapor line which furnishes live steam to keep the humidity at the desired point.

The other thermometer merely records the temperature existing within the kiln. During the experiments performed in this study, the bulb of this instruments was placed on the opposite side of the load from the two bulbs of the controller. It was placed in the path of return air as it left the lumber and before it was drawn down through the heating coils for recirculation. By comparing the "dry bulb" reading of the controller with the reading of this latter instrument the amount of heat consumed in evaporating the moisture can be read in degrees of temperature drop from one side of the load to the other. The change in this drop is a rough indication of the progress of drying within the load.

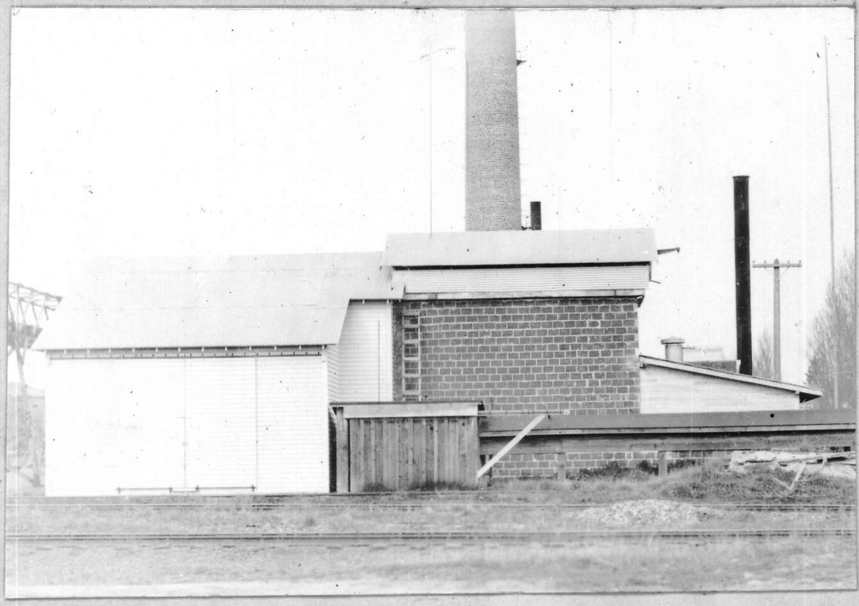
SCALES

However, the facts concerning the loss of moisture from the lumber within the kiln are read on the dial of the large scale. This scale is graduated in 25-pound divisions to read up to 37,000 pounds. The tracks on which the loaded kiln trucks are run are hung free by means of four iron rods from the system of compound levers on the roof of the kiln. These levers are carefully adjusted and the weight reduced and transmitted to a single rod which enters the operating room to the scale.

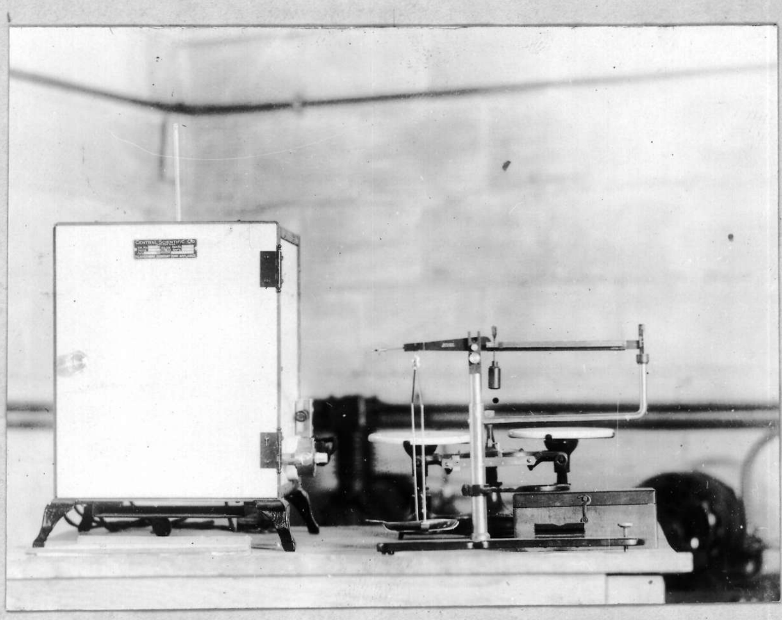
The weight of the baffles and stickers used in each load is set off on the beam of the scale and the weight of the lumber alone can be read to within 10 pounds on the dial.

FANS

Three fans in the base of the kiln provide air circulation. These fans are of the disc type, are 39 inches in diameter and have twelve blades each. They are hung on a single shaft running parallel to the long dimension



EXPERIMENTAL DRY KILN BUILDINGS



DRYING OVEN AND SMALL BALANCE

of the kiln and which is supported on three pedestal bearings. Oil is fed to these bearings by means of copper tubing from three oil cups, situated conveniently near the door of the kiln.

The fans are powered by a five horsepower induction motor, operating on a three phase, sixty cycle current at 220 volts and using 13.6 amperes at full load. Power is taken off this motor by means of a grooved pulley and three "V" belts running side by side. The motor speed is reduced about one-third by the size of the two pulleys.

The direction of the fans' rotation and their speed, which determine the direction and volume of the air movement across the load, are controlled by a two-way switch and a controller or rheostat. The latter allows speeds, ranging from 300 to 600 revolutions per minute.

HEATING

Steam furnishes the heat for the kiln. It is obtained from the College heating plant during the day and from the small boiler at the kiln during the night. Steam pressures vary from 30 to 40 pounds per square inch. The kiln boiler is of the fire tube type, is 12 feet long by 30 inches in diameter, and has had its original fire box remodeled for the installation of an automatic oil burner.

The heating coils within the kiln are in two banks of

24 pipes each. One bank is situated on each side of the kiln in a position a little below the level of the track. (See diagram on page 20.) The coils are of the combined return-bend header type, having the return-bend at the open end of the kiln and the headers at the back. These coils are placed to drain to the lower header and the condensate is then taken care of by two steam traps.

The vapor line consists of a single pipe, located under each heating coil. Small jets are placed at intervals along each of these pipes.

OTHER EQUIPMENT

Under this heading there may be listed several pieces of equipment. The most important of these are the air compressor, the small scales, the drying oven, and the band saw.

As was explained before, the air compressor furnishes the motive power for the regulation valves. This particular compressor is of the small unit type common in garages and service stations, having the compressor and motor mounted on top of the storage cylinder. The tank or cylinder carries air at from 70 to 100 pounds per square inch pressure, but this is reduced so that only 15 pounds pressure reaches the controller. Between the compressor and the controller, two filters are placed in the air line. These filters remove the water, oil, or other foreign matter from the air before it reaches the controlling instrument. These would be injurious if allowed to get into the instrument.

The oven, small scales, and the band saw are used in taking the moisture content samples. The band saw is a small upright model. The wheels are about 12 inches in diameter, and the drive is through a direct connected electric motor. The saw is about one-quarter inch in width, and lumber two inches in thickness can be cut with ease.

The sample wafers are weighed directly on the small triple beam balance. This is a very accurate scale, and when adjusted will weigh to centigrams.

Weighing is followed by a drying period in the oven. The one used this year is of a late type and operates from a lighting circuit at 110 volts. The temperature within the oven may be controlled to within a few degrees, and as high as 200 degrees Centigrade may be maintained.

E X P E R I M E N T A L   P R O C E D U R E

MATERIAL

As previously indicated this study has concerned Douglas fir lumber entirely. An arrangement was made between the College and the Corvallis Lumber Company, wherein the latter agreed to furnish the necessary lumber for this experimental work.

The lumber as received from the mill was ungraded clear, one inch in thickness and of various widths up to one foot. The bulk of the majority of the loads was made up of four and six inch widths with the former generally predominating. Each load consisted of from 1000 to 1300 board feet.

Coming as it did from small logs, the lumber contained a large percentage of sapwood. No effort was made to determine this percentage accurately, but in some cases loads contained at least 30% of sapwood.

The above paragraphs will give some idea of the heterogeneous nature of the material used in this study and a better appreciation of the difficulties encountered in correlation of results. Segregation of the material into groups more homogeneous in character would have been possible, but the question arises as to its value in this instance. It was not possible to secure all lumber in one certain dimension or per cent of sap, and the time in which the study was conducted was so limited that sorting at the kiln would have resulted in one or two charges only in each of many different classifications. As the experiments were conducted, the number of charges run of the general and all-inclusive classification of "mill-run" were too few.

PREPARATION OF LOADS

The lumber was piled flat on the three trucks, edge to edge with no space between boards and with the boards running longitudinally. Between each layer, five stickers about 1 inch thick, 2 inches wide, and 8 feet long were placed directly over a steel bunk of the trucks. This would space them about four feet apart.

Care was taken to "splice" the short lengths or butt their ends together in the center of the load as well as to keep the ends of the layers well filled out to the length limit. Gaps left in a layer would tend to deflect part of the air in its passage across the load and otherwise cause uneven drying in the load.

The thousand feet of lumber dried in each charge filled about seven or eight layers on the trucks and made a pile about 8 feet wide and 15 or 16 inches high above the bunks. To get circulation through the load, when such a small part of the kiln capacity was utilized, a temporary baffle was used. This baffle was a heavy piece of sheet iron about four feet wide and twenty feet long and was supplemented by two small pieces about three feet wide and five feet long, which were fitted around the ends of the load. The position of the baffle is indicated in the diagram on page 20. The stickers under the top layer of lumber were allowed to project some eight inches toward the right wall of the kiln. These stickers served to support the temporary baffle, which was laid partly on them and partly on the load and fitted up to the wall of the kiln. This cut off the circulation into the vacant space in the kiln and forced the air to find a path through the load.

Due to the smallness of the loads the bulbs for the controlling thermometers were removed from their position about half-way up the right hand wall of the kiln and placed below the temporary baffle. There they were placed in the path of the entering air. The recorder bulb was placed on the opposite side of the load in the path of the return air and directly across from the controller bulbs.

After the thermometer bulbs and baffles were in place, the doors were tightly shut and the loads weighed in the operating room. The trucks and baffles had

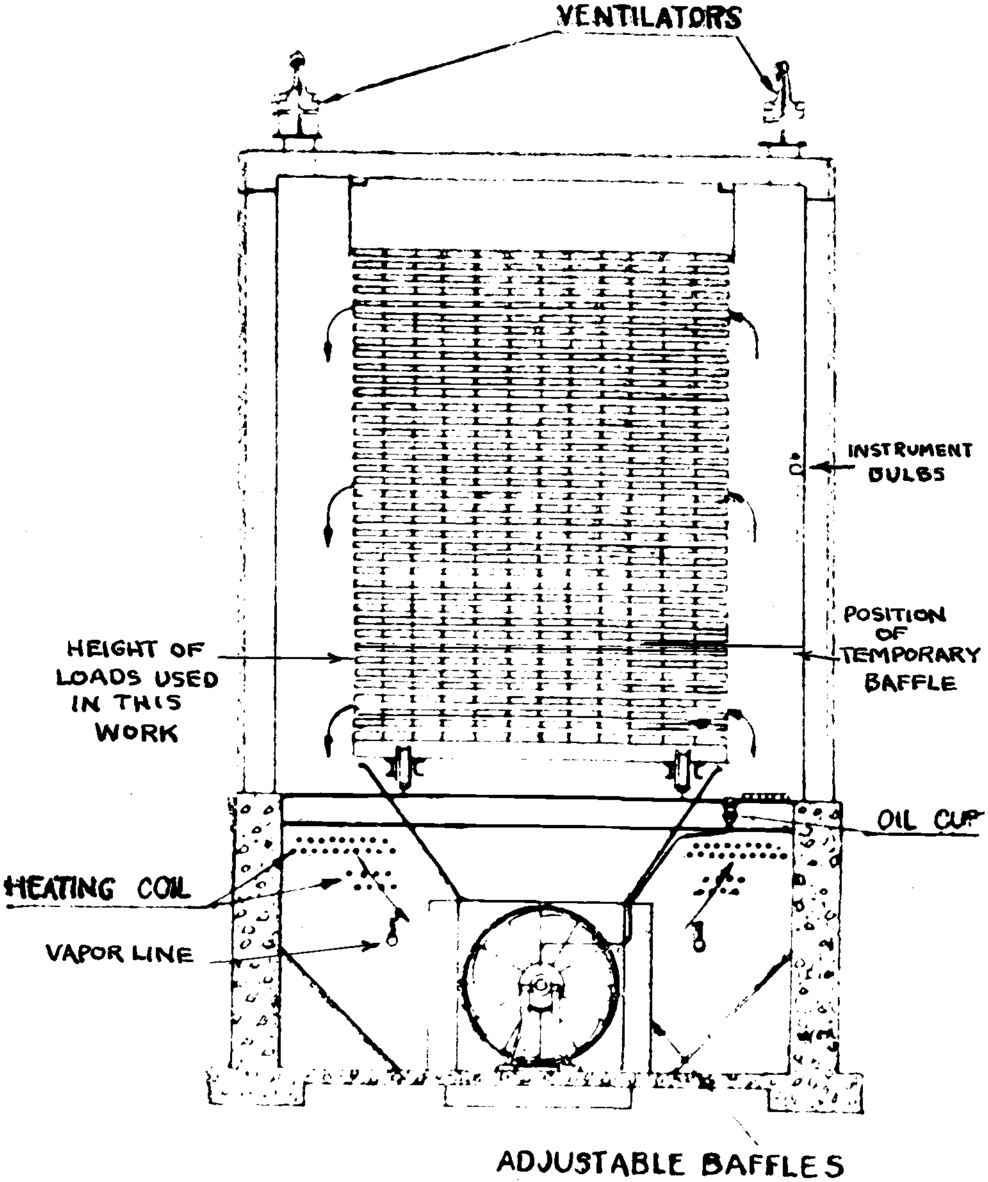


DIAGRAM OF THE CROSS SECTION OF

THE TYPE OF KILN USED IN THIS WORK

been weighed previously, and this weight together with an allowance of three pounds for each sticker used was set off for each load on the beam of the scales. The weight read on the dial was that of the lumber alone.

DRYING PROCEDURE

It has been previously intimated that the subjects of this study were three properties of water absorbed in wood, namely, capillarity, viscosity, and vapor pressure. The movement of moisture in wood at any temperature, neglecting a minor movement due to the expansion of the water in completely filled cell cavities, is due to the resultant of the forces of these properties. The value of the force of each is a function of the temperature of the surrounding air which is heating the water and wood, but the humidity of this surrounding air also affects the rate of evaporation from the surface of the wood. Thus, to study accurately their resultant forces as they vary with the temperature, the effect of the humidity of the surrounding air must be eliminated if possible or held constant at some point.

The effect of the humidity of the surrounding air on the moisture movement in wood may be traced to a great extent to its effect on the dryness of the outer layers or shell of the wood. In other words, if the shell moisture content could be maintained through a range of different temperatures, other things being equal, the results obtained in drying time or moisture movement could be attributed to the temperature alone. However, this disregards the holding capacity of air for moisture. This increases with the temperature and the adjustment of humidity for shell moisture content does not adjust the increasing differences in moisture holding capacities at higher temperatures.

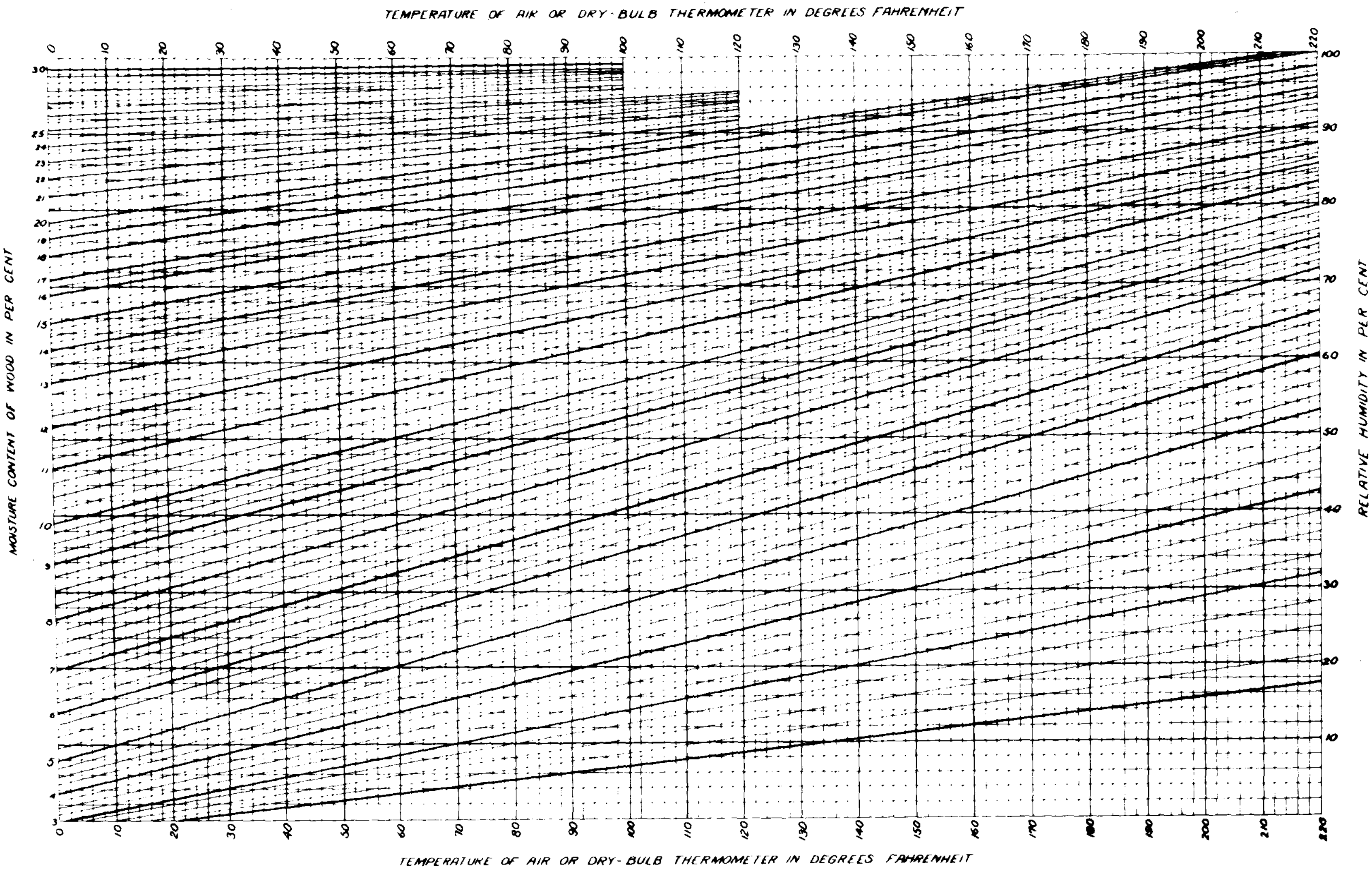
The United States Forest Products Laboratory made some extensive tests to determine at what point, expressed in moisture content, there would be no further loss of moisture from wood when exposed for an indefinite time to a certain combination of temperature and humidity. This is called the equilibrium moisture content for this temperature and humidity. These tests were made over a wide range of these combinations, and the results were published in the form of curves for the different temperatures. With the permission of the investigators, the Moore Dry Kiln Company used the data to prepare the chart which is here included. This chart simplifies the determination of the equilibrium moisture content. Reading the temperature on the horizontal and the humidity on the vertical axes, the desired moisture content is read from the oblique line which is cut at the junction of the certain temperature and humidity.

When drying at any temperature and humidity, the very outermost layers of the wood will readily drop to the moisture content which is in equilibrium with that temperature and humidity. Choosing an arbitrary moisture content for the shell to be maintained throughout the experiments, the humidity needed at each temperature to obtain this shell moisture content was read from the Moore Chart. The moisture content chosen was 11% in order not to reduce the surface moisture content to a point which would be likely to cut off capillarity. Thus, at 190 degrees Fahrenheit the humidity maintained was 78% and at 135 degrees, 70%.

The circulation of air through the load was kept constant for all the schedules. The circulation rate was approximately 200 lineal feet per minute through the load.

OPERATION DURING THE RUN

The procedure after the loading and starting of the kiln charge varied somewhat in different instances. With the higher temperatures and humidities it was found to be of advantage to let the lumber and kiln heat for awhile before starting the fans. This, of course had some effect on the rate of drying, but the moisture contents, which this condition affected, were outside the limits chosen for the final comparison of results.



MOORE DRY KILN COMPANY - NORTH PORTLAND OREGON

In most cases no difficulty was encountered in building up the temperature and humidity to the desired points.

As stated before, the loads were weighed as originally put into the kiln. This weighing was repeated at intervals throughout each schedule. At the beginning of the run when moisture loss was rapid, visits for inspecion were made every two to four hours. Later the time between visits was lengthened. When weighing, both the weight and the time were recorded.

During these visits a routine inspection of instruments was made. Both wet and dry bulb temperatures on the controller were checked with those scheduled. The recording instrument temperature was read, and the difference between it and the dry bulb on the controller noted. Added inspection of fan motor, compressor, boiler, etc., was made and in some cases averted accidents.

At some period in each schedule, the loss of weight of the lumber had slowed down to such an extent as to announce a condition of moisture content equilibrium in most of the lumber. Such further loss as did appear could be traced to certain pieces in the load which for some reason, such as greater density, had lagged in the drying process. At this point the kiln was opened temporarily and sampled for the average moisture content of the lumber.

In sampling, an effort was made to secure samples from different parts of the load. Some were taken from the center, right, and left sides at different heights in the load. The number taken varied from eight to eleven.

Each board sampled was pulled from the load and two feet cut from one end. The doors were closed as quickly as possible, and the 2-foot sections taken to the band saw in the operating room. At a point some three or four inches back from the freshly cut end of each piece, a thin wafer (from $\frac{1}{4}$ to $\frac{1}{2}$ inch thick) was cut transversely. After each wafer was cut, it was quickly weighed and its weight recorded. Then followed a drying period in the oven till repeated weighings showed no more loss of weight. The weight of each wafer then is the weight of the wood substance alone, and the per cent of water originally contained was calculated, using the following formula:

100 (Original weight — Oven-dry weight) ÷ Oven-dry weight = Moisture content in % of Oven-dry weight.

The average moisture content of the load was calculated from these samples, and if it was the desired 11% the kiln was shut off. If the lumber had not yet reached that point, the drying was continued and samples taken again before shutting the kiln off.

During these experiments the recording and controlling instruments were calibrated at the various temperature ranges. Their readings were checked with those of a liquid in glass thermometer having a United States Bureau of Standards certificate.

E X P E R I M E N T A L   R E S U L T S

PREPARATION OF DATA

The data taken during these experimental runs and used in the calculation of each drying curve were: the age in hours of the run each time the lumber was weighed and the weight of the lumber at that age. For most of the runs there were over twenty of these readings of age and weight.

Having determined the final moisture content of each run by sampling, the moisture contents of the lumber at different periods during the schedule were calculated. The moisture content is measured in per cent of the weight of the wood substance or oven-dry weight. Thus, at the end of the run at an equilibrium moisture content of 11%, the lumber weighed 111% of the weight of the wood substance, and at a place of x % moisture content it weighed (100% + x %) of the wood substance. Having the final moisture content and the weights of the load at different periods, the moisture content in per cent was calculated at each period, using the following formula:

111% : (100 + x%) :: final weight : weight at x%

Simplifying and solving for x;

$$x\% = \left(\frac{111 \text{ (weight at } x\%)}{\text{final weight}} \right) - 100$$

Using age in hours as the abscissas and moisture content in per cent of oven-dry weight as the ordinates, points were plotted on coordinate paper and a curve drawn through them. These curves are the graphic accounts of the loss of moisture from each of the charges run during the experiment.

INDIVIDUAL RUNS

In the course of this study eighteen kiln charges were run. Of these eighteen, thirteen were used as reliable data, the others being discarded for various reasons told below. The drying curves of these thirteen and short accounts of all the runs are given below.

RUN NO. 1

Started October 16, 1931

Finished October 19, 1931

Drying time--74 hours

Initial moisture content -- 57%

Final moisture content -- 14%

Schedule: 135 degrees F., 75% humidity -- 44 hours

135	"	".	44%	"	-- 24 "

Remarks: The load was steamed four hours at the beginning and two hours at the end of the run at 150 degrees and 100% humidity. This schedule was run as a practice or test schedule.

RUN NO. 2

Started October 24, 1931

Finished October 27, 1931

Drying time -- 76 hours

Initial moisture content -- 69%

Final moisture content -- 9%

Schedule: 145 degrees F., 70% humidity -- 18½ hours

145	"	".	50%	"	-- 22½ "
145	"	".	30%	"	-- 1½ "
145	"	".	50%	"	-- 2½ "
145	"	".	30%	"	-- 25½ "

Remarks: The load was given an initial steaming of 3½ hours and a final steaming of 2 hours at 150 degrees and 100% humidity. Run for the same purpose as above.

RUN NO. 3

Started November 5, 1931

Finished November 9, 1931

Drying time -- 94 hours

Initial moisture content -- 56%

Final moisture content -- 11%

Schedule: 135 degrees F., 70% humidity during the entire schedule.

Remarks: This was the first run used in the study. Constant temperature and humidity were maintained till the lumber reached an equilibrium moisture content. For curve see page 32.

RUN NO. 4

Started November 20, 1931

Finished November 23, 1931

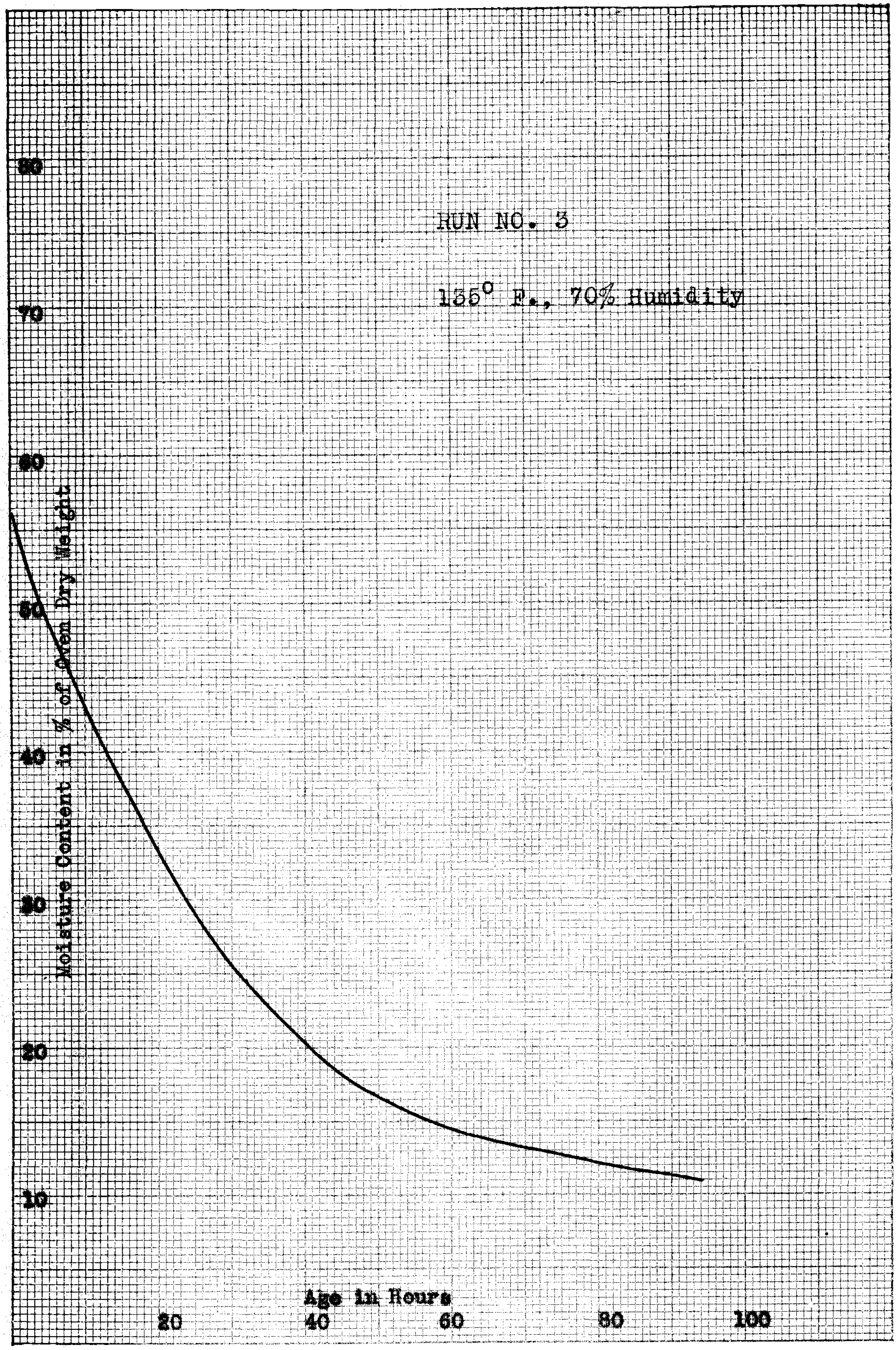
Drying time -- 64 hours

Initial moisture content -- 23.4%

Final moisture content -- 9%

Schedule:	150	degrees	F.,	70%	humidity	for 17	hours
	160	"	".,	53%	"	" 25½	"
	170	"	".,	41%	"	" 12	"
	170	"	".,	30%	"	" 9½	"

Remarks: This charge consisted of about eight thousand feet of one by four inch, vertical grain lumber which was already partially air-dried. It was run for the convenience of the Corvallis Lumber Company. Not used in this study.



RUN NO. 3
135° F., 70% Humidity
Moisture Content in % of Oven Dry Weight
80
70
60
50
40
30
20
10
Age in Hours
20
40
60
80
100

RUN NO. 5

Started December 4, 1931

Finished December 7, 1931

Drying time -- 69 hours

Initial moisture content -- 59%

Final moisture content -- 11%

Schedule: 160 degrees F., 75% humidity for the entire run

Remarks: Final steaming treatment was given this load. Considerable warping was noted, but it was due more to the character of the lumber than to the severity of the run. See page 34.

RUN NO. 6

Started December 12, 1931

Finished December 15, 1931

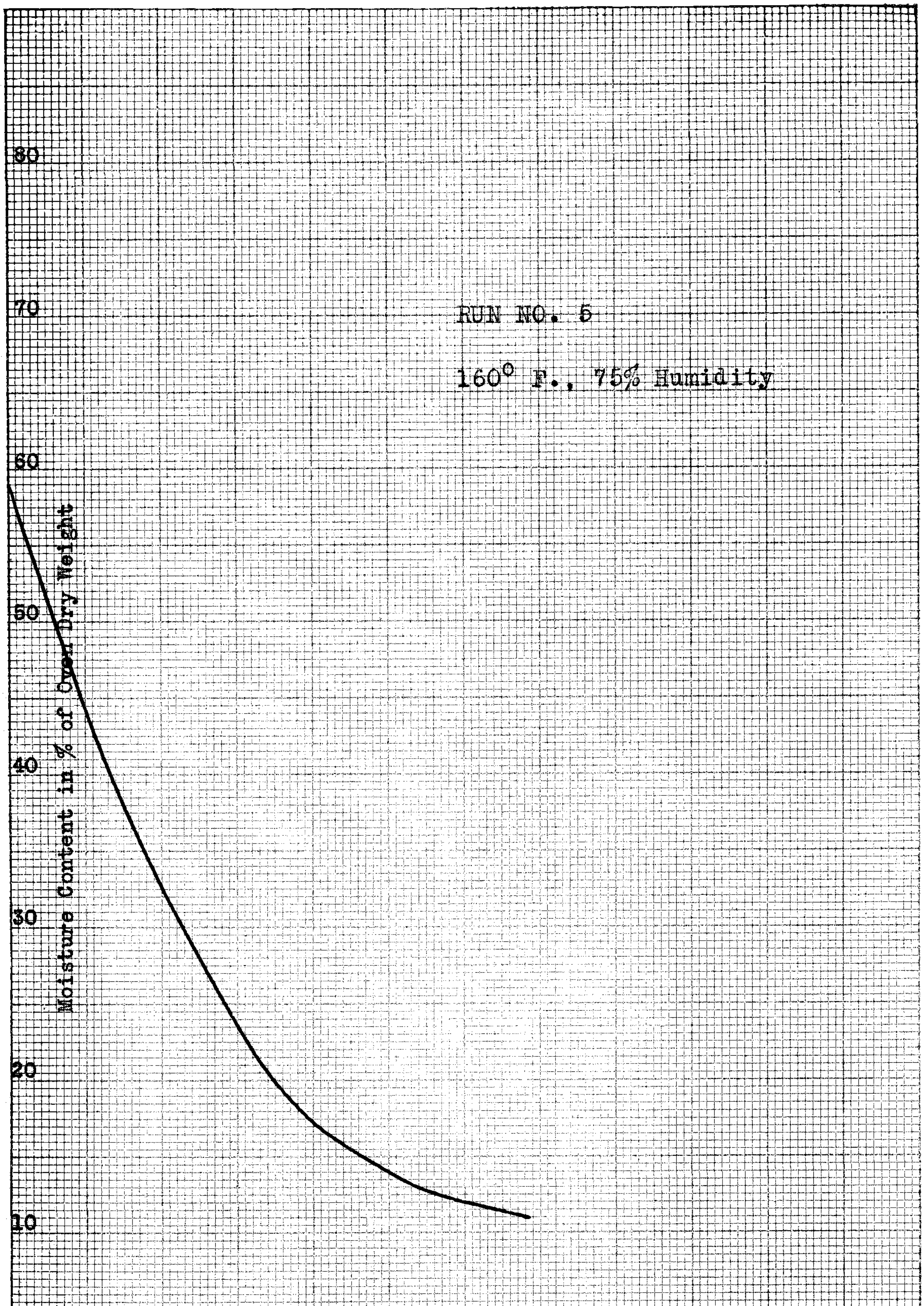
Drying time -- 61 hours

Initial moisture content -- 56%

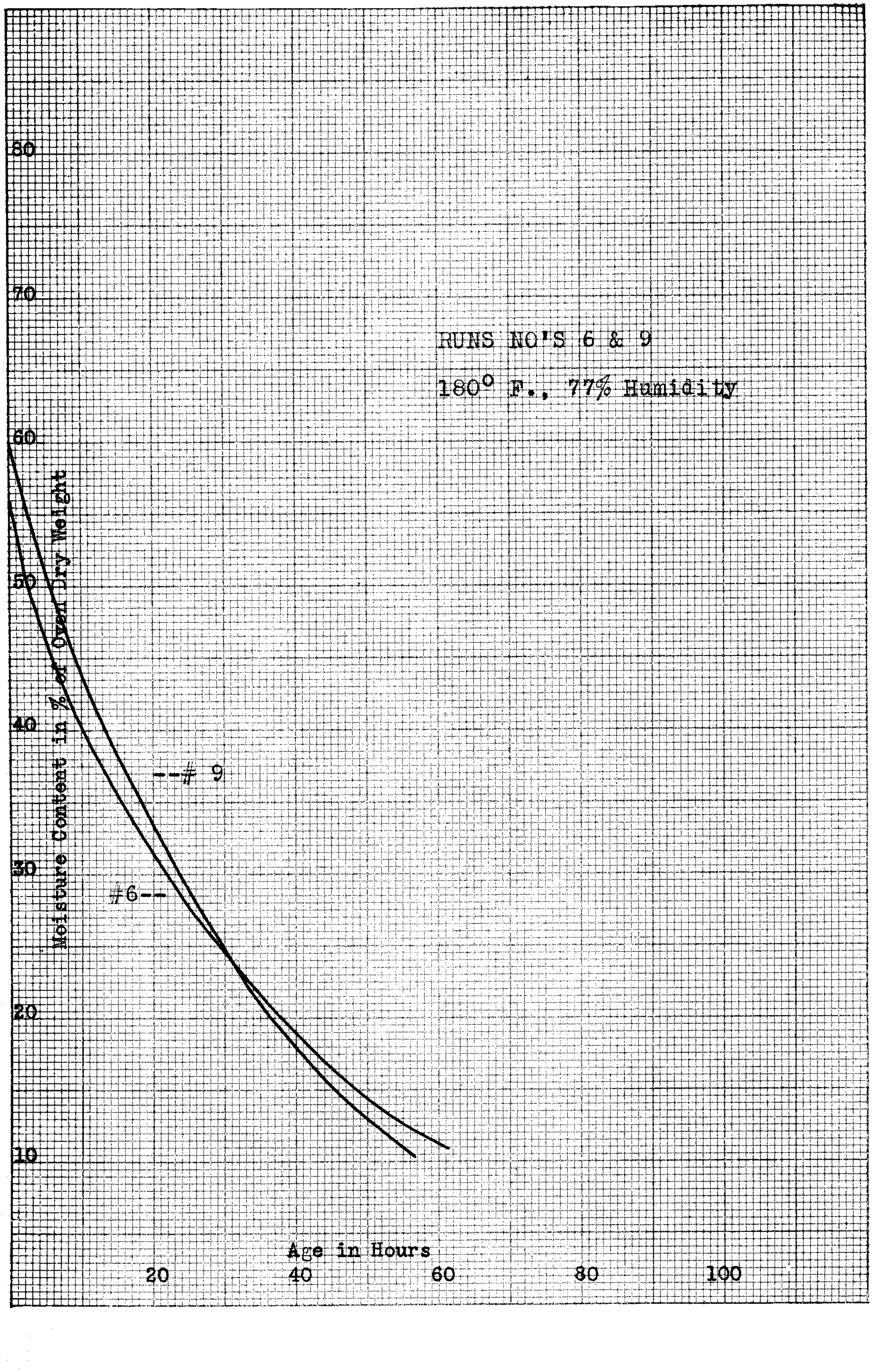
Final moisture content -- 11%

Schedule: 180 degrees F., 77% humidity for the entire run

Remarks: This run was started at 190 degrees and 78% humidity, but this point could not be reached and the temperature and humidity were dropped to 180 degrees and 77 %. The kiln boiler shut off for three hours in the morning, but the drying curve seems to give no



RUN NO. 5
160° F., 75% Humidity
Moisture Content in % of Oven Dry Weight
80
70
60
50
40
30
20
10
Age in Hours
20
40
60
80
100



RUNS NO'S 6 & 9
180° F., 77% Humidity
Moisture Content in % of Oven Dry Weight
Age in Hours
80
70
60
50
40
30
20
10
--# 9
#6--
20
40
60
80
100

indication of the lost time. See page 35.

RUN NO. 7

Started December 17, 1931

Finished December 20, 1931

Drying time -- 69 hours

Initial moisture content -- 74%

Final moisture content -- 10.5%

Schedule: 170 degrees F., 76% humidity for the entire run

Remarks: The college steam was turned off at two different times for about half an hour. No apparent ill effects resulted. See page 37.

RUN NO. 8

Started January 12, 1932

Finished January 15, 1932

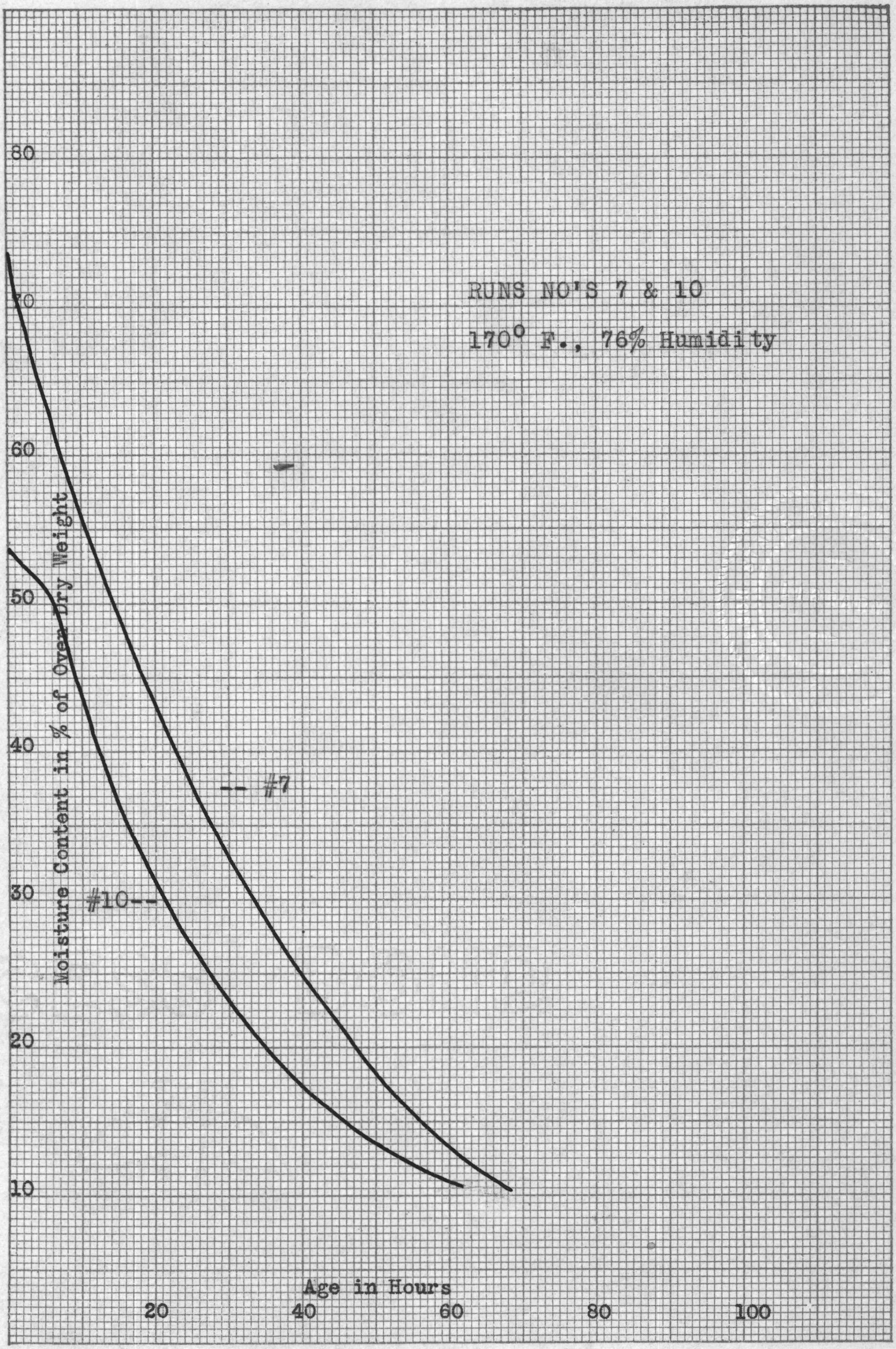
Drying time -- 70 hours

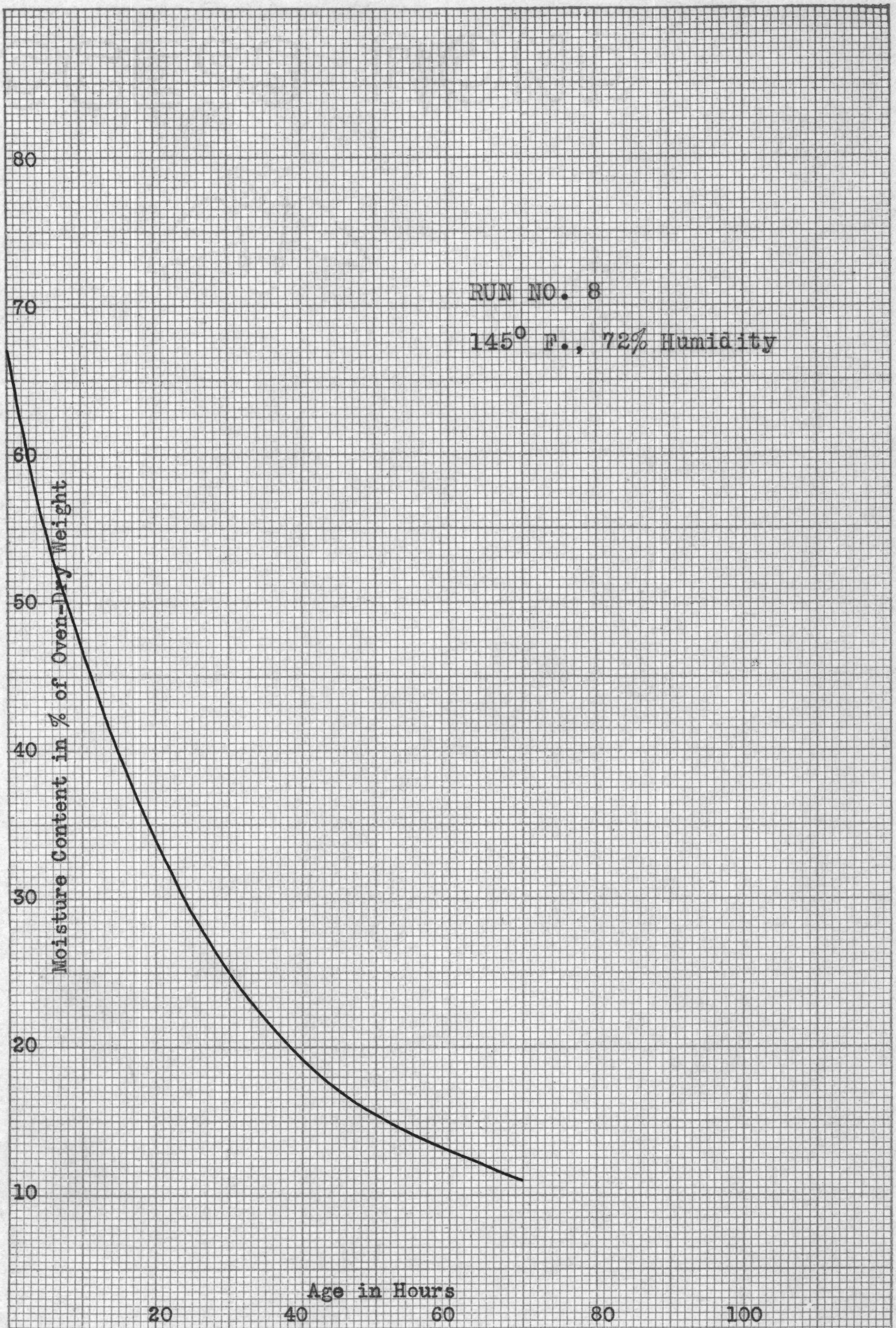
Initial moisture content -- 67%

Final moisture content -- 11%

Schedule; 145 degrees F., 72% humidity for the entire run

Remarks: See page 38.


RUNS NO'S 7 & 10
170° F., 76% Humidity
Moisture Content in % of Oven Dry Weight
Age in Hours
80
70
60
50
40
30
20
10
20
40
60
80
100
-- #7
#10--


RUN NO. 8
145° F., 72% Humidity
Moisture Content in % of Oven-Dry Weight
Age in Hours
80
70
60
50
40
30
20
10
20
40
60
80
100

RUN NO. 9

Started January 26, 1932

Finished January 29, 1932

Drying time -- 57 hours

Initial moisture content -- 60%

Final moisture content -- 10.5%

Schedule: 180 degrees F., 77% humidity for the entire run

Remarks: Some difficulty was encountered in getting the humidity up to the desired point. The first ten hours of the drying curve could be considered unreliable data. See page 35.

RUN NO. 10

Started February 4, 1932

Finished February 7, 1932

Drying time -- 63 hours

Initial moisture content -- 53.5%

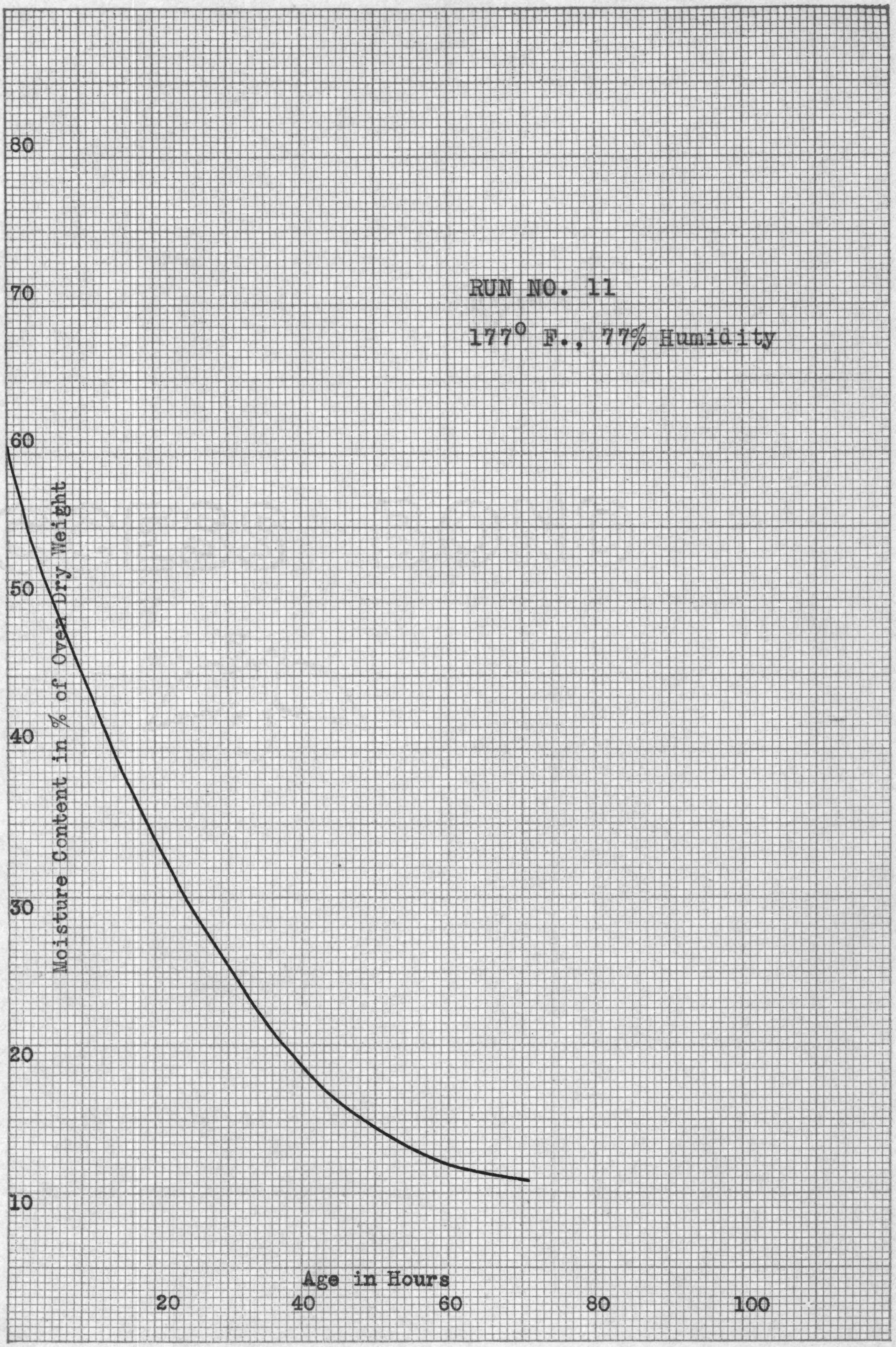
Final moisture content -- 11%

Schedule: 170 degrees F., 76% humidity for the entire run

Remarks: See page 37.

RUN NO. 11

Started February 10, 1932


RUN NO. 11
177° F., 77% Humidity
Moisture Content in % of Oven Dry Weight
Age in Hours
80
70
60
50
40
30
20
10
20
40
60
80
100

Finished February 13, 1932

Drying time -- 71 hours

Initial moisture content -- 60.3%

Final moisture content -- 10.6%

Schedule: 177 degrees F., 77% humidity for the entire run

Remarks: Some time was lost in reaching the right temperature and humidity. The first eight hours of the drying curve were subject to conditions other than those scheduled. See page 40.

RUN NO. 12

Started February 24, 1932

Finished February 27, 1932

Drying time -- 68 hours

Initial moisture content -- 55.5%

Final moisture content -- 9.7%

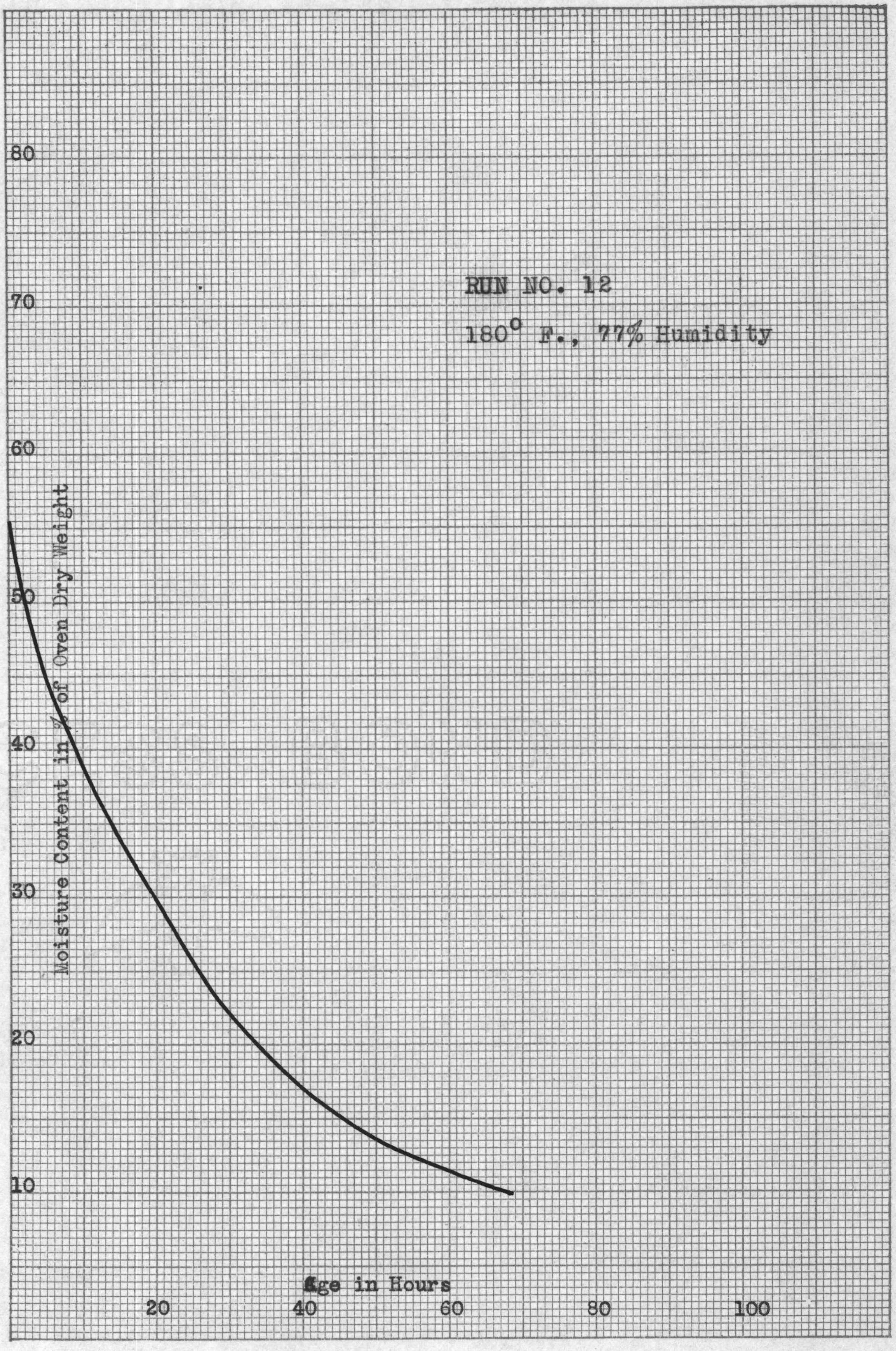
Schedule: 180 degrees F., 77% humidity for the entire run

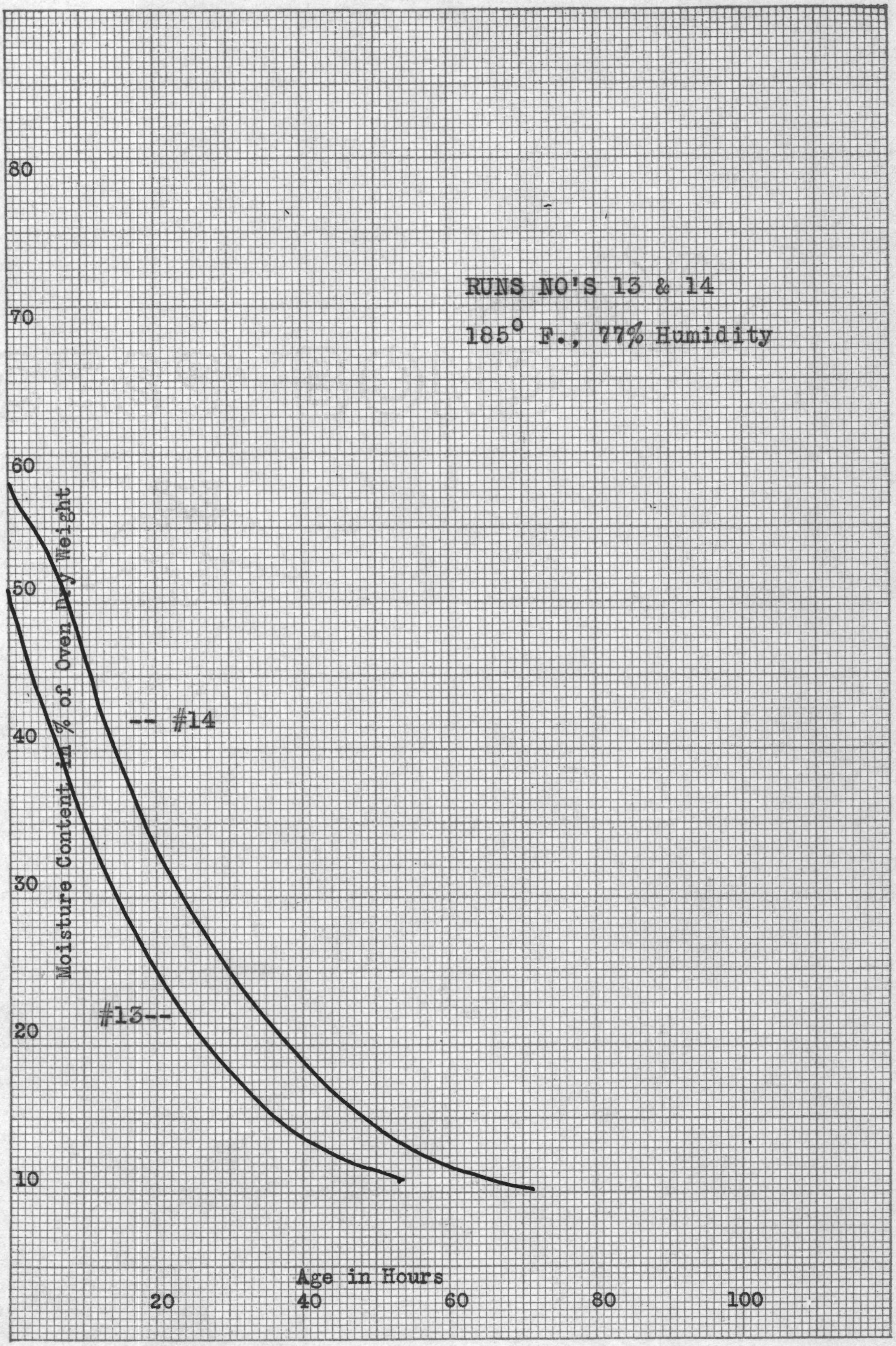
Remarks: The first eight hours of the drying curve are unreliable as the humidity was not up to the proper point. See page 42.

RUN NO. 13

Started March 2, 1932

Finished March 4, 1932


RUN NO. 12
180° F., 77% Humidity
Moisture Content in % of Oven Dry Weight
80
70
60
50
40
30
20
10
Age in Hours
20
40
60
80
100



RUNS NO'S 13 & 14
185° F., 77% Humidity
Moisture Content in % of Oven Dry Weight
80
70
60
50
40
30
20
10
-- #14
#13--
Age in Hours
20
40
60
80
100

Drying time -- 72 hours

Initial moisture content -- 51%

Final moisture content -- 11%

Schedule: 185 degrees F., 78% humidity for the entire run

Remarks: The humidity was not up to 78% for 12 hours. The drying curve on page 43 is not reliable data down to 32% moisture content.

RUN NO. 14

Started March 10, 1932

Finished March 13, 1932

Drying time -- 72 hours

Initial moisture content -- 58%

Final moisture content -- 10.7%

Schedule: 185 degrees F., 78% humidity for the entire run

Remarks: The first eight hours of the schedule were taken in reaching the proper temperature and humidity. See page 43.

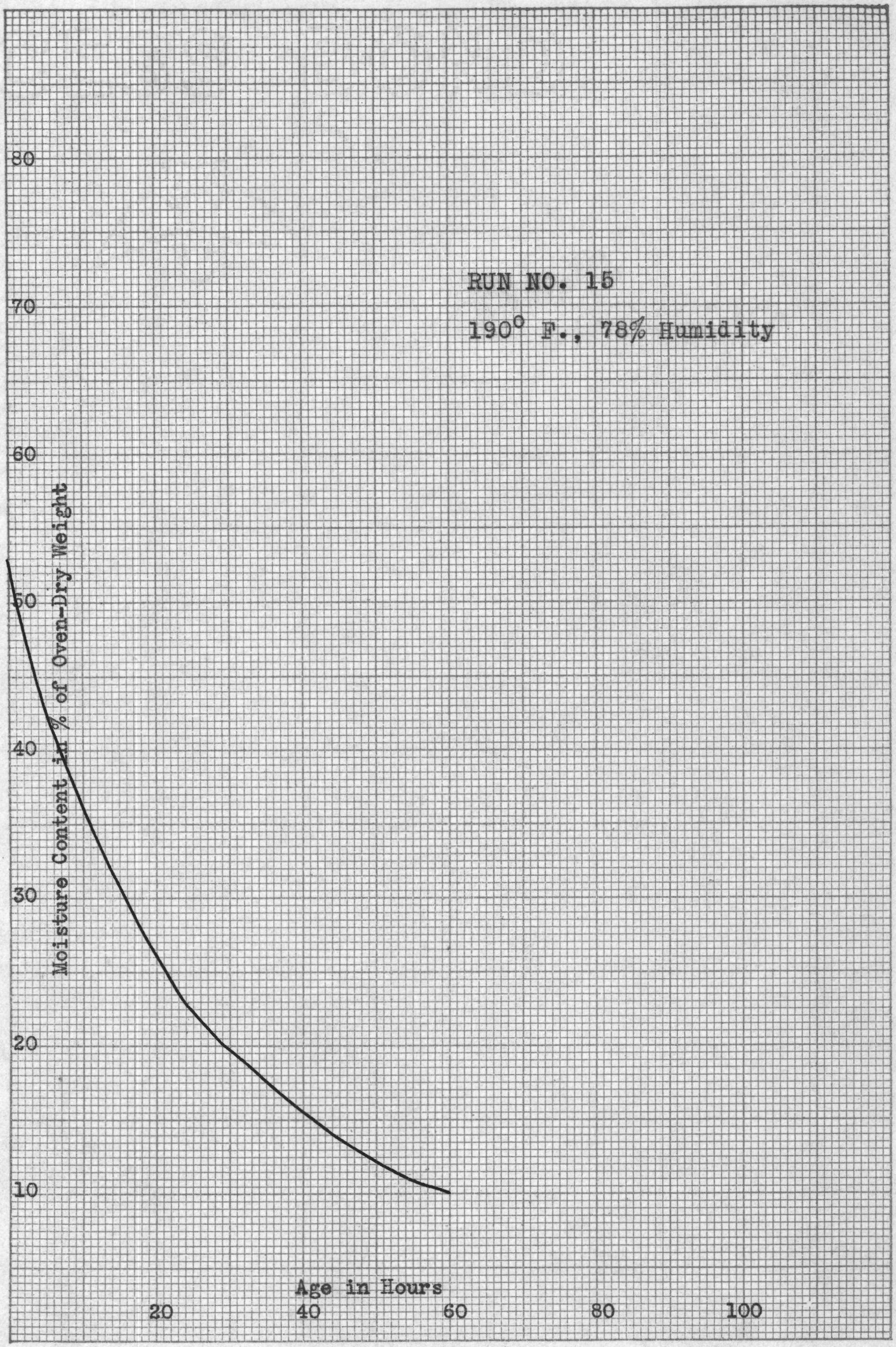
RUN NO. 15

Started March 15, 1932

Finished March 18, 1932

Drying time -- 60 hours

Initial moisture content -- 53%



RUN NO. 15
190° F., 78% Humidity
Moisture Content in % of Oven-Dry Weight
Age in Hours
80
70
60
50
40
30
20
10
20
40
60
80
100

Final moisture content -- 10%

Schedule: 190 degrees F., 78% humidity for the entire run

Remarks: The fans were not turned on till the temperature and humidity had reached the desired points. This took nine hours. The curve on page 45 is drawn from the time the fans were turned on.

RUN NO. 16

Started March 30, 1932

Finished April 3, 1932

Drying time -- 88½ hours

Initial moisture content -- 42%

Final moisture content -- 12.6%

Schedule: 170 degrees F., 76% humidity for the entire run

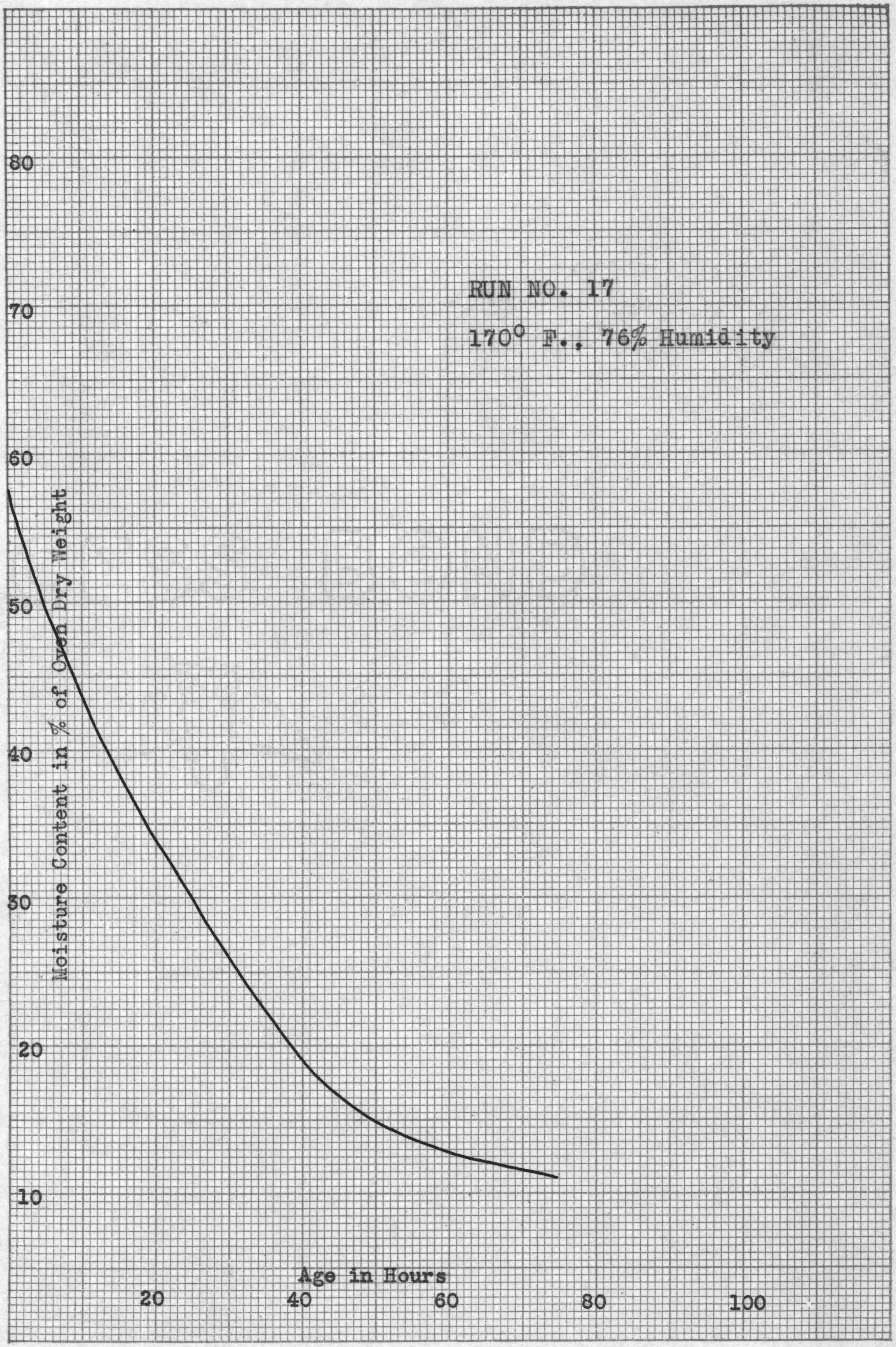
Remarks: This charge was discarded from the experimental data due to the fact that about 200 feet of 1¼ by 12 inch vertical grain lumber was included in the load and was responsible for the increase in drying time.

RUN NO. 17

Started April 6, 1932

Finished April 9, 1932

Drying time -- 75 hours



RUN NO. 17
170° F., 76% Humidity
Moisture Content in % of Oven Dry Weight
80
70
60
50
40
30
20
10
Age in Hours
20
40
60
80
100

Initial moisture content -- 11%

Schedule: 170 degrees F., 76% humidity for the entire run

Remarks: The fans were turned on after proper temperature and humidity were reached. See page 47.

RUN NO. 18

Started April 12, 1932

Finished April 15, 1932

Drying time -- 78 hours

Initial moisture content -- 54%

Final moisture content -- 13%

Schedule: 170 degrees F., 76% humidity for the entire run

Remark: This run was discarded from the data due to the failure to reach the approximate 11% moisture content. Readings of controlling and recording thermometers showed a condition of error in one or the other.

C O M P A R I S O N S

Because of the variation of initial moisture contents, the drying curves and total drying times represented could not be accurately compared. Also, for the reason that in most cases scheduled conditions did not exist immediately at the beginning of the runs, a moisture content was chosen which would be found in the drying curves somewhere below the initial moisture content. This procedure also made sure that transfusion had begun before results were taken for comparisons. The moisture content of 50% was not low enough in a few cases to bring the succeeding parts of the curve into scheduled conditions, but it was thought advisable to use that moisture content rather than a lower one.

It was further decided that for greater accuracy in comparisons the drying curves should be divided into two parts, the first being from the 50% moisture content, chosen as above, to the fibre saturation point which, in Douglas fir, is about 25% moisture content. The remaining part of the curves from 25% moisture content to 11% was considered separately.

Below is given a comparison of the drying curves of this experiment in the time in hours read on these curves between the moisture contents of 50% and 25%.

Each run or charge is listed separately, and the average time for each temperature is given in the column on the extreme right.

DRYING TIMES FROM 50% TO 25% MOISTURE CONTENT

Below is given a list of the different runs with their drying times for the upper parts of their drying curve; listed separately and averaged for each temperature.

Temperature	Humidity	Time in Hours From 50% to 25% M.C.	Average
190° F.	78%	20	20
185° F.	78%	22	
" "	"	19	20.5
180° F.	77%	25	
" "	"	26	
" "	"	24	25
177° F.	77%	24	24
170° F.	76%	26	
" "	"	22	
" "	"	26	24.6
160° F.	75%	22	22
145° F.	72%	22	22
135° F.	70%	28	28

Having only thirteen runs with which to work, the more elaborate statistical methods of correlation would be of little value and the "scatter" diagram herein included may even be misleading.

CORRELATION OR "SCATTER" DIAGRAM

Temperatures	Time in Hours from 50% to 25% M. C.									
in degrees F.	19	20	21	22	23	24	25	26	27	28
190		1								
185	1			1						
180						1	1	1		
175						1				
170				1				2		
165										
160				1						
155										
150										
145				1						
140										
135										1

However, if further schedules should conform to the frequencies noted in the thirteen already taken, some slight correlation might be indicated between temperature and drying time between 50% and 25% moisture contents. In the diagram the only indication of correlation is the grouping of short drying periods in the high temperature corner of the rectangle. This grouping suggests a line drawn diagonally from the upper left to the lower right hand corners or a correlation of high temperatures with short drying periods. In opposition to this possible correlation is the fact that the drying time of 22 hours occurs at four different temperatures, ranging from low to high. This indicates no correlation between temperature and drying time between 50% and 25% moisture content and only further experiments will determine which trend will be followed.

DRYING TIMES BETWEEN 25% AND 11% MOISTURE CONTENT

In comparing the curves from 25% to 11% moisture content, the same difficulty of an insufficient number of samples was encountered. A list, similar to that on page 50, of drying times for this range of moisture contents is included. The diagram on page 54 shows the average time for each temperature plotted and an attempt at an average line drawn through these points. This curve shows a flattening off between 170 and 180 degrees and a slight rise at 190 degrees. The majority of these runs were made at around 170 and 180 degrees, and the points representing the average time for these temperatures are more accurately placed than the point for the

190 degree schedule, at which temperature only one run was made and which is responsible for an upward tilt in the average curve.

LIST OF DRYING TIMES FROM 25% TO 11% MOISTURE CONTENT

Temperature	Humidity	Time in Hours From 25% to 11% M.C.	Average
190° F.	78%	34	34
185° F.	78%	33	
" "	"	37	35
180° F.	77%	36	
" "	"	32	
" "	"	25	31
177° F.	77%	37	37
170° F.	76%	32	
" "	"	26	
" "	"	33	30.3
160° F.	75%	40	40
145° F.	72%	39	39
135° F.	70%	62	62

The minimum average time from 25% to 11% moisture content is found at 170 degrees. The average time at 180 degrees is but .7 of an hour longer. This, in itself, is too small a difference to be of importance as an average of three runs, but, by going further and including all those runs over 170 degrees,

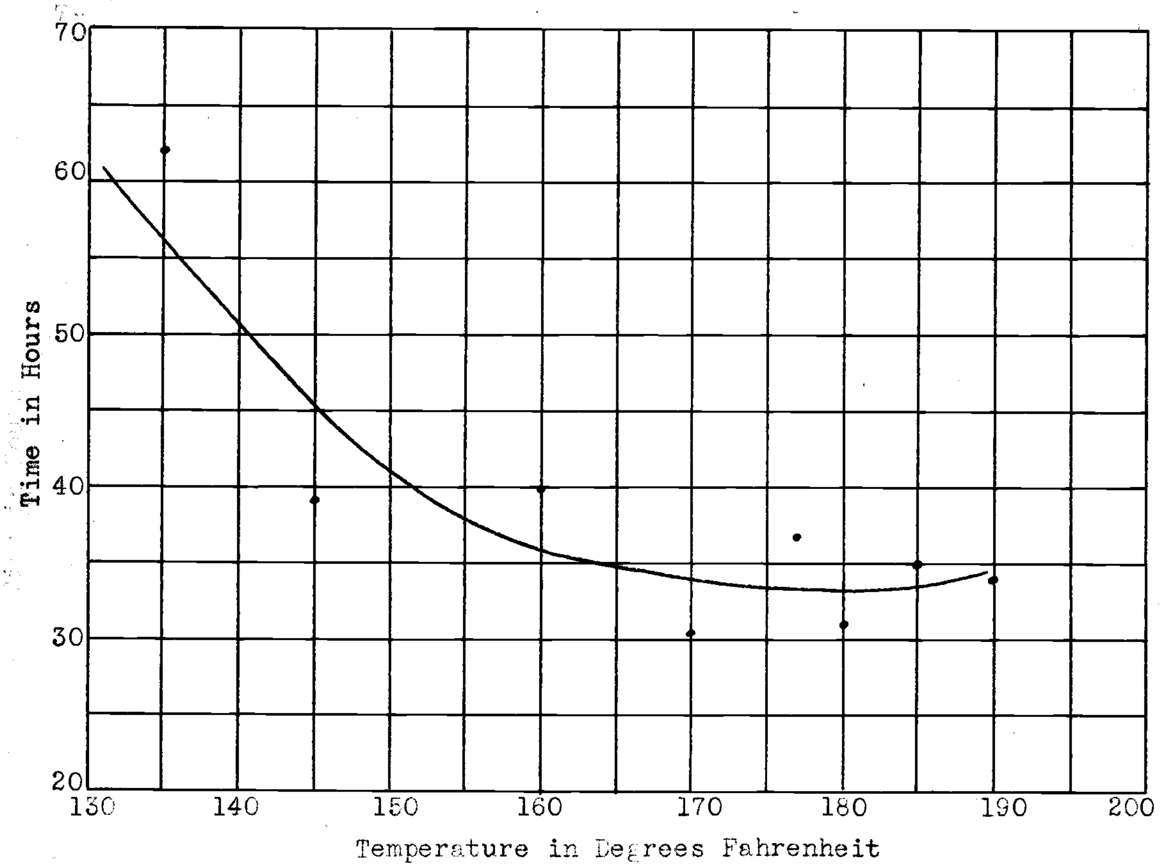


DIAGRAM: AVERAGE DRYING TIMES FOR DIFFERENT TEMPERATURES FROM 25% TO 11% MOISTURE CONTENT PLOTTED AND AN AVERAGE CURVE DRAWN.

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the average time mounts to 33.4 hours or an increase of 3.1 hours over the average at 170 degrees.

Here again we have a difference in drying time which is of slight importance in commercial practice, but the trends are more easily followed than in the upper parts of the drying curves and these trends are important due to the conclusions which may be drawn.

DISCUSSION

FIBRE SATURATION POINT

In dividing the drying curves into two parts, one above and one below the average moisture content of 25%, it was the idea of the writer to have the parts differing in one characteristic. This characteristic was the presence of free water in the cell cavities of the wood being dried. While 25% moisture content is the accepted fibre saturation point for Douglas fir, the fallacy of thinking that at an average moisture content of 25% in a board all the free water is gone from the cell cavities is evident.

If the structure of wood were strictly homogeneous and if drying took place without the presence of a moisture gradient, that is, if there were no difference between the moisture contents of the shell and core, accurate determination of the moisture content at which no free water existed would be possible. The 25% value for Douglas fir is one which must exist uniformly to hold true to the definition and must not be the average of an 18% shell and a 32% core.

Thus, one has no means of telling just where on the drying curves the free water no longer exists in the cell cavities of the wood. Tests for moisture gradients, if exhaustive enough, might disclose this point, and it may be approximated by a study of the drying curves themselves. Theoretically, the drying process slows up at the fibre saturation point. The point at which the flattening or break in the drying curves begins should indicate the approximate point of the disappearance of free water. Studying the curves included it can be seen that this break does not come at 25% moisture content, but much lower on the curve and varies greatly among the runs. It cannot be claimed that the curves were divided on each side of the fibre saturation point, therefore, but merely at 25% moisture content.

CIRCULATION AND TEMPERATURE

It has been fairly well established that the rates of drying wood, down to the fibre saturation point, is a function of the circulation within certain limits. This is because a more rapid circulation will bring heat more quickly to the lumber to replace heat lost through evaporation of water and also will remove the moisture-laden air from the surface of the wood, allowing a more rapid transfusion of water from the interior of the wood.

Also, authorities on the drying of wood agree that an increase in the temperature will result in an increase in the drying rate. From the included table of water-holding capacities of air in grains per cubic foot at different temperatures and humidities, it is found that air at 190 degrees and 78 per cent humidity has a little more than twice the capacity for moisture than that at 160 degrees and 72 per cent humidity. With these figures alone it would seem that the moisture loss at 190 degrees and 78 per cent humidity would be much faster than at 160 degrees and 72 per cent humidity. The actual results at these temperatures show a decrease in drying time of only two hours or 9 per cent from the lower to the higher temperature. This would indicate that the air had sufficient capacity at the lower temperature.

The argument arises that using one rate of circulation which was comparatively low a condition might exist wherein the moisture-laden air was not removed rapidly enough or enough heat conducted to the lumber at the higher temperatures to allow them to dry at the proper rate. An answer to this is the fact that the drop in temperature across the load was more than eight degrees in only two instances even at the beginning of the charges, and one which registered a temperature drop that would make the return air at 100 per cent humidity did not suffer in drying time. For the first twenty-four hours of every run of the higher temperatures the vapor and heating lines were using steam in large quantities to

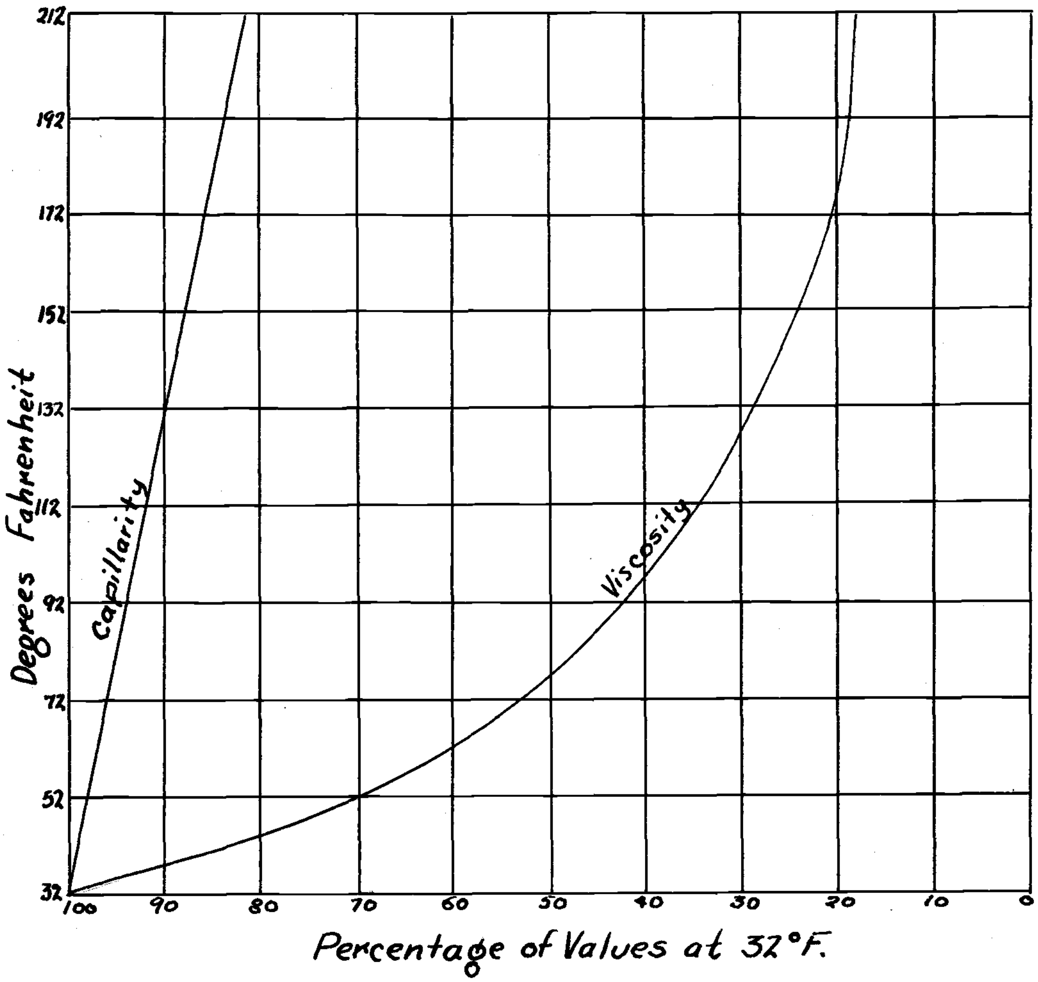

DIAGRAM SHOWING THE EFFECT ON TEMPERATURES ON CAPILLARITY AND VISCOSITY OF WATER

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supply heat lost in evaporation of water to keep the humidity at the proper point.

Viewing these results as fairly as possible the conclusion appears that for these runs, at least, the movement of moisture within the wood rather than the rate of evaporation from the surface was the limiting factor in the drying rate, and that temperature had little effect on this rate.

Considering the comparison of drying curves below the 25% moisture content, the results are more marked than those above. At the lower temperatures the time is considerably longer, and, as has been shown, a minimum drying time seems to appear at between 170 and 180 degrees.

CAPILLARITY AND VISCOSITY

Examining the diagram of the effect of temperature on capillarity and viscosity on page 58, it is noted that at a point between 170 and 180 degrees the distance between viscosity and capillarity curves is the greatest. Both capillarity and viscosity decrease with an increase in temperature but not at the same rate. As has been explained, a decrease in viscosity aids, while a decrease in capillarity hinders moisture movement. Thus, the difference in the space between these curves at different temperatures corresponds to the resultant of a positive and a negative force. Leaving the third factor of vapor pressure out of the discussion for the time being, it is reasonable to expect greater moisture movement at 112 degrees than at 52 degrees and further, due to the shape of the curves, more at 172 degrees than at 192 degrees.

The fact that drying times from 25% to 11% moisture content were lower around 170 degrees has been mentioned and seems to bear out the theory of a maximum resultant of capillarity and viscosity mentioned above. The position of this maximum resultant is responsible for the greater number of runs in the vicinity of 170 and 180 degrees, which were made in an effort to let any tendency become evident.

VAPOR PRESSURE

Bringing in the part which vapor pressure plays in moisture movement is fraught with dangers of misinterpretation of facts. Results from these experiments would suggest that vapor pressure has little effect either above or below the fibre saturation point on drying time.

While the wood contains free water in the cell cavities at the core, the temperature gradient in the piece will range from the temperature of the air at the shell to the temperature of the dewpoint or "wet" bulb at the core. The lower temperature of the core is due to the loss of heat used in evaporating the water in the outer layers. Thus, the vapor pressure at the shell will be the vapor pressure of the air in the kiln at the humidity maintained, and the vapor pressure at the core will theoretically be that of air at 100% humidity and the temperature of the "wet" bulb. The following table can be formulated from vapor pressures of saturated vapors at different temperatures.

Temperature in °F.		Vapor pressures in cm. of Hg.		
At shell	At core	At shell	At core	Difference
170°	159°	22.9	23.9	1.0
180°	169°	29.6	30.2	0.6
190°	179°	36.5	37.9	1.4

Considering the largest difference between shell and core vapor pressures, we find a gradient or differential of 1.8% of an atmosphere of pressure at 190° favoring the movement of moisture from the core to the shell. Whether this difference in pressure is of great consequence is questionable from the light of the figures secured in these experiments.

Below the point at which free water is present in the cell cavities, the temperature of the core approaches that of the shell until theoretically, when the wood is completely dry or drying has ceased at a uniform moisture content of shell and core, the two will be identical. Thus, with a uniform moisture content of shell and core and a uniform temperature throughout , no differential in vapor pressures would exist between shell and core.

With the saturation deficit expressed as the number

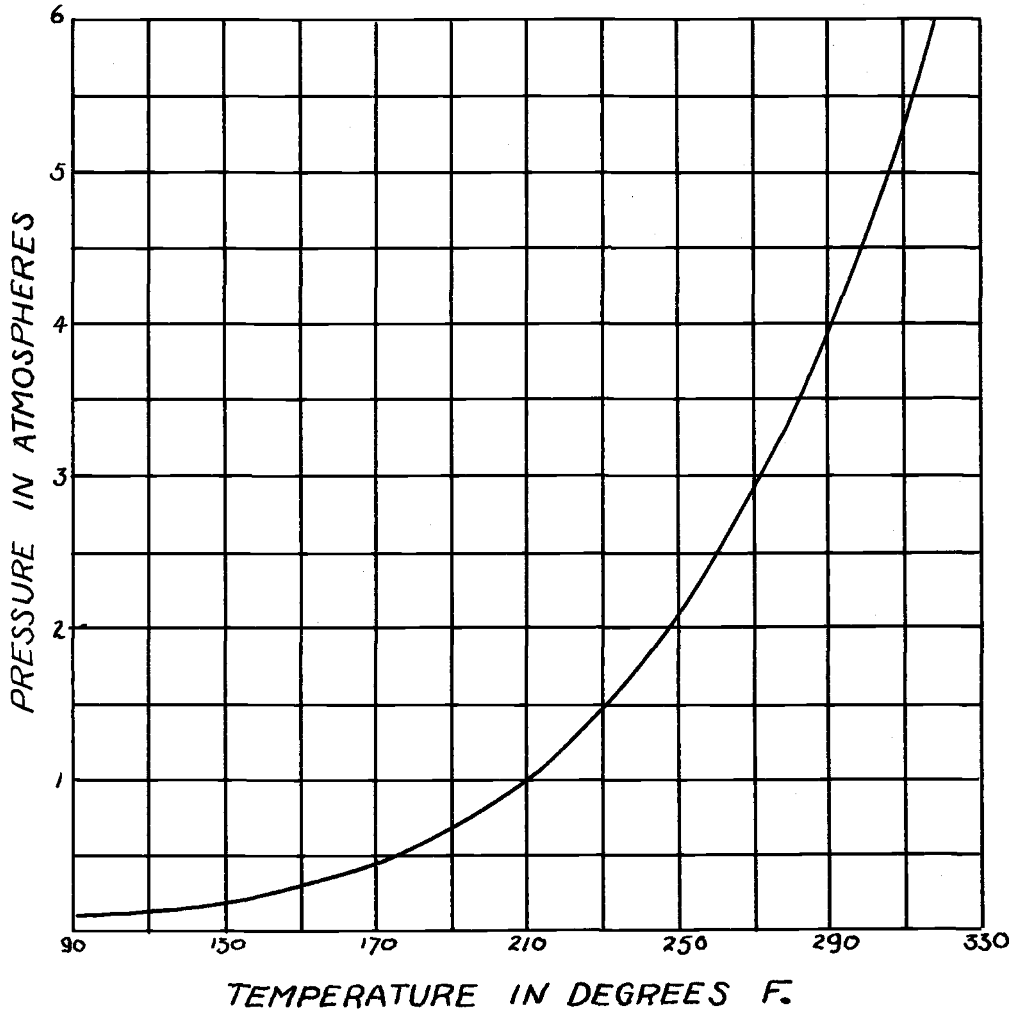

DIAGRAM SHOWING THE VAPOR PRESSURE OF WATER AT DIFFERENT TEMPERATURES

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of additional grains of moisture per cubic foot needed to saturate the air at any certain humidity and temperature, the following table was prepared, showing the difference between the saturation deficits during the conditions maintained for four runs of the range covered by this experiment.

Temperature °F.	No. of grains per cubic foot at 100% humidity.	No. of grains per cubic foot at humidity maintained.	Saturation deficit in No. of additional grains per cubic foot required to saturate the air at the humidity maintained.
145	65	48 (72%)	17
160	90	70 (75%)	20
170	115	88 (76%)	27
190	173	137 (78%)	36

Above the point of 25% average moisture content this difference in saturation deficit seems to have only the slightest, if any, effect on the drying time. Below that point the drying time could not have been limited by the saturation deficit, if it had no effect previously, for the reason that evaporation from the surface is so much slower that the moisture-holding capacity of the air would inhibit it only in cases of extremely small saturation deficits.

Relative Humidity in %	Temperature in degrees Fahrenheit							
	90	100	110	120	130	140	150	160
10-	1.7	2.3	3.0	4.0	5.0	6.6	8.4	11.0
20-	3.3	4.4	5.7	7.5	10.0	12.5	15.5	20.0
30-	4.8	6.3	8.5	11.0	14.3	18.0	21.0	29.0
40-	6.2	8.5	11.0	14.5	18.7	24.0	30.0	38.0
50-	7.8	10.3	13.9	18.0	23.0	29.5	38.0	48.0
60-	9.3	12.2	16.2	21.0	27.5	35.0	45.0	57.0
70-	10.6	14.2	18.6	24.3	32.0	41.0	53.0	66.0
80-	12.0	16.0	21.0	27.6	36.0	47.0	60.0	74.0
90-	13.5	18.0	23.5	31.0	41.0	52.0	65.0	82.0
100-	15.0	20.0	26.0	34.0	45.0	58.0	72.0	90.0

	170	180	190	200	210	220
10-	13.2	16.8	20.	24.	30.	35.
20-	24.5	31.	38.	47.	56.	79.
30-	37.	45.	56.	68.	80.	100.
40-	49.	60.	73.	89.	110.	130.
50-	60.	74.	90.	111.	135.	160.
60-	71.	87.	108.	132.	160.	190.
70-	82.	102.	124.	150.	182.	220.
80-	92.	115.	140.	170.	205.	250.
90-	104.	128.	155.	190.	230.	275.
100-	115.	142.	173.	212.	255.	300.

TABLE SHOWING THE CAPACITY OF AIR FOR MOISTURE IN GRAINS PER CUBIC FOOT AT DIFFERENT TEMPERATURES AND HUMIDITIES.

C O N C L U S I O N S

The data secured in this study indicate several conclusions. First, under the conditions of equal circulation and moisture content of the shell held in the experiments, the effect of temperature on the rate of drying of wood from 50% to 25% moisture content is not recognizable from drying times obtained at the different temperatures. Second, there appears to be an optimum point for the movement of moisture between the moisture contents of 25% and 11% at between 170 and 180 degrees Fahrenheit. The position of this optimum point coincides with the position of the greatest resultant of capillarity and viscosity as read from the diagram on page 58. Third, the factor of vapor pressure in the movement of moisture in wood appears to be of little or no consequence in these experiments. It must be added that these experiments were conducted at temperatures between 135 and 190 degrees Fahrenheit. At higher temperatures this third conclusion might not hold true.

These conclusions cannot be announced as definite without further study because of the heterogeneous nature of the material used, the lack of sufficient data, and because of the inaccuracies which result from a new and untried experimental technique.

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