AN ABSTRACT OF THE THESIS OF

George Harry Atherton for M. S. in Mechanical Engineering
(Name) (Degree) (Major)

Date thesis is presented May 13, 1966

Title DRYING RATES OF DOUGLAS FIR VENEER IN SUPERHEATED STEAM

Redacted for Privacy

Abstract approved
(Major professor)

Douglas fir sapwood veneer was dried in superheated steam at a constant velocity of 10 feet per second. Three steam temperatures 400 F, 600 F, and 800 F were used.

Drying times from an initial moisture content of about 57 percent to a final moisture content of about 5 percent were 6, 3, and 2 minutes for steam temperatures of 400 F, 600 F, and 800 F, respectively.

Experimental convective heat transfer coefficients were 4.5 to 6.7, 4.8 to 10.0, and 4.5 to 6.4 (Btu/sq ft, hr, F) when steam temperature was 400 F, 600 F, and 800 F, respectively.

DRYING RATES OF DOUGLAS FIR VENEER IN SUPERHEATED STEAM

by

GEORGE HARRY ATHERTON

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1966

APPROVED:

Redacted for Privacy

Associate Professor of Mechanical Engineering
In Charge of Major

Redacted for Privacy

Head of Department of Mechanical Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented May 13, 1966

Typed by Alice Gould

ACKNOWLEDGEMENT

The author wishes to express appreciation for advice and assistance of Dr. James R. Welty of the Mechanical Engineering Department. He also expresses appreciation to Mr. Stanley E. Corder and Mr. Donald J. Miller of the Forest Research Laboratory who assisted during tests.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DRYING RATES OF DOUGLAS FIR VENEER IN SUPERHEATED STEAM

INTRODUCTION

Plywood is made from thin sheets of wood (veneers) glued together. The thickness to which veneer is cut varies depending upon the desired thickness of the finished plywood panel. Common thicknesses for softwood veneers are 1/10th or 1/8th inch. Since these veneers usually are peeled from fresh-cut or water-stored logs, the moisture content of the wood is too high for gluing or for adequate dimensional stability of the finished plywood panel. Therefore it is necessary that veneers be dried to about 5 per cent moisture content before assembly into plywood panels.

Present veneer drying practice

Veneer dryers usually are steam-heated and veneer is dried by forced circulation of a mixture of steam (from the wood) and air passing over the surface of the veneer as the veneer is fed through the dryer between steel hold-down rolls. Dryer temperatures usually are below 400 F and the time to dry 1/10th inch thick sapwood varies from 7-15 minutes, depending on type of dryer. The presence of atmospheric air in the dryer is undesirable because dryer fires can occur if oxygen is present. Furthermore, because steam from the wood provides an adequate drying medium, it is unnecessary and uneconomical to continually intake and heat cool air at one point in the dryer and exhaust hot steam well above the condensation temperature at another (2). Because operators of present commercial dryers recognize the benefits of excluding air from dryers, many present-day dryers are operated so as to minimize intake of atmospheric air and provide mainly a superheated steam atmosphere inside.

Object of study

The previous discussion indicates that superheated steam is a good drying medium for veneer. Present dryer temperatures usually are below 400 F. The objective of this study was to investigate drying rates of Douglas fir veneer at atmospheric pressure in superheated steam at 400 F to 800 F; beginning at, and extending well above the present temperature range of commercial practice. Previous work in this area has been conducted mainly by Fleischer (5), but his study was in air at a maximum temperature of 350 F. Others, notably Milligan (19), have conducted experiments on drying veneer at high temperature. In Milligan's study air was the drying medium at temperatures ranging from 300 F to 550 F and perpendicular-to-veneer-face impingment velocities from 50 to 150 feet per second.

Scope of study

Small samples of veneer were dried at 400 F, 600 F, and 800 F in superheated steam at a parallel-to-grain velocity of 10 feet per second. Five different drying times were used at each temperature for a total of 15 test conditions. Each condition was replicated four times for a total of 60 tests in all. For each temperature and time, a heat balance was made and convective heat transfer coefficients were calculated.

Equipment design for the study was a large task in that it was necessary to design a heat source and counterflow heat exchanger to supply steam at the desired temperatures before tests could begin.

GENERAL CONSIDERATIONS

To those not familiar with wood properties it may seem that results in this study are quite variable. This variability is to be expected since the physical properties (moisture content, permeability, diffusion relationships, specific gravity, specific heat) all vary more or less from wood sample to sample and within samples. In some instances little is known of certain wood properties over the range of this study. For example, specific heat was extrapolated and assumed linear from 223 F to 440 F. The emissivity of wood was assumed constant from 80 F to 440 F. These assumptions may not strictly be true, but they appear reasonable and other information is not available.

About the wood

At temperatures used in this study one might expect that wood would ignite or char. Ignition, of course, is not possible because no free oxygen is present in the system and temperature is too low for a water-gas reaction to take place. It is possible that an exothermic reaction could occur in the wood in the absence of oxygen (6), but this is a time-temperature dependent relationship and, if it occurred in this experiment, it was not detected. Another investigator found that western larch wood samples ignited in air after 25 minutes at 400 F and 0.5 minutes at 800 F beginning with oven-dry wood (18). This compares to drying times of about nine minutes and 0.8 minutes in this experiment for the same temperatures respectively, beginning with wet wood at nearly 60 per cent moisture, oven-dry basis.

Considerably simplified, water is held or contained in wood in two ways (24). When water is condensed from vapor onto oven-dry wood, the polar attraction of the wood for the water molecules is so great that heat is liberated over and above the heat of condensation. This excess heat is called *heat of adsorption*. If the water is attracted to the wood from liquid water, the heat liberated is called *heat of wetting*. Upon drying, heat equivalent to the heat of wetting must be added to wood to remove adsorbed water. It has been estimated that the first few molecular layers attracted to the wood are attracted so strongly that the density of this water may be increased to 1.3 or even as high as 2.4 gm/cm^3 (24). As the moisture content of wood is increased, the heat of adsorption decreases until it becomes zero. This zero point is defined as the *fiber saturation point* (fsp). Wood can still take on water above the fsp until the void spaces such as the lumina of the cells become full of liquid water, called *free water*. The adsorbed water will be called *bound water* in this report. Addition of water to wood above fsp does not affect many of the properties of wood, but below the fsp many properties change with moisture content.

The fsp varies with temperature (23). The effect of temperature is to reduce the fsp. For example, when the relative vapor pressure (partial pressure of water vapor divided by pressure of the vapor at saturation for the stated temperature) is 1.0 and the temperature is 90 F, the fsp for Douglas fir is 28 per cent moisture content.[1] At 212 F in a steam atmosphere the fsp is 21.2 per cent. The heat of wetting for Douglas fir may be estimated from figure 11, appended, as plotted from data by Kramer (15). This curve is considered to give approximate maximum values for the heat of wetting; all other curves at temperatures higher than 212 F must lie below the curve of figure 11. The intersection of the curve with the absicissa at 21.2 percent moisture content is agreed upon by two investigators (23,24), but two investigators (8,23) appear to disaggree on the intersection of the curve with the ordinate when wood temperature is increased.

The moisture content of wood, when it is at moisture equilibrium with its surroundings, is defined as the <u>equilibrium moisture</u>

---

[1] Moisture content, in this report, is defined as the weight of moisture present in wood divided by the weight of wood substance when oven-dried.

content (emc). Figure 12, appended, shows this emc relationship for Douglas fir in a steam atmosphere at temperatures up to 400 F. Note that for the conditions of this experiment (400 F to 800 F at atmospheric pressure) the emc always will be less than 1 per cent.

Movement of water through wood is governed by the phenomena of diffusion and capillarity. To quote Stamm (23), "...diffusion may involve the movement of a gas or a vapor through or into the void structure, the movement of a bound liquid through or into the gel substance, or the movement of a solute through or into the solvent saturated solid. The movement of a liquid into the coarse capillary structure, on the other hand, is due to capillarity rather than the tendency to equalize concentration." Stamm goes on to note that the rate at which moisture diffuses through wood depends upon the form or state of the water, (i.e. bound water, free water), instantaneous moisture content at a particular place in the wood, moisture content gradient with respect to distance, and the particular paths through the wood available to the water. The problem is further complicated because wood drying is not a steady-state process. To describe the process by diffusion then results in a second order differential equation with continuously changing boundary conditions. Solution of the equation is complicated and accuracy depends upon the number of terms used (23). Since this study is not concerned primarily with the mechanism of moisture movement in wood, the principles will not be discussed further. For the purposes of this report, it is sufficient to say that moisture movement in wood is a complex, dynamic process which depends upon many factors not evaluated in this study.

It is important to establish the physical state of water which remains in the wood after drying. The quantity of heat absorbed by this moisture depends upon whether it exists as a liquid or as a gas or a mixture of the two. The following discussion attempts to show that it is reasonable to assume that this moisture exists as liquid water under pressure. In this study it will subsequently be indicated that wood temperatures above 212 F were usual during tests. In one test the wood temperature was 360 F when average moisture content was continually above fiber saturation. If the average moisture content was above fiber saturation, the outer surface of the wood probably was well below and the inside of the wood well above fsp since it is certain that a steep moisture gradient exists at these elevated temperatures. At temperatures above the saturation temperature (212 F), what is the state of water remaining in the wood? Is it held chemically? It seems unlikely that all remaining water in these tests could be held chemically, since free water exists in the cell cavities. Therefore, all but a small part of the water may be held in the wood as steam or liquid. That the water could be held as steam is not possible since a calculation shows that the volume of the steam at 360 F and atmospheric pressure would be about 500 times the void volume of the wood. The remaining possibility is that the unevaporated moisture exists as water under pressure in the wood. Steam pressure corresponding to a wood temperature of 440 F would be 367 psig. To see what average stress this pressure would induce in a cell wall in the wood, a hoop stress calculation was made. Assuming that the lumen has an average diameter of 28 microns and a cell wall is 3.5 microns thick (23) and that steam pressure in the lumen is 367 psig, hoop stress is calculated to be 1460 psi in the cell wall. Considering that the cell walls are wrapped with relatively strong fibrils that would tend to be in tension when the cell was under pressure, it may be that cells could withstand 1460 psi average tensile stress in the walls. Moreover, since a moisture gradient is present, free water may not exist in the outer fibers when the temperature is high. In this case the gross structure of the wood would tend to aid inner cells in resisting internal forces. Whatever the case, in this report it is assumed that the unevaporated water remaining in the wood exists as water under pressure.

Heat, moisture, wood, and fluid relations

The steam velocity in this work was measured using a sharp-edged orifice. The velocity was determined by the relationship (1):

$$W = 0.0997K\ Fa\ d^2\ Y_1\ (\gamma h_w)^{\frac{1}{2}},$$

where

$K = (C)\ (1 - \beta^4)^{-\frac{1}{2}}$, dimensionless,

C = discharge coefficient, dimensionless,

β = orifice to pipe diameter ratio, dimensionless,

Fa = area factor for the thermal expansion of the orifice, dimensionless,

d = orifice diameter, inches,

Y_1 = compressibility factor to allow for effects of expansion when a compressible fluid flows through an orifice, dimensionless,

γ = specific weight of steam, lb per cu ft,

h_w = pressure drop across orifice for flange taps in. of water at 68 F.

and W = steam flow, lb per sec.

A sample calculation of weight flow is shown in the appendix.

Since velocity was held constant in this study, mass flow varied for the three steam temperatures. Velocity was held constant so that test conditions would approximate those existing in commercial dryers. It has been estimated that velocity at the face of the veneer may be on the order of 10 feet per second in commercial dryers (26).

Reynolds number in the free stream at the test section was calculated by (16):

$$R = \frac{u_\infty r \gamma}{\mu} ,$$

where

R = Reynolds number, dimensionless,

u_∞ = velocity in the free stream, ft per sec,

r = hydraulic radius of the rectangular duct = (4) (duct area)/duct perimeter, ft,

γ = specific weight of steam, lb per cu ft, and μ = absolute viscosity, lb (force) sec per sq ft.

Reynolds number was 11,600 at 400 F, 7400 at 600 F, and 5200 at 800 F.

Calculation of a heat transfer coefficient is an object of this study. Convective heat transfer coefficients can be approximated from the following relation, provided flow in the boundary layer is laminar (16):

$$h = \frac{0.332}{L} k P_r^{\frac{1}{3}} \left(\frac{u_\infty \gamma}{\mu}\right)^{\frac{1}{2}} \int_{x_1}^{x_2} x^{-\frac{1}{2}} dx,$$

where

L = length of veneer sample, ft,

h = Convective heat transfer coefficient, Btu per hr, sq ft, F,

$Pr = (C_{ps}\mu)/k$, Prandtl number, dimensionless,

C_{ps} = specific heat of the steam, Btu/lb, F

k = thermal conductivity of the steam, Btu per hr ft F,

x = distance along the heat transfer surface from the leading edge, ft,

and other units have been defined previously.

Values calculated from this formula indicate that, in this study, the heat transfer coefficient may be approximately 2 Btu/sq ft, hr, F.

To show that the boundary layer of steam flowing over the wood surfaces is laminar, the critical distance from the leading edge of the wood to the zone of transition between laminar and turbulent flow in the boundary layer was calculated by (21):

$$x_c = (R_c \mu / u_{\infty} \gamma,$$

where

x_c = critical distance from leading edge of wood to transition zone, ft

R_c = estimated critical value of Reynolds number at the transition zone, dimensionless

and other terms have been defined.

This calculation yields a value indicating that transition occurs at 13.7 ft. Since the wood sample is but 6 inches long, it is shown that flow is laminar over the samples in this study.

Schlichting (21) shows that approximate boundary layer thickness may be calculated by

$$\delta^2 = \frac{25\,\nu x}{u_\infty} ,$$

where

δ = boundary layer thickness at distance x from leading edge of heat transfer surface, ft,

ν = kinematic viscosity, sq ft per sec,

and other terms have been defined.

Values from this formula indicate that the boundary layer was about 0.1 inches thick at the center of the wood surface in the samples in this study. At the leading edge of samples the boundary layer thickness was about 0.03 inches, calculated by the above formula.

Thus far, nothing has been said of mass transfer in drying of wood. When drying wood in air, mass transfer of steam from the wood to the air is proportional to the concentration gradient (4). In this study the drying fluid is steam and since water is being evaporated from the wood, pure phases are involved and no concentration gradient exists. In this case, mass transfer is governed by the rate at which heat is supplied to the liquid (16).

A heat balance on a wood sample in this experiment must evaluate the following heat fractions:

I. Input to wood and water in the wood:

1. Radiation from steel surfaces,
2. Radiation from the steam,
3. Conduction from the steel device holding the veneer,
4. Convection from the steam.

II. Distribution of input heat:

5. Heat to raise temperature of wood,
6. Heat to raise temperature of water remaining in wood,
7. Heat to raise temperature and evaporate water,
8. Heat of wetting.

Treating each of these fractions in order, formulas used to evaluate each were:

1. Radiation from steel to wood (10)--,

$$q = \sigma A_w F_\epsilon (T_s^4 - T_w^4)(1 - \alpha g),$$

where

q = net heat transferred, Btu per hr,

σ = Stefan - Boltzmann constant, Btu per sq ft, hr, T^4,

A_w = total surface area of wood, sq ft,

T_s = absolute temperature of the steel, degrees Rankine,

T_w = absolute temperature of the wood, degrees Rankine,

$$F_\epsilon = \frac{1}{\frac{1}{\epsilon_w} \; \frac{1}{\frac{A_s \epsilon_s}{A_w}} \; \frac{1}{\frac{A_s}{A_w}}}, \text{ dimensionless,}$$

ϵ_w = emissivity of wood, dimensionless,

α_g = absorptivity of the gas (steam), dimensionless

ϵ_s = emmissivity of steel, dimensionless,

and A_s = area of steel, sq ft.

The quantities ϵ_s and F_ϵ have been plotted as calculation aids in figures 13 and 14, appended. The factor (1 - α(g) is to account for the quantity of heat radiation that is absorbed by the steam as heat is radiated from the steel to the wood through the steam.

2. Radiation from steam to the wood (10)--

$$q = \sigma A_w \ F \ \left[\epsilon_g T_g^4 - \alpha_g T_w^4\right],$$

where

F = shape factor (10), dimensionless,

ϵ_g = emissivity of the steam at the steam temperature, dimensionless,

α_g = absorptivity of the gas at the wood temperature, dimensionless,

T_g = absolute temperature of the gas, degrees Rankine.

Other factors in the above equation have previously been explained.

3. Conduction from the steel veneer-holder --

A calculation was made of steady state conduction from the steel veneer holders by the relation,

$Q = k\theta A(t_2 - t_1)/b$,

Q = heat transferred, Btu,

k = conductivity of wood, Btu per hr, ft, F,

θ = time, hr,

A = cross-sectional area of wood, sq ft,

t_2 = temperature at holder, F,

t_1 = temperature at point 1 inch from holder, F,

and b = distance from holder, in.

This calculation showed that if steady state conditions had prevailed, heat transfer by conduction to a point near the holders would have been less than 0.24 Btu when total heat transferred otherwise was about 35 Btu. Because steady state conditions did not prevail, actual heat transferred by conduction was less than that indicated by the steady state equation. Conducted heat was considered insignificant in this study because the preceding calculation indicates that this quantity was less than 1 percent of heat transferred by other means.

4. Convection from the steam --

This was calculated as the difference between the total heat transferred to the wood, minus the radiated fractions.

5. Heat to raise temperature of wood --

$$Q = W_w C_{pw}(t_w - t_i),$$

where

Q = total heat transferred, Btu,

W_w = weight of wood, lb,

C_{pw} = specific heat of wood, Btu, per lb, F,

t_w = final temperature of the wood, F,

t_i = initial temperature of the wood, F.

The specific heat variation of wood from Dunlap (3) has been plotted in figure 15, appended.

6. Heat to raise temperature of water in wood --

This value was obtained directly from the steam tables (12), using the differences between enthalpies of water at initial and final saturation temperatures.

7. Heat to evaporate water --

This value was obtained directly from the steam tables by subtracting the enthalpy of the superheated vapor at the final wood temperature from that of the liquid at the initial wood temperature.

8. Heat of wetting --

The average heat of wetting for a given final moisture content (fmc) was determined from figure 11. The quantity of water evaporated in the interval from fiber saturation to fmc was determined from figure 16, appended, by taking the difference between values at the fsp and the desired fmc.

A final calculation should be discussed. When the total heat transferred to the wood by convection has been determined by the foregoing calculations, an average convective heat transfer coefficient can be calculated.

$$h = Q/A_w(t_g - t_w),$$

where h is the convective heat transfer coefficient tg is the temperature of the steam, F, and other terms have been defined.

Note that in calculations for radiation and for the convective heat transfer coefficient where t_w occurs, an average value of t_w was used over the time interval. This approximation was justified because the time intervals were short.

DESIGN OF EXPERIMENT

The design of this experiment is indicated by the sketch below. Sixty veneer samples 4" x 6" x 1/10" thick were cut from a single sheet of Douglas fir sapwood veneer. The veneer was carefully selected by appearance for uniformity of wood density and moisture content to eliminate excessive variation among samples. At three temperatures, each of four samples were dried at each time interval for a total of five time intervals. In this manner data from the second time interval, θ_2, traversed the paths of data from the first

Time	Temperature, F		
	400	600	800
θ_1	4	4	4
θ_2	4	4	4
θ_3	4	4	4
θ_4	4	4	4
θ_5	4	4	4

Figure 1. Design of experiment

interval and proceeded beyond by some additional interval. Differences between values for two overlapping intervals gave values for the incremental increase in heat values. This design was used because it appeared to be the only way that a continuous moisture-loss curve could be generated. If a method of periodic weighings of a single sample had been used to generate a moisture-loss curve, heat and moisture losses in the weighing interval would have nullified the experiment. For example, in a preliminary experiment with periodic weighings of a sample, total time to dry the sample was 11 minutes. A similar sample allowed to remain in the steam without periodic removal for weighing dried in six minutes.

APPARATUS

A schematic sketch of the test apparatus appears in figure 2. With respect to physical size, much of the equipment was for the purpose of superheating steam. Air, supplied to the superheater tube by a positive displacement blower, was heated by means of a propane burner operating in an expanded section of the duct. The hot gas was passed countercurrent to steam flowing inside a two inch pipe within the four inch superheater tube. The steam temperature entering the superheater was about 300 F, and entering gas temperature was about 1300 F when the steam temperature was 800 F.

Steam leaving the superheater was metered through an ASME-approved orifice equipped with flange taps. The orifice diameter was 1.000 inch at 68 F. The orifice pressure drop was measured by a water manometer, as was static pressure upstream of the orifice. The layout of orifice piping was as recommended by Spink (22). Large diameter copper manometer tubes were sloped and trapped to facilitate drainage of condensate. A barometer, not shown, was used to indicate atmospheric pressure. All manometric pressures were corrected to 68F before observations were entered into calculations. Temperatures were recorded at 24-second intervals

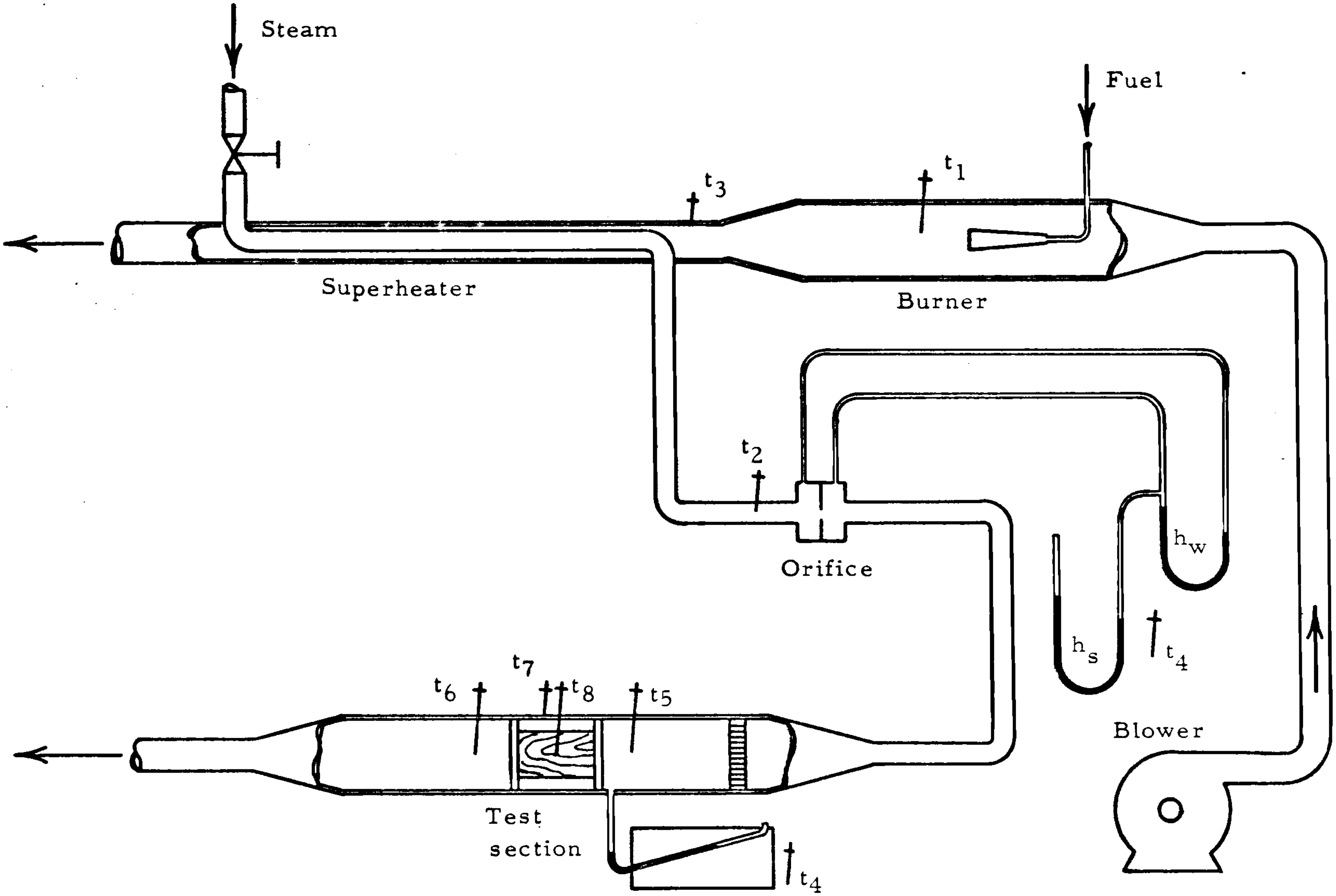

Figure 2. Test apparatus

(12 points x 2 seconds per point) during tests by a 12-point General Electric temperature recorder using chromel-alumel thermocouples.

Downstream from the orifice, steam entered an expander section, the sides of which were sloped four degrees to allow expansion into the 5" x 6" duct without separation or excessive turbulence. A straightener with a $\frac{1}{2}$-inch grid was installed upstream of the test section to level the velocity profile as recommended by Spink (22). A draft gage indicated that static pressure at the test station was less than 0.1 inch of water gage in all tests.

Slots to hold veneer samples during tests were oriented vertically in the drying duct with a clearance of 1 inch above and below the four-inch sample.

Temperature measurements t_5 and t_6 at the test station were just upstream and downstream of the veneer with bare thermocouples partially shielded to minimize radiation interference. Duct wall temperature for use in radiation calculations was indicated by temperature t_7. All ductwork and pipes were encased in a minimum thickness of four inches of glass wool. Sections hotter than about 800 F were first wrapped with wire mesh and heavy asbestos fiber tape before glass wool was applied.

Figure 3 is a view of the superheater, orifice piping, burner, and blower before the test duct and insulation were installed. Design

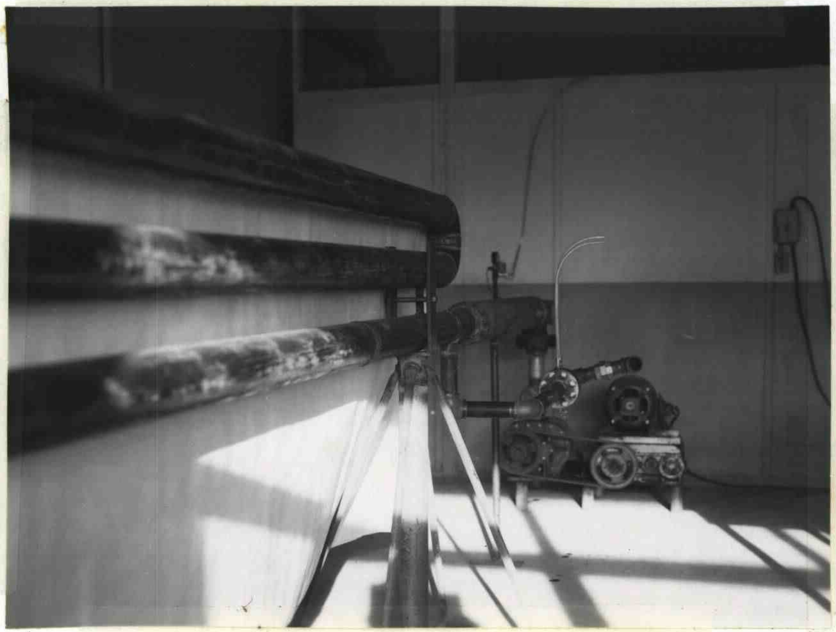

Figure 3. Superheater, burner, blower, and orifice piping

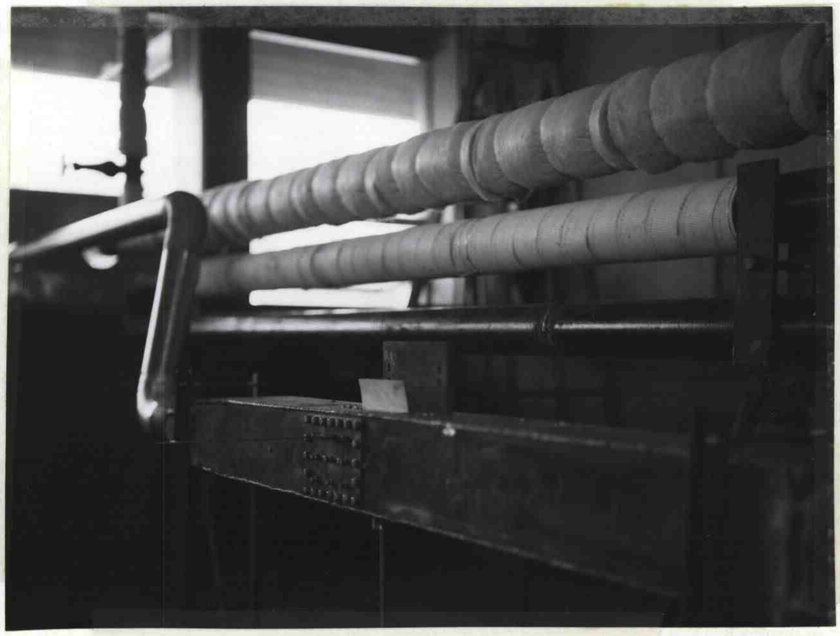

Figure 4. Test station

length for the superheater was 40 feet. Three 13-foot runs with 180 degree bends were used to shorten the length of the installation. The design heat rate, including losses, for the superheater was 43,000 Btu/hr when the steam temperature was 800 F and the gas entering the superheater was at 1200 F. Another view of the apparatus looking in the opposite direction (figure 4) shows the superheater partially insulated and the test duct in place. A piece of veneer is shown protruding from the test slot in the center of the picture. In practice the veneer was pushed down into the slot and the small vertical door was closed. A sample-ejector rod extends downward under the duct. A plate bored at nine stations and bolted over an opening in the duct may be seen on the left side of the duct. The intent was to use this plate to position a pitot tube (see photo) for measuring velocity near the face of a sample. The calculated manometer readings for the pitot tube varied from about 0.005 inches of water (400 F steam temperature) to 0.009 inches of water (800 F) to maintain a velocity of 10 feet per second. Attempts to measure these minute pressures failed when reproducible results could not be obtained. The fault was traced to inability to zero the micromanometer with a tolerance less than ± 0.005 inch.

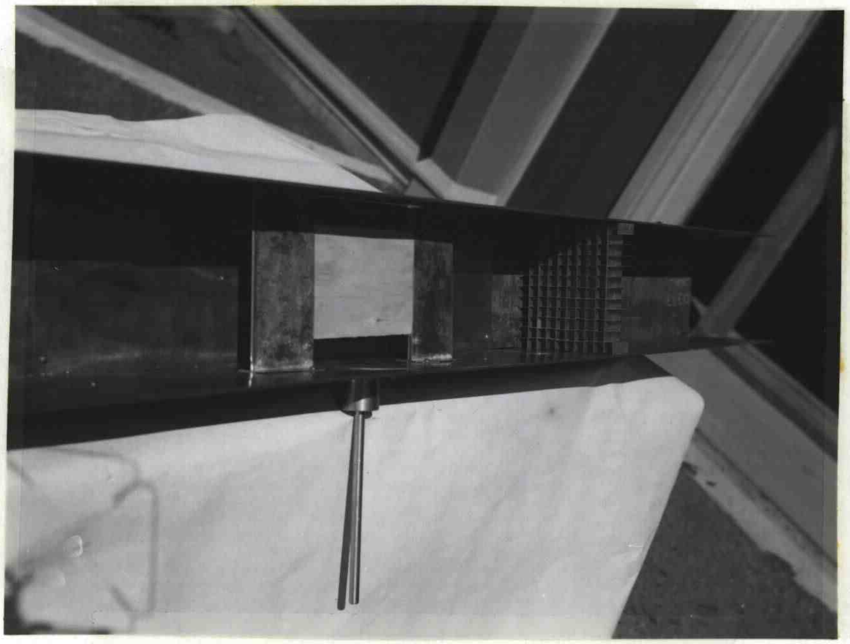

Figure 5. Veneer sample in place in duct

A view inside the test duct before assembly (figure 5) shows the knife-like, slotted, veneer holders oriented parallel to the steam flow. A veneer sample is shown in place and the sample-ejector plate and rod appear beneath the sample. Upstream, the flow straightener has been installed. The duct was lined with polished stainless steel to reduce its emissivity.

Because an accurate determination of wood temperature is all-important, the technique for its measurement will be described. A hole was bored at the center area of each wood sample. The diameter of this hole was such that a 20-gage thermocouple could be forced into it with difficulty. The hole was slant-bored so that all of the fused part of the thermocouple was embedded. After some initial failures with copper-constantan wire and a millivolt indicator, reproducible results were obtained using a small chromel-alumel thermocouple with leads almost completely encased in ceramic insulators where wires were exposed to the hot steam.

PROCEDURE

Preliminary tests

Temperature-measurement instruments and the barometer were calibrated before use. Initial runs were made to establish pressure and temperature distributions within the system when mass flow at the orifice was such as to produce an average velocity of 10 ft per second at the test section. Initial approximate calculations of h_w at the orifice were refined once the static pressure and orifice temperature had been established.

Finally, samples similar to test samples were dried in the system at the three test temperatures to obtain advance predictions of the drying rates which might be expected.

Heat balance tests

Precautions were taken to insure that samples did not lose or gain moisture except in the drying system. From the time samples were peeled at the veneer lathe in a plywood plant until they were inserted into the drying duct, they were either stored in plastic, aluminum foil, or maintained continuously wet except for a brief interval when they were drilled or were inserted in the steam duct.

Tests always began by recording all temperatures and pressures (plus barometric pressure) indicated in figure 2. Samples for one complete temperature run were drilled and placed in individual plastic bags. A new weight of each wet sample was determined by first measuring the tare weight of a square of aluminum foil, then removing the sample from its plastic bag and wrapping it in foil. Foil was used because heat from hot samples from the steam duct would not melt it.

Test samples were quickly inserted into the drying duct after foil wrapping was removed, a thermocouple inserted into the wood, and the initial wood temperature was recorded. A common initial drying interval (θ_1) was 30 seconds with the wood temperature being recorded every six to ten seconds. Since wood temperature and time were the only variables at the test station, it sufficed to read other pressures and temperatures once per sample. At the proper instant the wood sample was ejected from the drying duct, the thermocouple was removed, the sample was rewrapped in the same piece of foil used previously, and the sample was reweighed. The final act was to place the sample in an oven set at 220 F for subsequent determination of oven-dry weight. This procedure was repeated until all 60 samples had been processed.

RESULTS

Wood temperature

A plot of wood temperature with time is shown in figure 6. The slope of the 400 F plot appears to be substantially less than that of the 600 F and 800 F plots. This difference does not seem unreasonable, however, when one considers that the limit of wood temperature in this run is 400 F. Limits of the other two plots are well beyond the upper range of this graph. The lower limit of the temperature curves is not shown in figure 6. In all cases, the indicated wood temperature rose from 80 F to about 208 F in less than about three seconds.

Drying rates

Drying curves (figure 7) show that the veneer dried to 5 per cent moisture content in approximately 6, 3, and 2 minutes for steam temperatures of 400 F, 600 F, and 800 F respectively. The two lower time values are extrapolated as shown by dotted curves in figure 7.

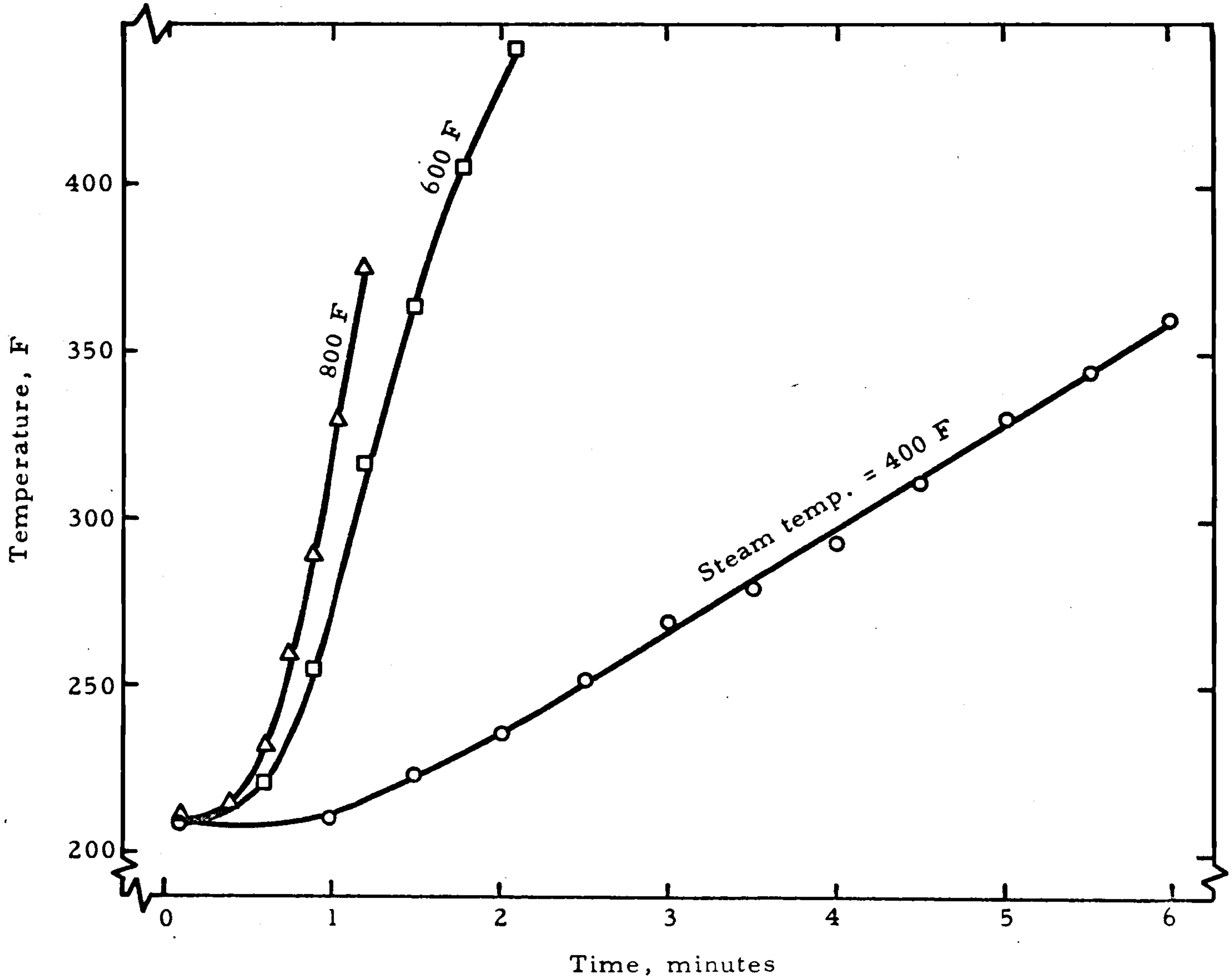

Figure 6. Variation of wood temperature with time at three steam temperatures

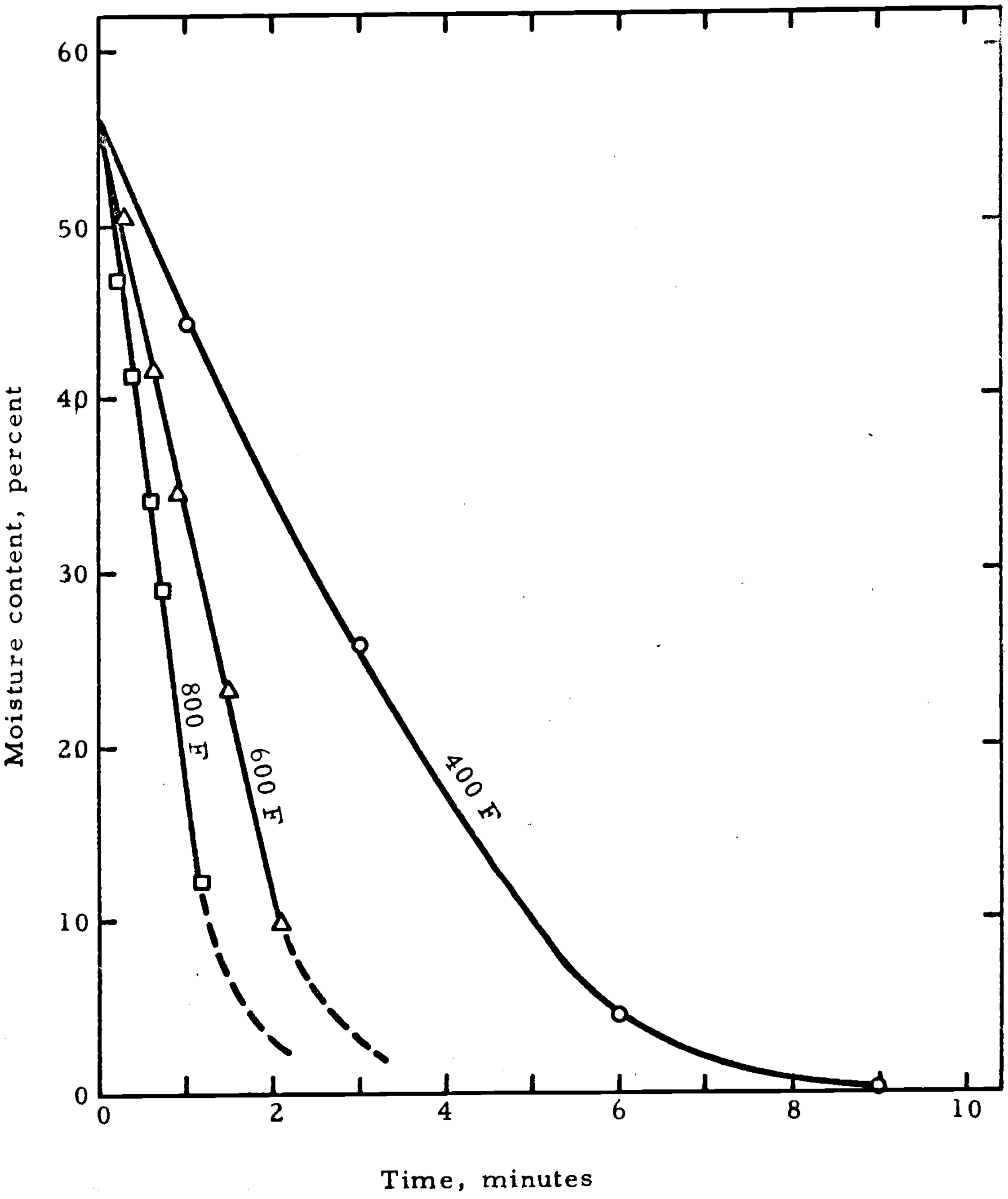

Figure 7. Drying times of one-tenth inch thick veneer at three steam temperatures

Radiant heat transfer

Calculation methods for various heat fractions have been explained in a previous section. Results of radiation heat transfer calculations have been plotted as instantaneous heat rates for various wood temperatures in figures 17 through 22, appended. Average values of radiant fractions of heat for the appropriate wood temperature within a given time interval were determined from these curves. These instantaneous average values multiplied by the time interval gave the total radiant transfer of heat for the interval. Results of these calculations and summations of total heat transferred to the wood and moisture are shown in figures 8, 9, and 10. Radiation heat transfer varied from about 28 per cent of the total heat at 400 F to 34 per cent at 600 F, and 50 per cent at 800 F.

Convective heat transfer

At each temperature (400, 600, 800 F) the initial test run at highest moisture content showed the greatest heat transfer. This no doubt was because steam condensed upon the sample when it was inserted in the steam flow, giving up its heat of vaporization in large part to the wood sample. Because the initial time (θ_1) always was

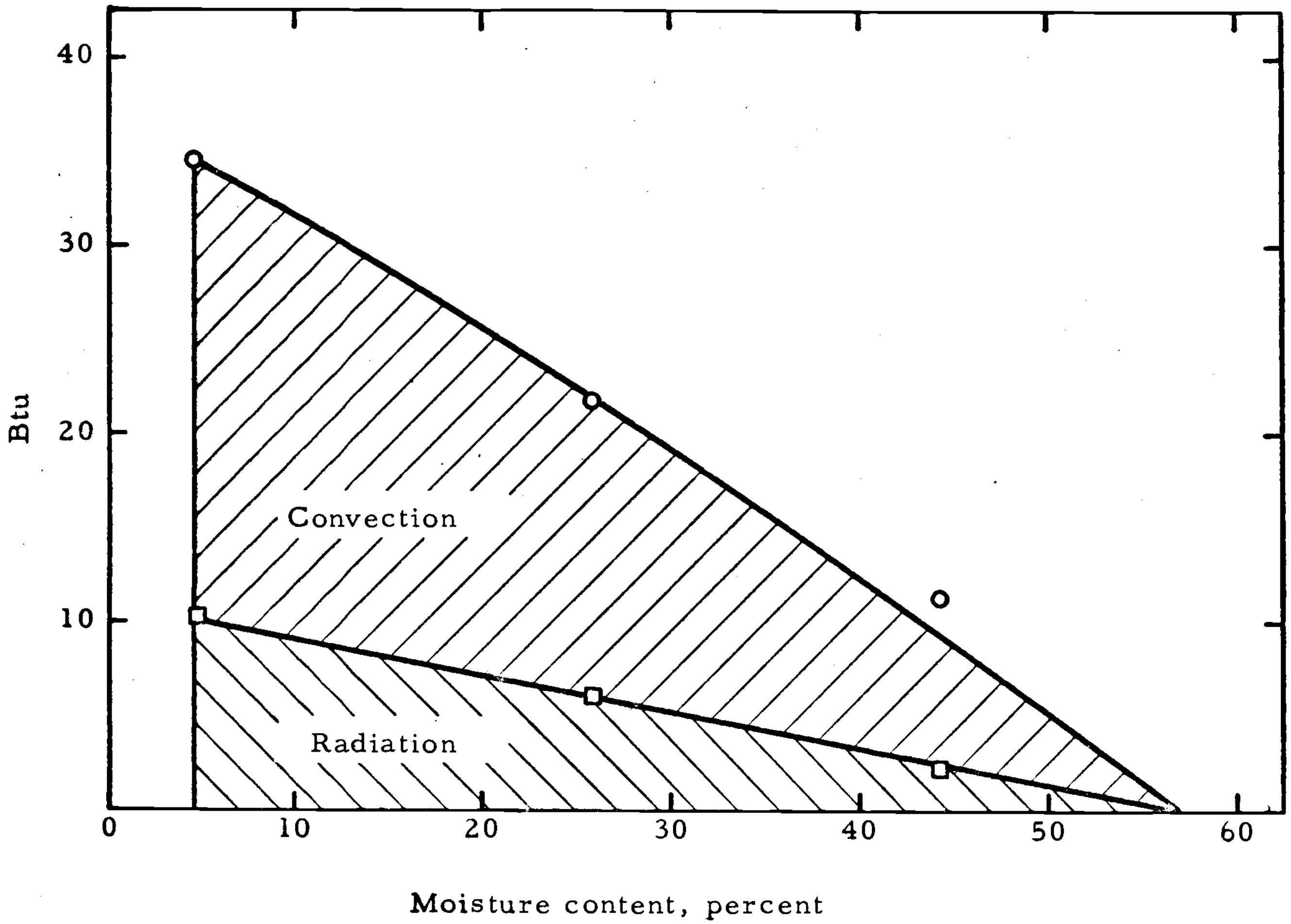

Figure 8. Total and radiated heat absorbed by wood and moisture when steam temperature was 400 F.

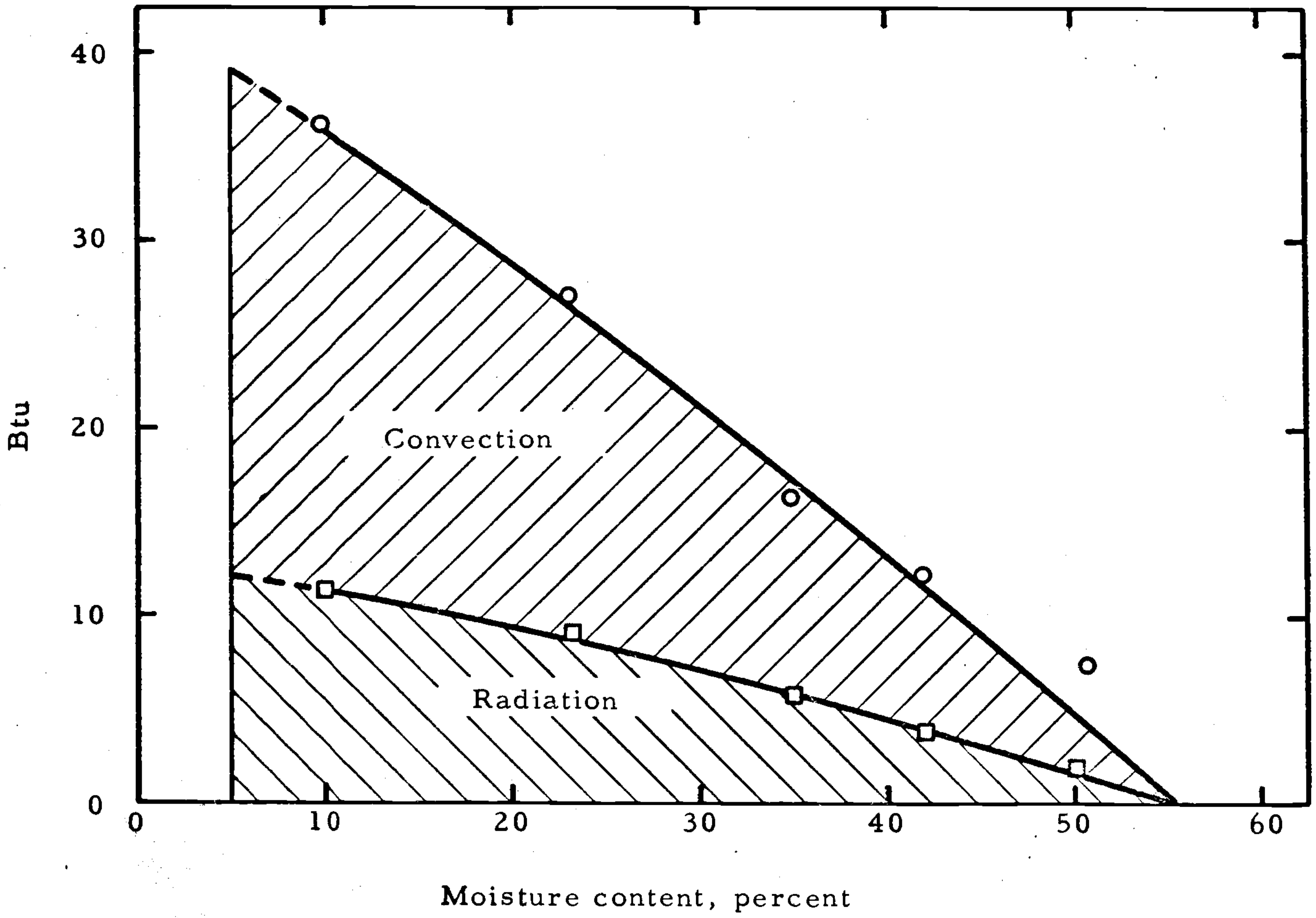

Figure 9. Total and radiated heat absorbed by wood and moisture when steam temperature was 600 F.

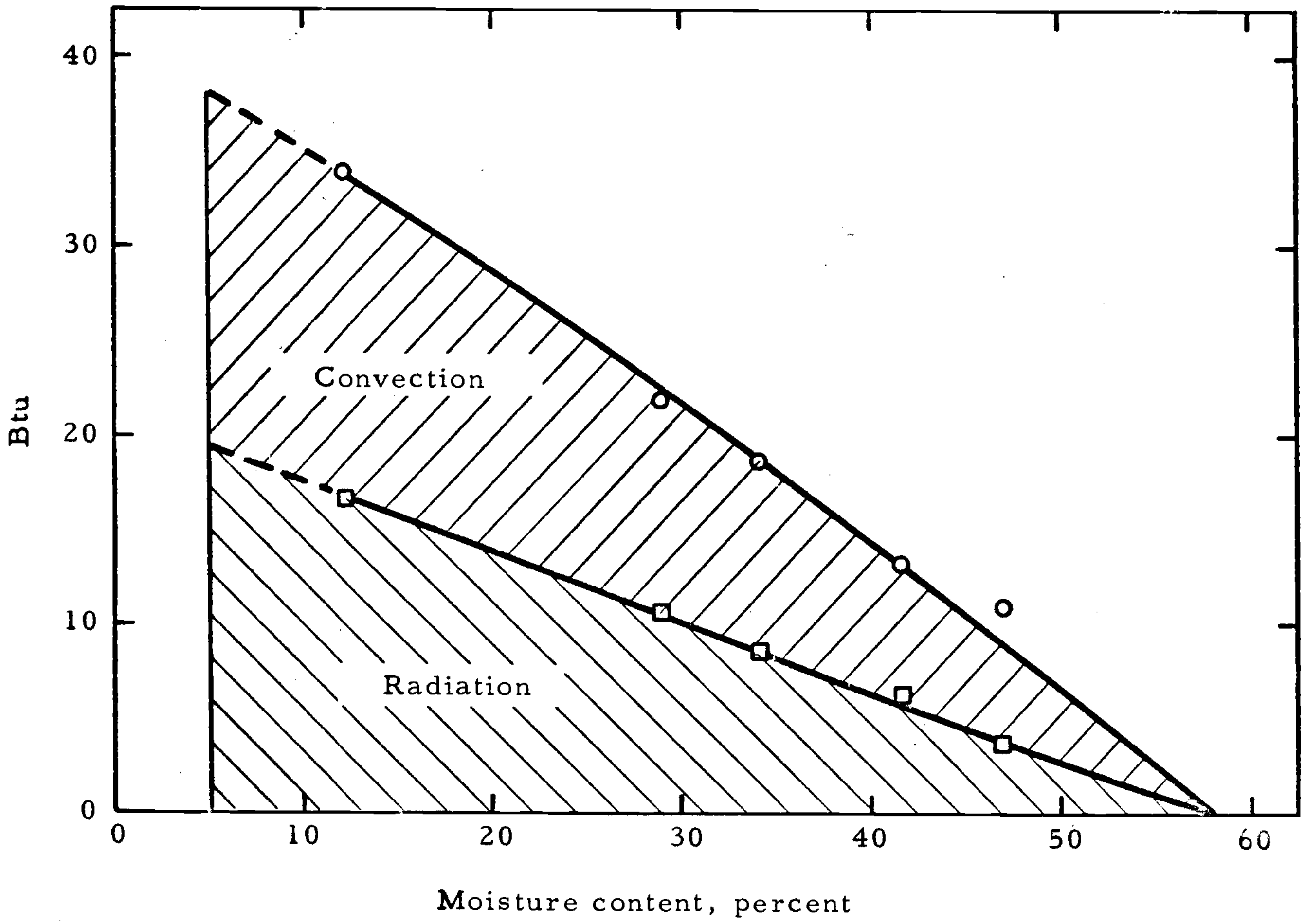

Figure 10. Total and radiated heat absorbed by wood and moisture when steam temperature was 800 F.

the shortest, this heat of condensation was large in proportion to total heat transferred. Subsequent longer runs tended to average the high initial heat transfer and result in a smooth curve.

Heat transfer fractions were scaled from figures 8, 9, and 10 for calculation of convective heat transfer coefficients shown in table 1.

Table I. Calculated coefficients of convective heat transfer.

Run temp., F	M. C. Range, per cent	h, Btu/hr, sq ft, F
400	57-44	6.7
	44-26	5.5
	26-5	4.5
600	55-51	4.8
	51-42	7.5
	42-35	6.1
	35-23	6.7
	23-10	10.0
800	58-47	6.4
	47-42	5.0
	42-34	5.1
	34-39	4.7
	29-12	4.5

CONCLUSIONS

Convective heat transfer coefficients in table 1 vary from 4.5 to 10.0. The higher value appears to be excessively so, but in careful reexamination of test data and calculations no error can be found. Examination of the individual values within temperatures reveals no consistent variation in h with varying moisture content. Values of h ranged from a low of 4.5 to 6.7 at 400 F, 4.8 to 10.0 at 600 F, and 4.5 to 6.4 at 800 F.

Heat transfer coefficients calculated from the theoretical relationship on page 11 were 1.6, 1.6, and 1.7 at 400 F, 600 F, and 800 F, respectively. Test values were higher than the values calculated by the theoretical relationship by about 3 to 6 times. It seems logical that these increases of the actual over the theoretical heat transfer coefficient can be attributed to mass transfer from the wood surface. The theoretical relationship does not provide for mass transfer. While it appears at first thought that mass transfer would increase the thickness of the boundary layer and reduce the coefficient, a conflicting effect is that the moisture evaporating to steam on the wood surface may cause a more agitated boundary layer than is assumed in the derivation of the theoretical equation. Turbulence in the boundary layer will tend to increase the heat transfer coefficient. To support the contention that evaporation may cause considerable turbulence in the boundary layer, a calculation shows that water at 212 F undergoes a sixteen-hundredfold increase in volume when expanding to steam at 212 F.

In another study (6) on ignition of wood dowels in still air, a convective coefficient of heat transfer was found to be 2.2 Btu/hr, sq ft, F. Since forced convection was used in this veneer study it is to be expected that the calculated coefficient would be higher than that for wood dowels in still air.

At the outset of this study it was not expected that evaporation from the exterior veneer surfaces would be controlled by the rate at which moisture moved from the interior of the veneer to the exterior surfaces. Observation of high-speed movies of the veneer cutting process indicate that on a microscopic scale the wood is cut, torn, and crushed by the lathe nosebar and knife. It would seem that many short paths for escape of water from the wood would be created by this crushing action. Apparently this was not necessarily the case because the wood temperature rose above 212 F in all tests. If ample moisture always had been available to the surface of the wood, wood temperature would have remained at 212 F. Therefore it is concluded that drying rate was regulated mainly by rate at which moisture migrated to the wood surface.

A final conclusion is that it is possible to dry veneers at temperatures used in this study, but other factors should be investigated such as gluability, strength of veneers, and moisture variation within large sheets. It comes to mind that perhaps in practice it would be advisable to stage veneer dryers so that steam at the highest temperature (800 F, for example) passed over the wettest veneer, and steam at lower temperature be employed as a drying medium when veneer moisture content was low. In this manner wood temperature would be kept low and wetter areas would dry without danger of charring dry areas in the veneer sheet.

To reduce the scope of this study so that work could be comleted within a reasonable time, the original list of variables was narrowed considerably. The main variables from the original list were:

1. moisture content,
2. direction of steam flow with respect to wood-grain direction,
3. mode of heat transfer,
4. wood species,
5. sapwood or heartwood,

6. wood thickness,
7. temperature,
8. angle of gas impingement on wood,
9. drying medium (steam, air, other),

and 10. gas velocity.

Of these variables, all but moisture content and temperature were fixed in this study. If this study were to be continued by others, it is recommended that gas velocity and initial moisture content be given first consideration for inclusion as variables. Several thesis projects could be conducted with this apparatus by selecting gas velocities and initial moisture contents different from those used in these tests.

BIBLIOGRAPHY

1. American Society of Mechanical Engineers. Research Committee. Fluid meters; their theory and application. 5th ed. New York, 1959. 203 p.

2. Corder, Stanley E.. Ventilating veneer dryers. Forest Products Journal 31:449-453. Oct. 1963.

3. Dunlap, Frederick. The specific heat of wood. Washington, 1912. 28 p. (U. S. Forest Service. Bulletin no. 110)

4. Eckert, E. R. G. Heat and mass transfer. 2d ed. New York, McGraw-Hill Book Company, 1959. 530 p.

5. Fleischer, Herbert O. Drying rates of thin sections of wood at high temperatures. New Haven, Yale University, 1953. 86 p. (Yale University. School of Forestry. Bulletin no. 59)

6. Galligan, William L. et al. Some studies on the combustion of small wooden dowels. Pullman, Washington, 1965. 111 p. (Washington State University. Technical Extension Service. Bulletin no. 294)

7. Hawley, L. F. Wood-liquid relations. Washington, U. S. Department of Agriculture, 1931. 34 p. (U. S. Department of Agriculture. Technical Bulletin no. 248)

8. Hearmon, R. F. S. and J. N. Burcham. The specific heat and heat of wetting of wood. Chemistry and Industry, 1956, p. 807-808.

9. Hottel, H. C. Radiant heat transmission. Mechanical Engineering 52:699-704. July 1930.

10. Hsu, Shao Ti. Engineering heat transfer. Princeton, New Jersey, D. Van Nostrand, 1963. 613 p.

11. Kauman, W. G. Equilibrium moisture content relations and drying control in superheated steam drying. Forest Products Journal 6:328-332. 1956.

12. Keenan, Joseph H. and Frederick G. Keyes. Thermodynamic properties of steam. New York, Wiley, 1947. 89 p.

13. Kelsey, K. E. and L. N. Clarke. Effect of temperature and initial moisture content on the heat of wetting of wood. Nature 176:83. 1955.

14. Kelsey, K. E. and L. N. Clarke. The heat of sorption of water by wood. Australian Journal of Applied Science 7:160-175. 1956.

15. Krahmer, R. L. Calorimetric measurement of heat of wetting of wood: unpublished report of wood physics experiment. Syracuse, State University of New York, College of Forestry, November 30, 1961.

16. Kreith, Frank. Principles of heat transfer. Scranton, Pennsylvania, International Textbook Company, 1963. 553 p.

17. Li, Jerome C. R. Introduction to statistical inference. Ann Arbor, Michigan, Edwards Brothers, 1957. 553 p.

18. McNaughton, G. C. Ignition and charring temperatures of wood. Madison, Wisconsin, 1944. 4 p. (U. S. Department of Agriculture. Mimeo. no. R 1464)

19. Milligan, Frederick H. and Raymond D. Davies. High speed drying of western softwoods for exterior plywood. Forest Products Journal 13:23-29. Jan. 1963.

20. Runstadler, P. W., S. J. Kline and W. C. Reynolds. An experimental investigation of the flow structure of the turbulent boundary layer. Stanford, California, Stanford University, Department of Mechanical Engineering, 1963. 307 p.

21. Schlichting, Dr. Herman. Boundary layer theory. 4th ed. New York, McGraw-Hill Book, 1960. 647 p.

22. Spink, L. K. Principles and practice of flow meter engineering. 8th ed. Norwood, Mass., The Plimpton Press, 1958. 549 p.

23. Stamm, A. J. Wood and cellulose science. New York, Ronald Press Company, 1964. 549 p.

24. Tieman, Harry Donald. Wood technology. 3rd ed. New York, Pitman Publishing Corporation, 1951. 396 p.

25. U. S. Department of Agriculture. Forest Products Laboratory. Wood handbook. Washington, 1955. 528 p. (Agriculture Handbook no. 72)

26. Villiere, A. The drying of veneers in the plywood industry. Bois et Forets des Tropiques 96:27-49. 1964.

APPENDIX

APPENDIX

Sample calculations

The formulas in this section were introduced and explained in the General Considerations section of this report.

1. Average velocity of the steam at the test station when test temperature is 400 F was,

$W = 0.0997\ K\ Fa\ d^2\ Y_1\ (\gamma h_w)^{\frac{1}{2}}$, lb per sec (1)

$K = 0.6253$, from tables in (1)

$Fa = 1.005$, from curves in (1)

$d^2 = 1$ sq in.

$Y_1 = 0.9747$, from curves in (1)

$\gamma = 0.0294$ lb per cu ft

$h_w = 33$ in. of water.

The constant comes from,

$$0.0997 = \frac{\pi}{4}\ \frac{1}{144}\left[\frac{(2)\ (32.174)\ (62.316)\ (144)}{1728}\right]^{\frac{1}{2}}$$

which is exactly the value as derived in the reference (1).

For 435 F orifice temperature,

$$W = (0.0997)\ (0.6253)\ (1.005)\ (1)\ (0.9747)\left[(0.0294)\ (33)\right]^{\frac{1}{2}}$$

$$= 0.0602 \text{ lb per sec.}$$

At the test station, temperature is lower than orifice temperature. Volume flow and velocity must be evaluated at the lower temperature of 400 F.

$$V = W/\gamma A_D$$

where V = velocity, ft per sec,

W = steam mass flow, lb per sec,

γ = steam density, lb per cu ft,

and A_D = area of duct, sq ft,

$$V_{400} = (0.0602)/(0.0288)(0.2056)$$

$$= 10.16 \text{ ft per sec.}$$

By similar calculations,

V_{600} = 10.34 ft per sec,

and V_{800} = 10.06 ft per sec.

2\. Reynolds number at test station at 400 F was,

$$R_{400} = \frac{u_\infty r \gamma}{\mu} = \frac{\left[(10)(0.454)(0.0288)\right]}{1.130 \times 10^{-5}}$$

$$= 11{,}600.$$

By the same formula,

R_{600} = 7400,

and R_{800} = 5200

3\. Estimation of the convective heat transfer coefficient was by the theoretical relationship,

$$h_{400} = \frac{0.332}{L}\, k\, P_r^{\frac{1}{3}} \left(\frac{u_\infty \gamma}{\mu}\right)^{\frac{1}{2}} \int_{x_1}^{x_2} x^{-\frac{1}{2}}\, dx,$$

$$\frac{(2)(0.332)(0.020)(0.94)^{\frac{1}{3}}}{(5.5)/12} \left[\frac{(10)(0.0288)}{1.130 \times 10^{-5}}\right]^{\frac{1}{2}}$$

$$\left[2\, x^{\frac{1}{2}}\right]_{0.229}^{0.688} ,$$

$$= 1.6 \text{ Btu/sq ft, hr, F.}$$

Other coefficients were,

$$h_{600} = 1.6,$$

and $h_{800} = 1.7.$

4. Approximate boundary layer thickness at mid-area of wood sample was,

$$\delta_{400} = \left[(25\, \nu x)/u_\infty\right]^{\frac{1}{2}} ,$$

$$= \left[(25)(3.95 \times 10^{-4})(0.50)/(10)(144)\right]^{\frac{1}{2}},$$

$$= 0.094 \text{ inches},$$

and $\delta_{600} = 0.117$ inches,

and $\delta_{800} = 0.139$ inches.

5. Radiation from steel to wood when steam was at 400 F was,

$$q = \sigma A_w F_\epsilon (T_s^4 - T_w^4)(1 - \alpha_g).$$

Values of F_ϵ were calculated from,

$$F = \frac{1}{\frac{1}{\epsilon_w} + \frac{1}{\frac{A_s}{A_s}\epsilon_s} - \frac{1}{\frac{A_s}{A_w}}} ,$$

and plotted in figure 14 for various steel temperatures. For example, at a steel temperature of 400 F with ϵ_s = 0.093 (taken from figure 13),

$$F = \frac{1}{\frac{1}{0.9} + \frac{1}{\left(\frac{9.2}{0.313}\right)0.093} - \frac{1}{\left(\frac{9.2}{0.313}\right)}} = 0.697.$$

Then, for a constant steel temperature of 368 F when steam temperature was 400 F, F_ϵ was read from figure 14 and radiation heat rate was calculated for various wood temperatures. Results of these calculations were plotted in figure 17. A sample calculation of radiation heat rate is,

$$q = (0.1714 \times 10^{-8})(0.313)(0.692)\left[(828)^4 - (675)^4\right](1-0.290),$$

$$q = 69.14 \text{ Btu/hr when wood temperature is 215 F.}$$

To determine total heat, Q, radiated to wood from steel at the average wood temperature for the interval, q was multiplied by time for the interval,

$$Q = q\,\theta \text{ Btu}.$$

Similar calculations were made to plot figures 18 and 19.

6. Radiation from steam to wood was calculated from the formula below for various wood temperatures and plotted in figures 20, 21, and 22,

$$q = \sigma A_w \; F \left[\epsilon_g \; T^4 - \alpha_g \; T_w^4 \right] .$$

For a steam temperature of 400 F and a wood temperature of 200 F the following result is obtained,

$$q = (0.1714 \times 10^{-8})(0.313)(1) \left[(0.290)(860)^4 - (0.305)(660)^4 \right] ,$$

$= 54.03$ Btu per hr (α_g was averaged over the range of wood temperature).

7. Heat to raise temperature of the wood,

$$Q = W_w \; C_{pw} \; (t_w - t_i).$$

For the time interval θ_1 at $t_g = 400$ F,

$$Q = (0.0484)(0.340)(215 - 80) = 2.17 \text{ Btu}.$$

8. Heat to raise temperature of water remaining in wood,

$$Q = W_w \; (h_{f2} - h_{f1}) ,$$

where h_{f1} and h_{f2} = enthalpy of saturated water at t_i and t_w, respectively.

At 400 F and θ_1 time interval,

$Q = (0.0222)(180 - 48) = 2.93$ Btu.

9. Heat to evaporate water,

$Q = W_w(h_{g2} - h_{f1})$,

where h_{g2} = enthalpy of steam at atmospheric pressure and temperature t_w.

At 400 F and θ_1 time interval,

$Q = (0.00575)(1102.4) = 6.339$ Btu.

10. Total convective heat transfer was the sum of heat value calculated in items 7, 8, and 9, above, minus the radiated heat values in items 5 and 6.

11. Convective heat transfer coefficient was,

$h = \Sigma Q / A_w(t_g - t_w)$.

The ΣQ values have been plotted in figures 8, 9, and 10. Q values used in the formula above were read from these curves. For example, for the θ_1 interval when $t_g = 400$ F and fmc = 44.3 percent,

$h = (6.7)/(0.313)(400 - 208)(0.0167)$,

$= 6.7$ Btu per hr, sq ft, F.

Calculation aids

Figures 11 through 22 used as calculation aids appear on the following pages.

Test data

Tabulations of test data appear on pages 65, 66, and 67.

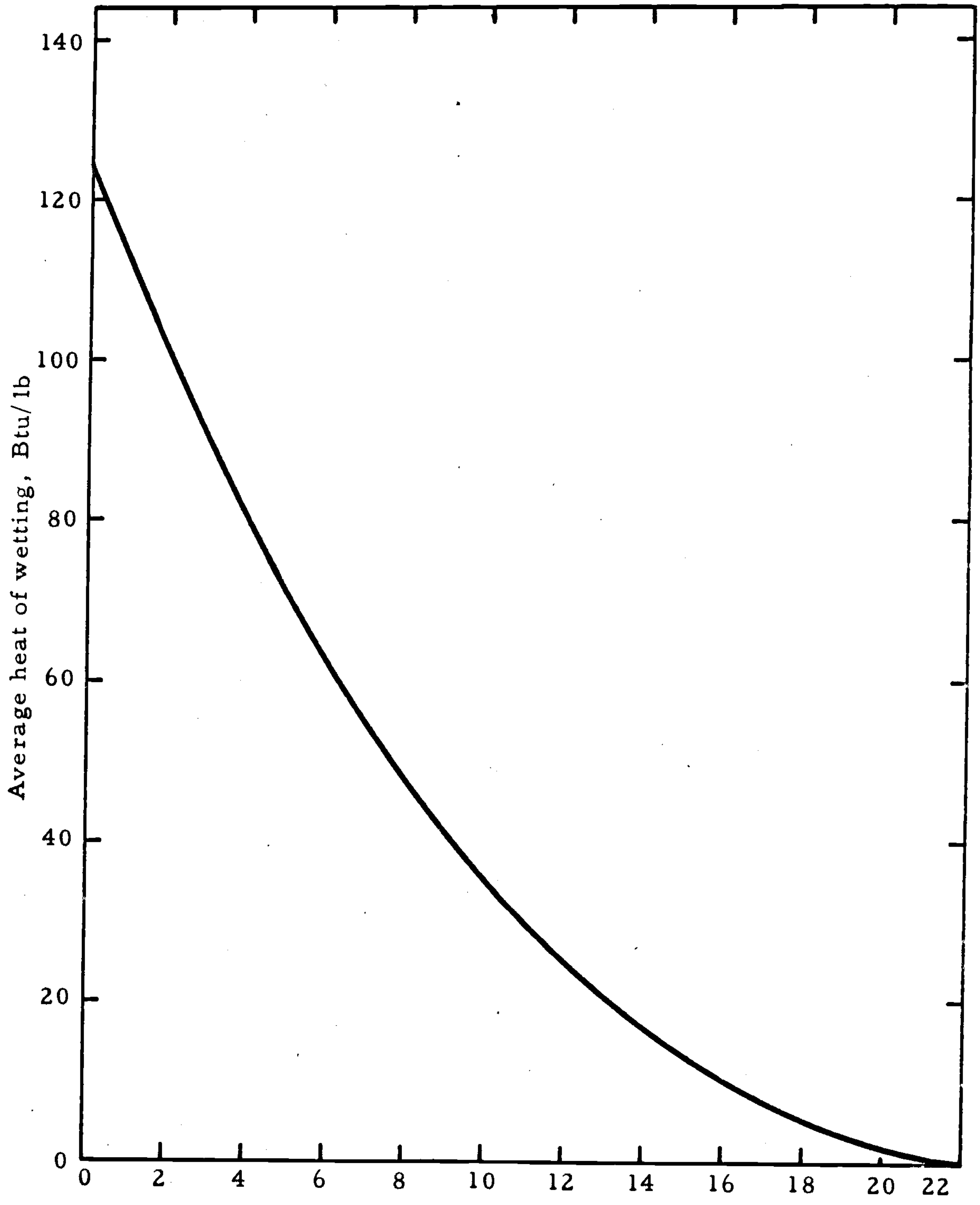

Figure 11. Heat of wetting for Douglas fir wood at 212 F and atmospheric pressure estimated from data on sitka spruce (15).

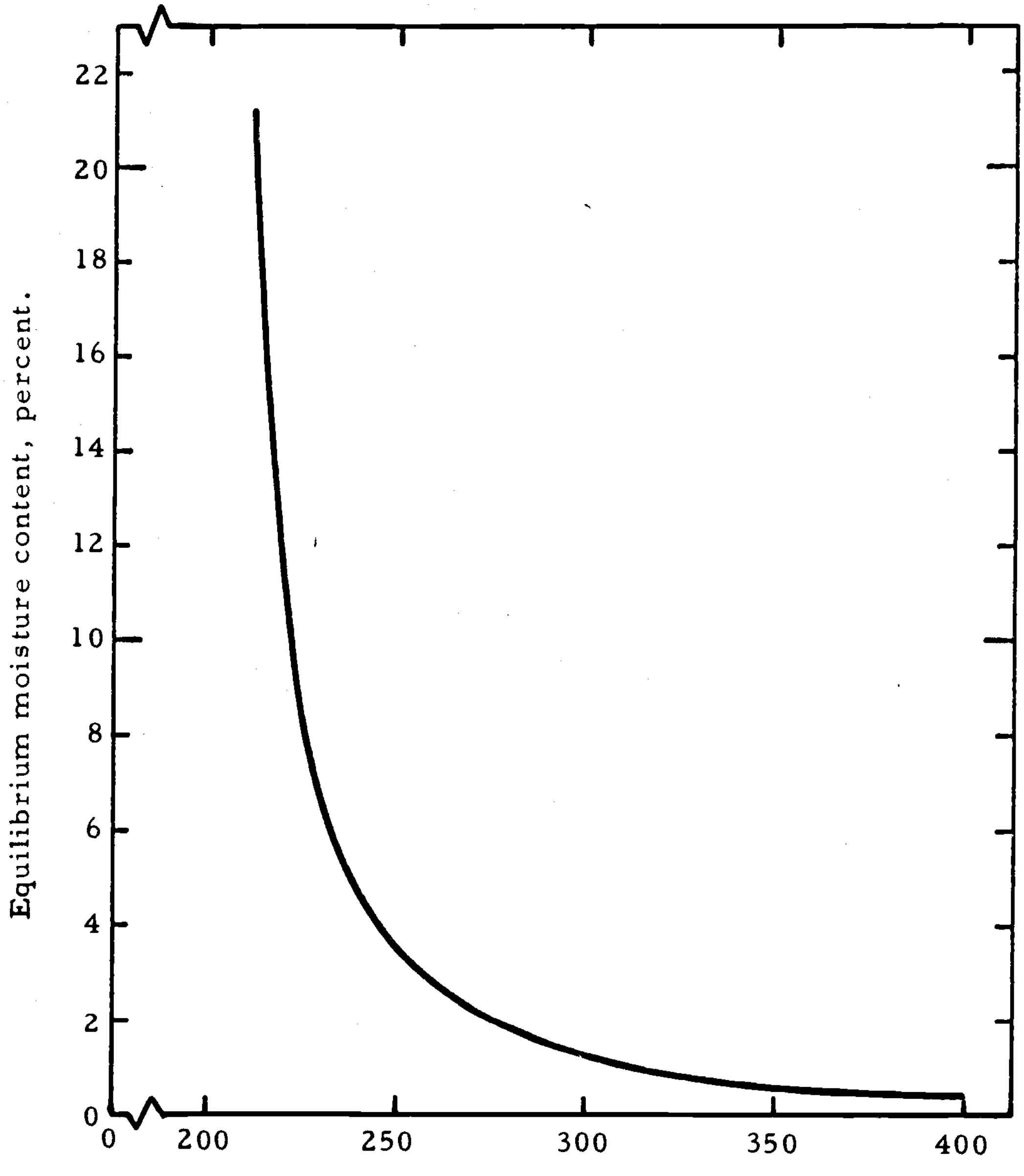

Figure 12. Equilibrium moisture content of Douglas fir at atmospheric pressure, data from Kauman (11).

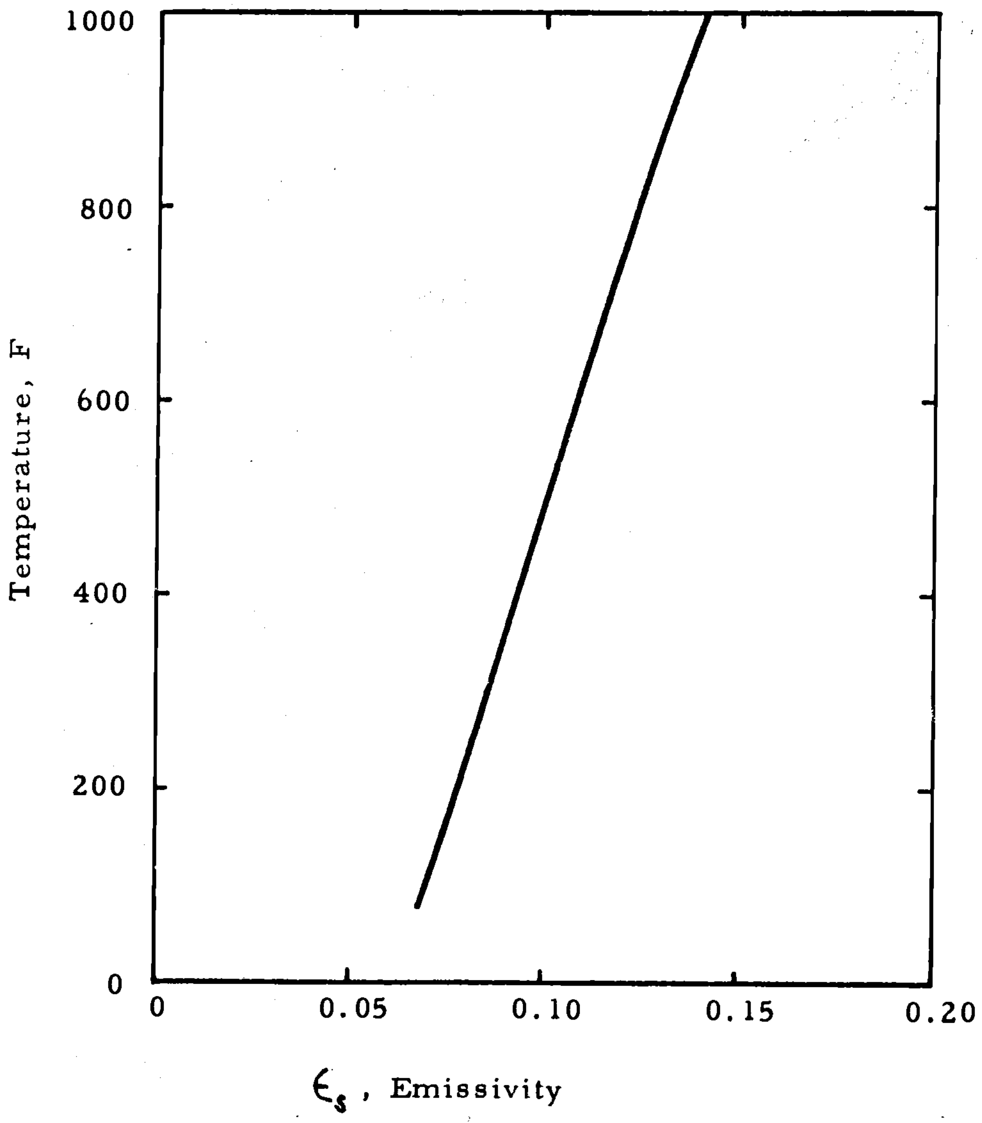

Figure 13. Emissivity of polished steel, from Hsu (10).

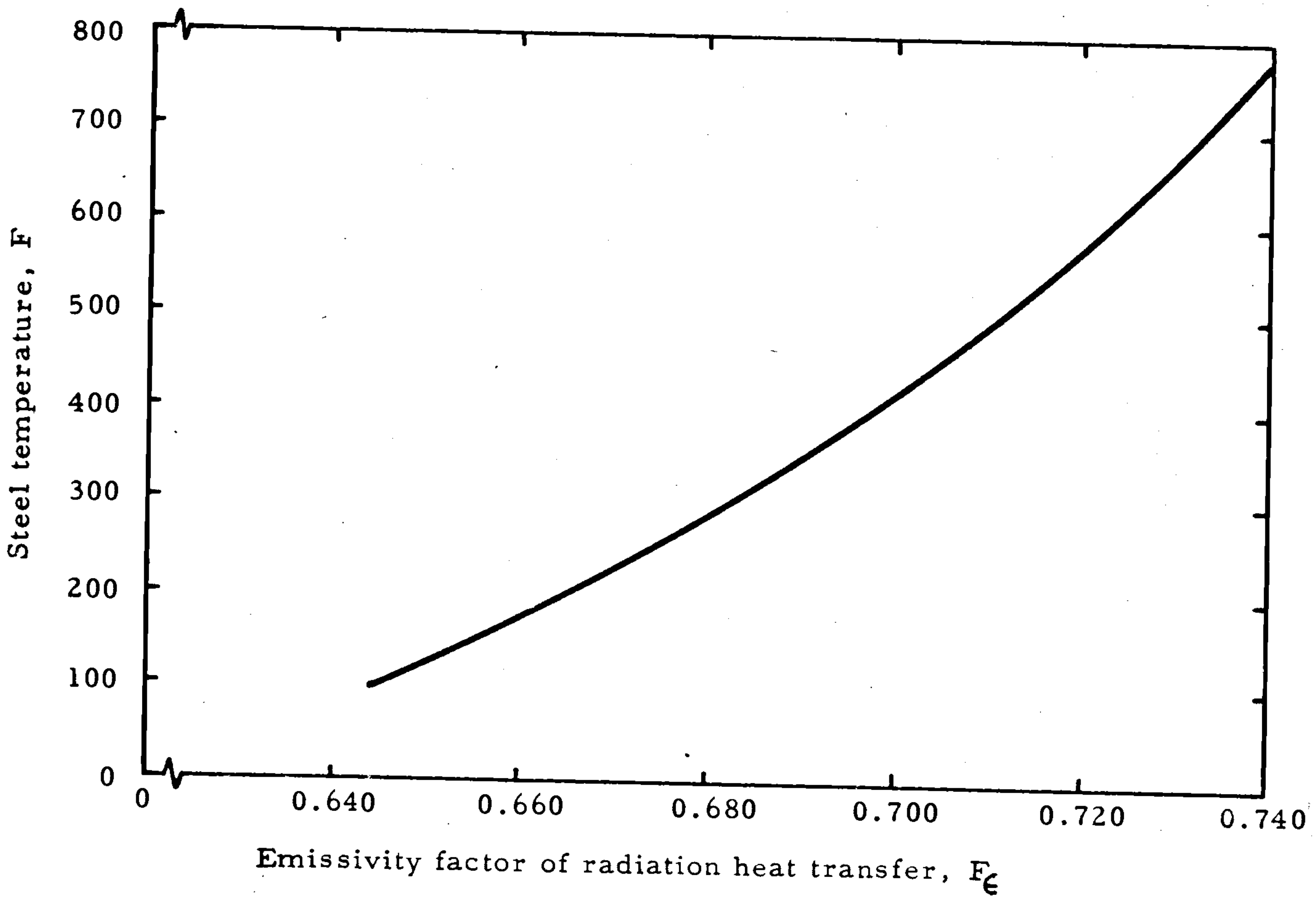

Figure 14. Emissivity factor calculated from Hsu (10).

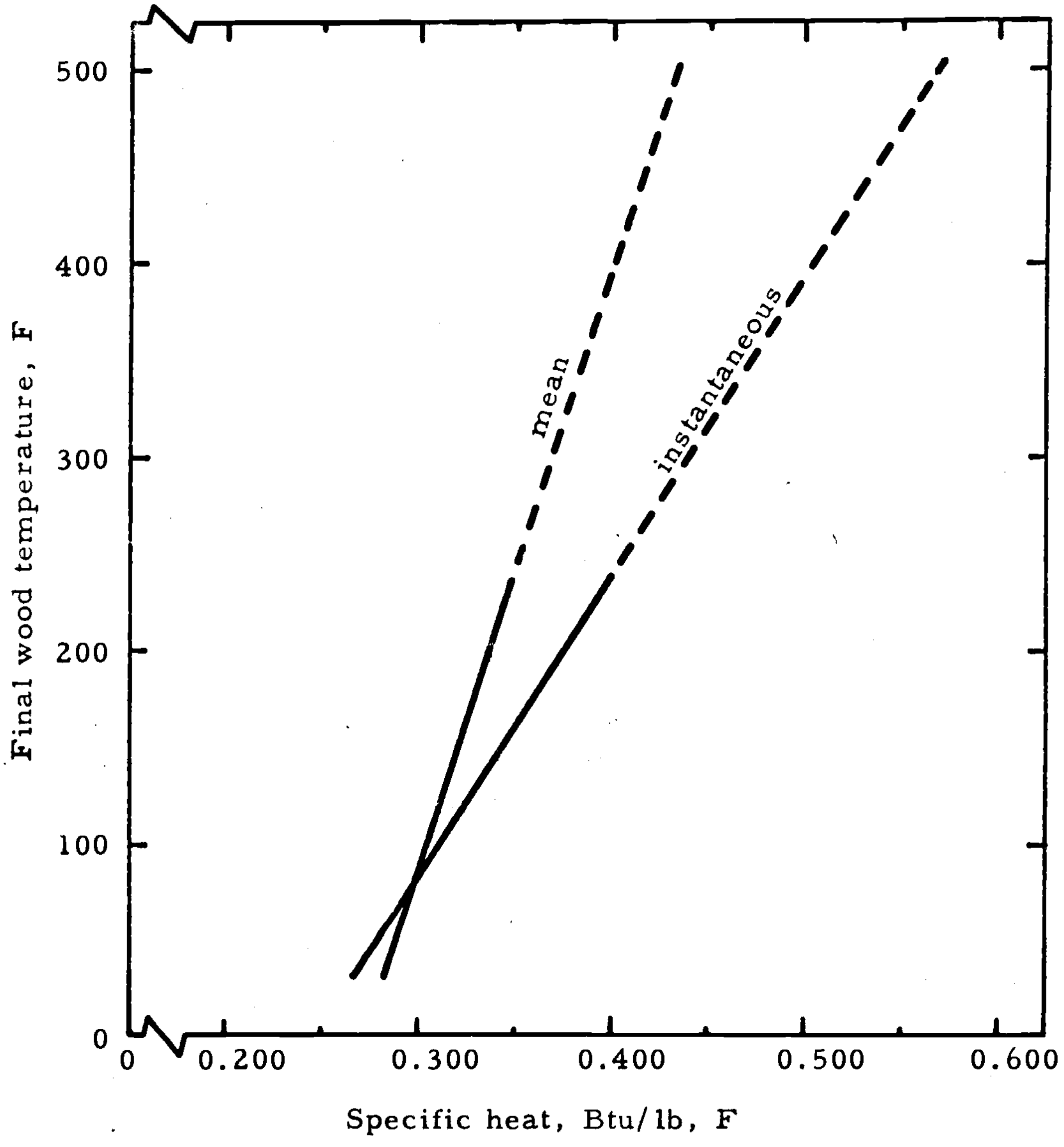

Figure 15. Mean and instantaneous specific heats for Douglas fir with mean based on initial wood temperature of 80 F, from Dunlap (3).

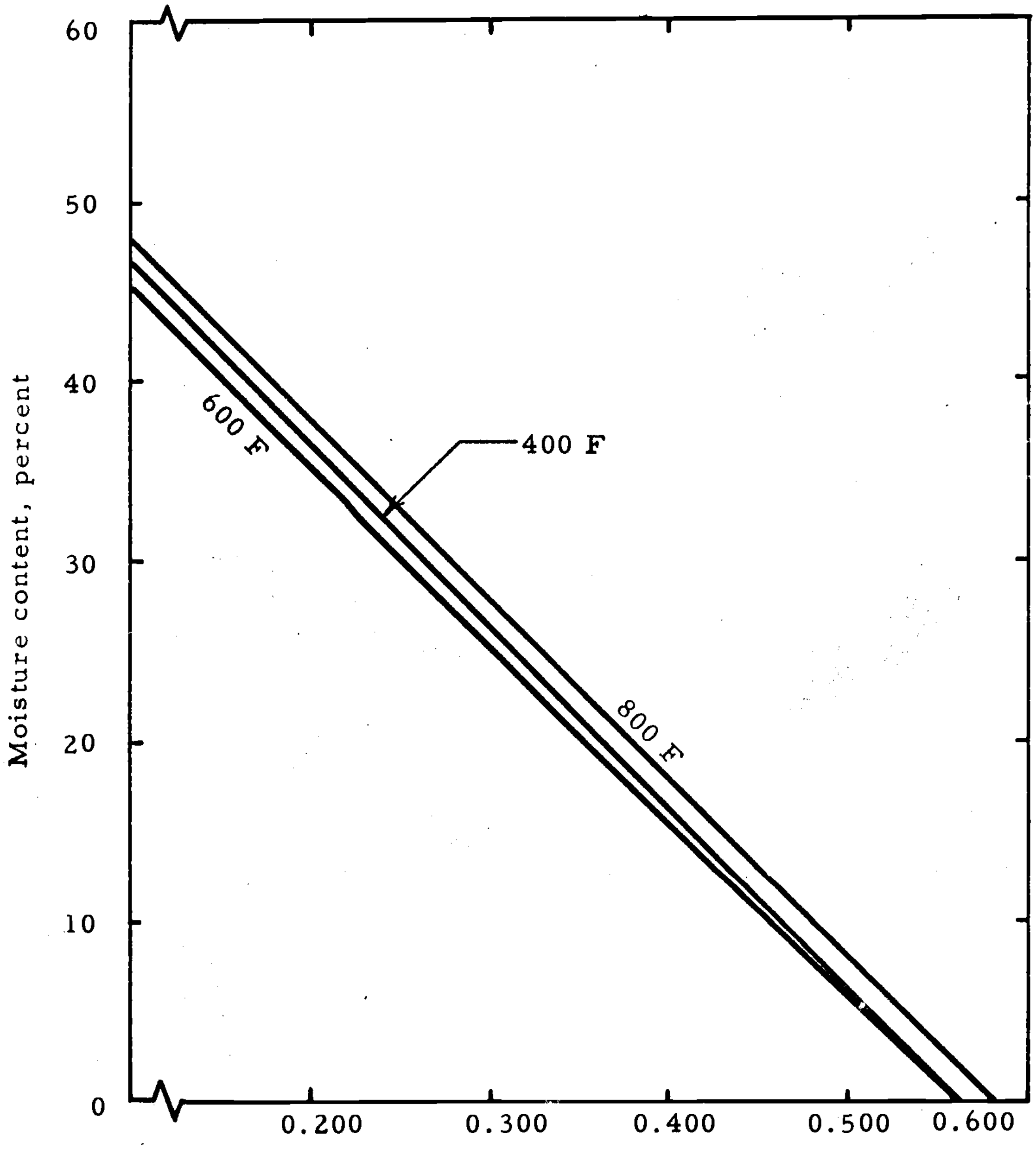

Figure 16. Weight rate of evaporation of water at three steam temperatures

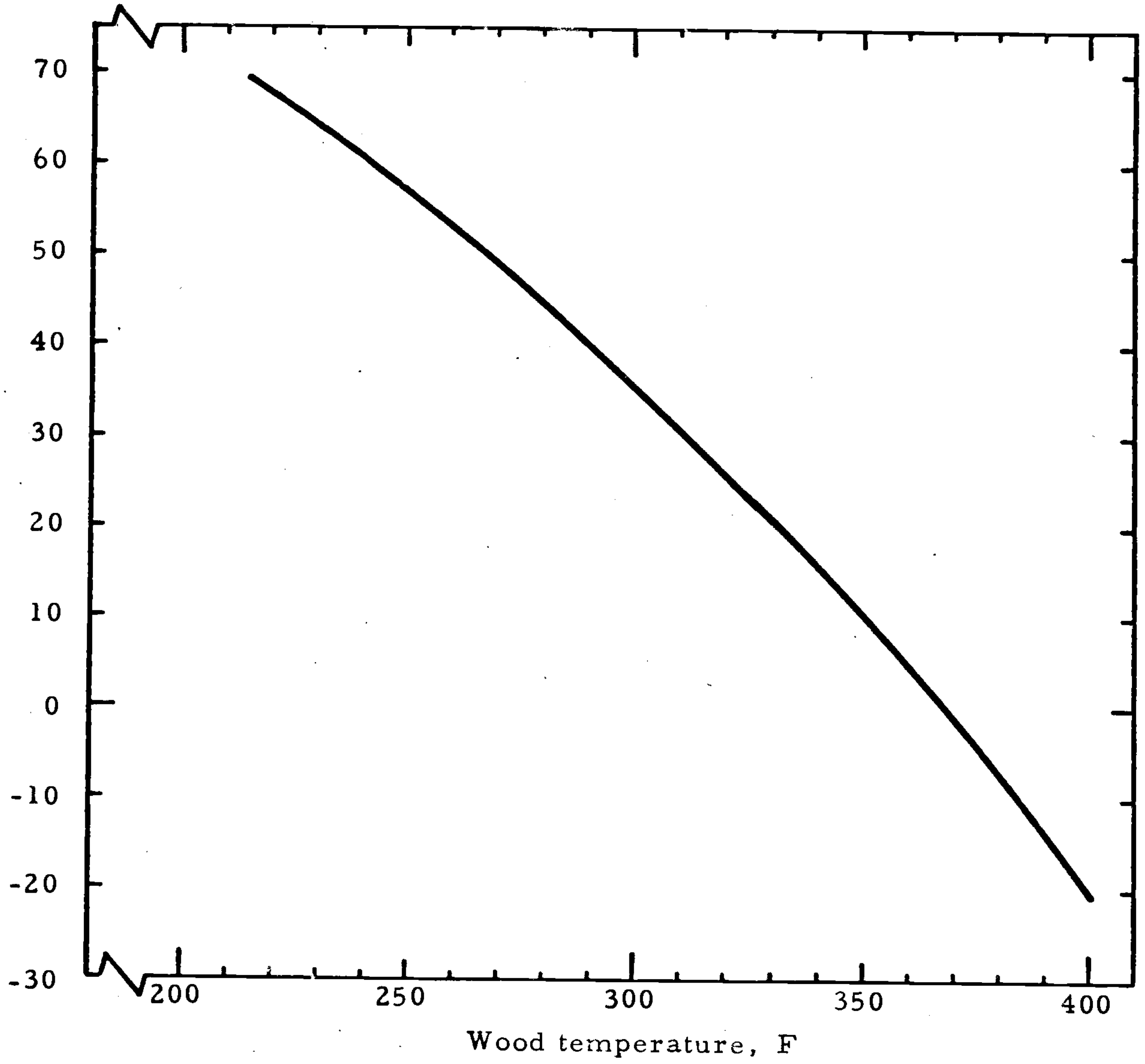

Figure 17. Instantaneous rate of net radiation from steel to wood when steel temperature was 368 F

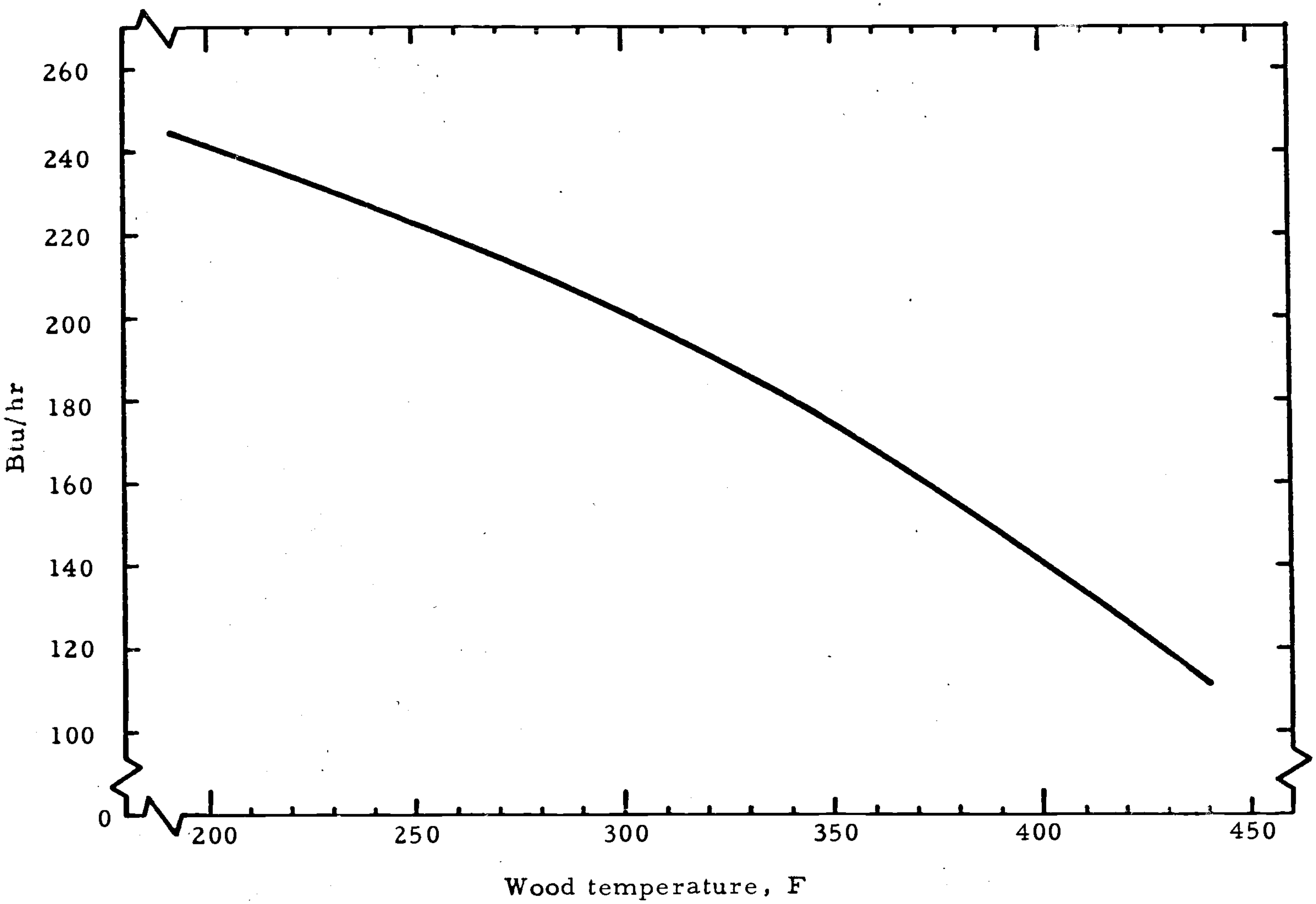

Figure 18. Instantaneous rate of net radiation from steel to wood when steel temperature was 554 F.

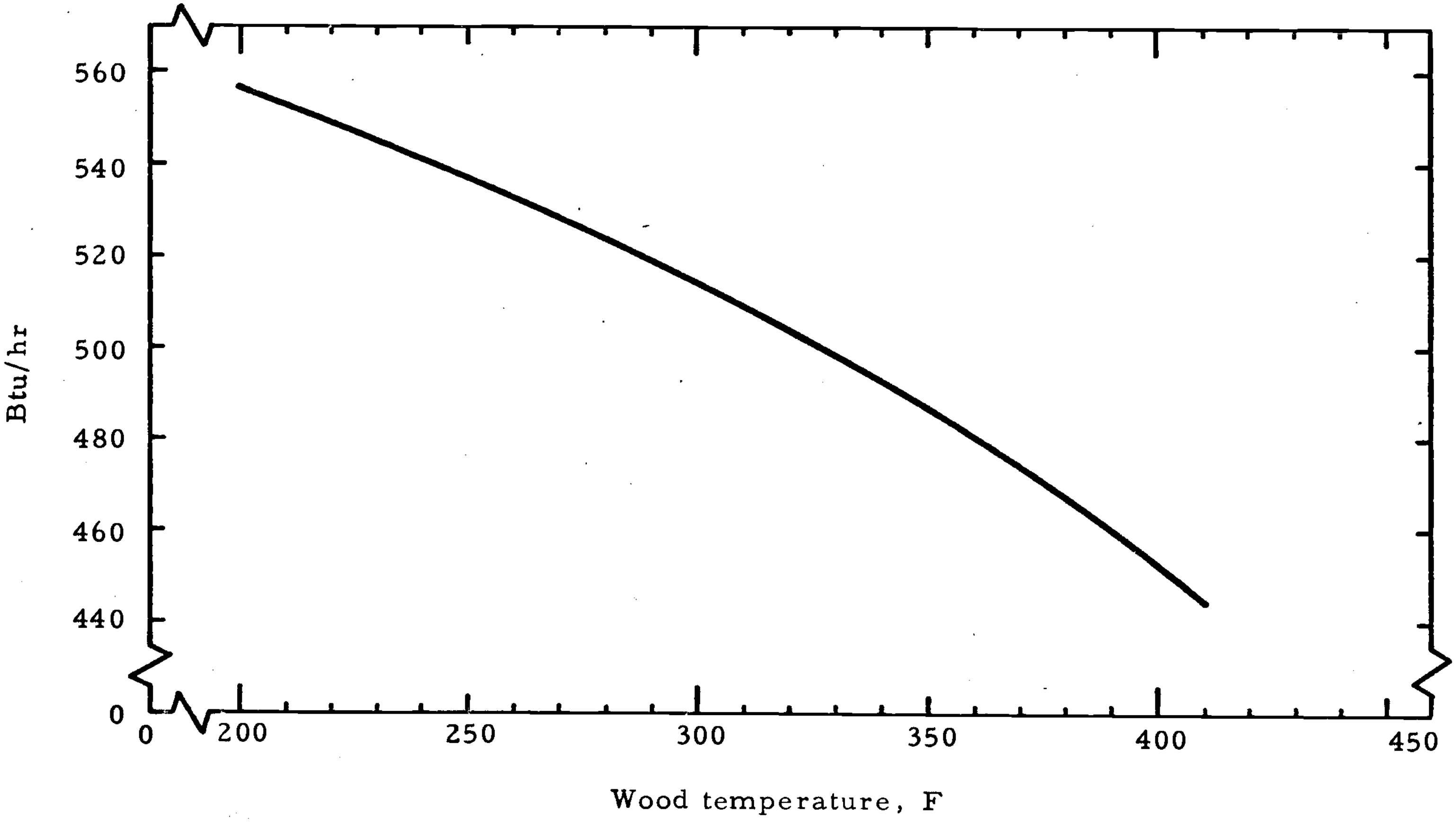

Figure 19. Instantaneous rate of net radiation from steel to wood when steel temperature was 743 F

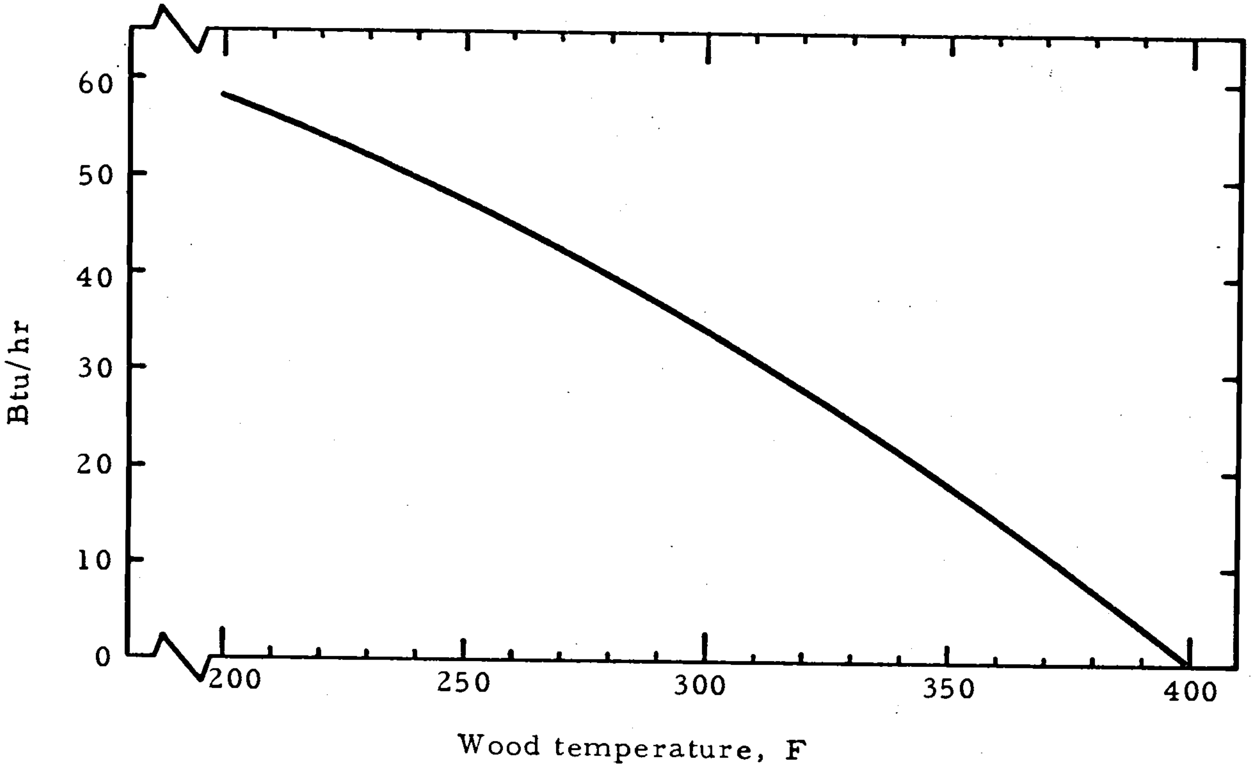

Figure 20. Instantaneous rate of net radiation from steam to wood when steam temperature was 400 F

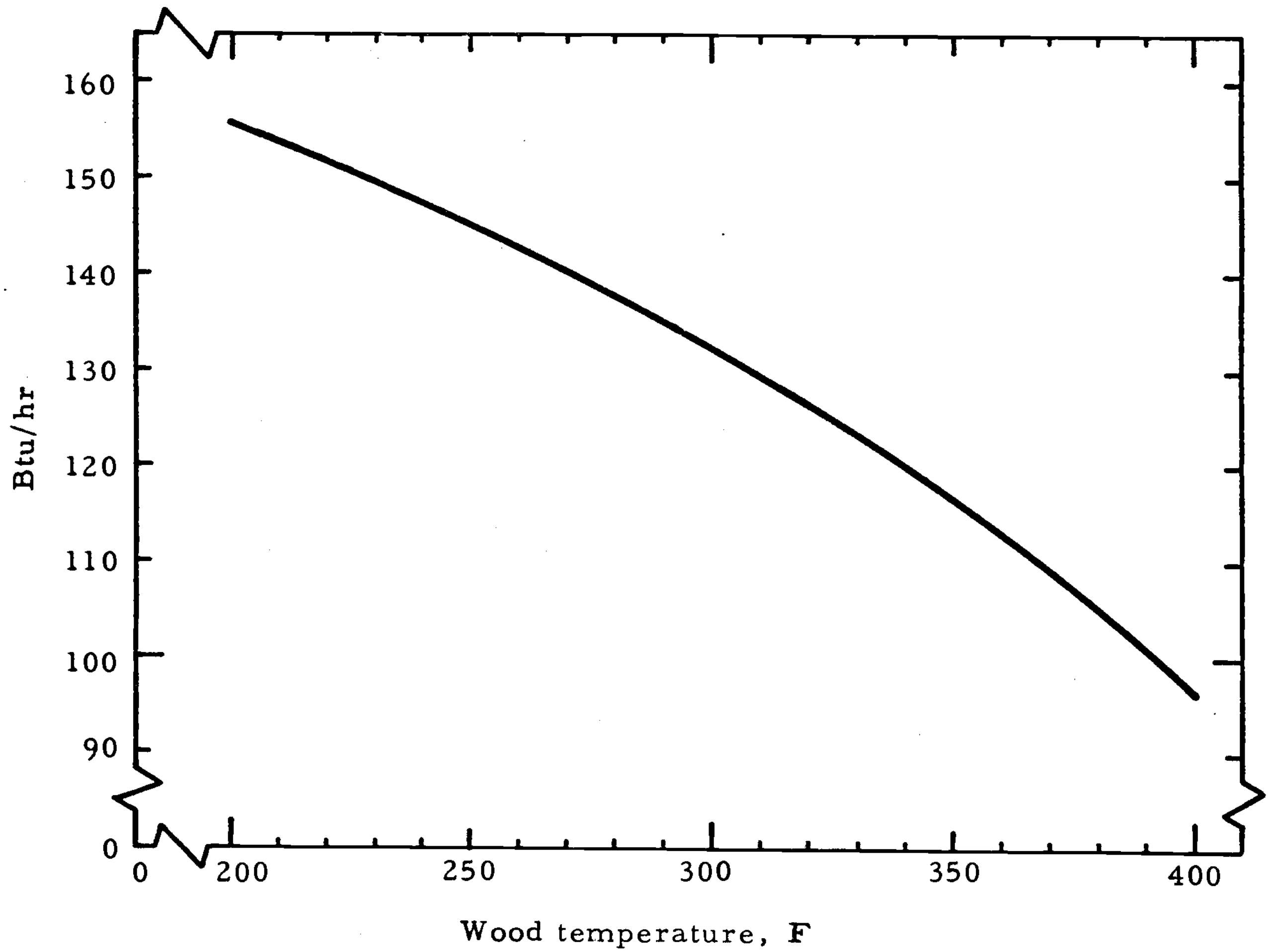

Figure 21. Instantaneous rate of net radiation from steam to wood when steam temperature was 600 F

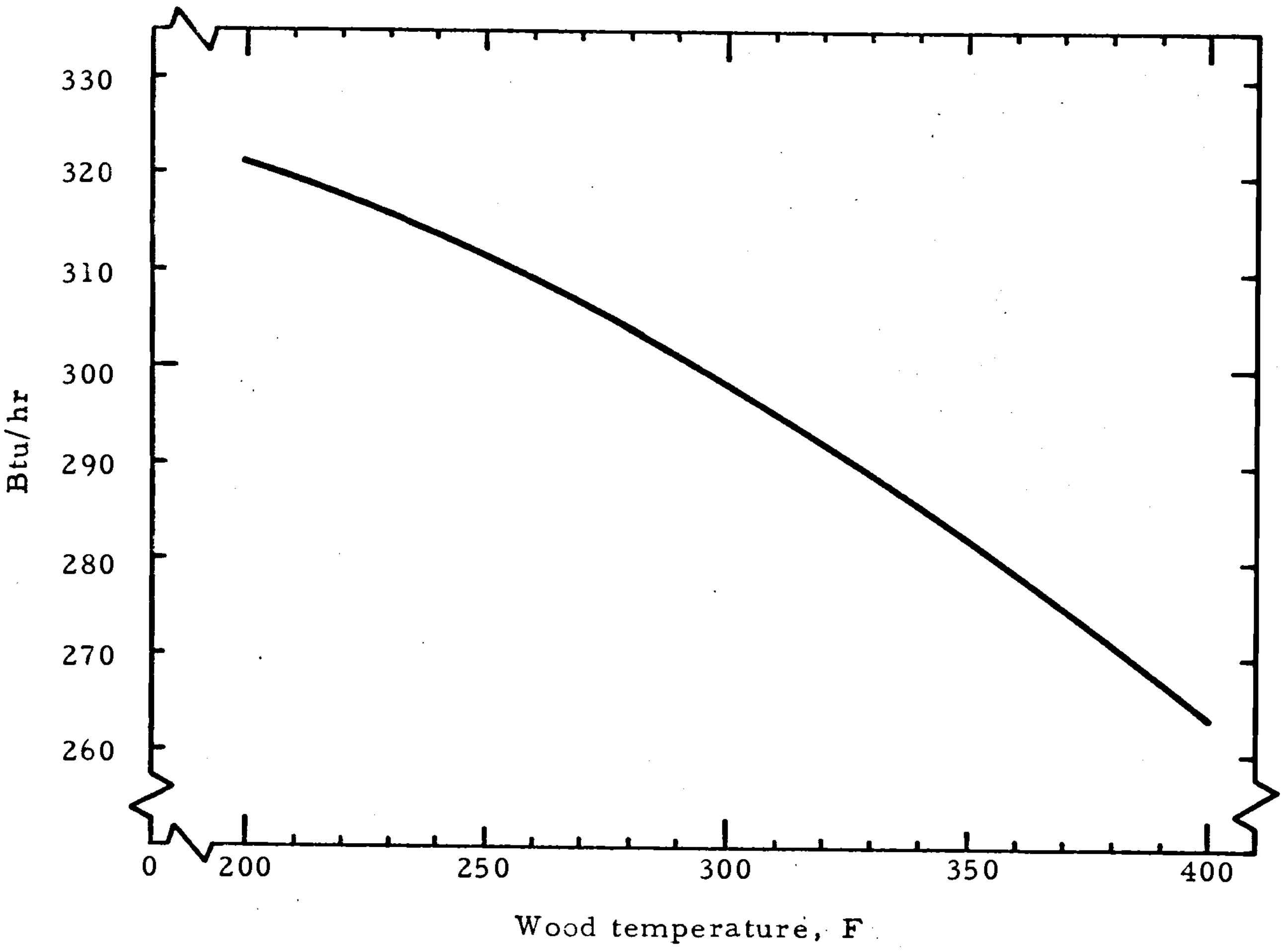

Figure 22. Instantaneous, rate of net radiation from steam to wood when steam temperature was 800 F

Table II. Test data for samples dried at 400 F[1]

Sample (Number)	(Min)	Oven-dry Weight (Gm)	Water Evaporated (Gm)	Water Remaining (Gm)	Initial Moisture (Percent)	Final Moisture (Percent)
2A11	1	21.97	2.61	10.08	57.8	45.9
B	1	22.74	3.13	9.55	55.8	42.0
C	1	21.37	2.36	9.53	55.6	44.6
D	1	22.21	2.55	9.88	56.0	44.5
2A21	3	22.41	6.65	6.01	56.5	26.8
B	3	22.46	6.82	5.95	56.9	26.5
C	3	22.05	6.55	5.52	54.7	25.0
D	3	21.85	6.65	5.43	55.3	24.9
2A31	6	21.63	11.60	1.05	58.5	4.9
B	6	22.10	11.50	0.88	56.0	4.0
C	6	22.75	11.52	1.18	55.8	5.2
D	6	21.91	11.09	0.91	54.8	4.2
2A41	9	21.40	12.45	0.12	58.7	0.6
B	9	21.62	12.19	0.04	56.6	0.2
C	9	21.64	12.81	0.01	59.2	0.0
D	9	22.72	12.37	0.02	54.5	0.1

---

[1] During this test the following temperatures were constant: Orifice - 435 F, ambient air - 80 F, and steam - 400 F. Static pressure at the orifice was 26 inches of water, and h_w was 33 inches of water.

Table III. Test data for samples dried at 600 F[1]

Sample (Number)	(Min)	Oven-dry Weight (Gm)	Water Evaporated (Gm)	Water Remaining (Gm)	Initial Moisture (Percent)	Final Moisture (Percent)
2A14	0.30	22.26	0.86	11.49	55.5	51.6
B	0.30	21.61	0.61	10.67	53.6	49.4
C	0.30	21.99	0.95	11.20	55.3	50.9
D	0.30	21.77	0.81	10.97	54.1	50.4
2A24	0.60	23.15	2.73	9.80	54.1	42.3
B	0.60	22.47	2.73	9.20	53.1	40.9
C	0.60	21.28	2.79	9.00	55.4	42.3
D	0.60	22.09	3.00	9.27	55.5	42.0
2A34	0.90	21.77	4.50	7.38	54.6	33.9
B	0.90	21.57	4.30	8.12	57.8	37.6
C	0.90	23.51	5.09	7.69	54.4	32.7
D	0.90	21.67	4.44	7.57	55.4	34.9
2A44	1.20	---	---	---	---	---
B	1.50	22.21	7.79	5.01	57.9	22.7
C	1.50	22.76	7.46	5.32	56.2	23.4
D	1.50	---	---	---	---	---
2A54	1.95	---	---	---	---	---
B	2.10	21.60	10.21	2.01	56.6	9.3
C	2.10	22.27	9.96	2.25	54.8	10.1
D	2.10	21.95	10.17	1.90	55.0	8.7

[1] During this test the following temperatures were constant: Orifice - 682 F, ambient air - 78 F, and steam - 600 F. Static pressure at the orifice was 22 inches of water, and h_w was 28 inches of water.

Table IV. Test data for samples dried at 800 F[1]

Sample (Number)	(Min)	Oven-dry Weight (Gm)	Water Evaporated (Gm)	Water Remaining (Gm)	Initial Moisture (Percent)	Final Moisture (Percent)
2A13	0.25	21.89	3.37	9.52	58.9	43.5
B	0.25	21.75	2.01	10.10	55.7	46.4
C	0.25	22.21	1.98	10.81	57.6	48.7
D	0.25	22.54	1.77	11.13	57.2	49.4
2A23	0.40	22.95	3.44	9.63	56.9	47.0
B	0.40	22.40	3.32	9.36	56.6	41.8
C	0.40	22.18	3.20	9.27	56.2	41.8
D	0.40	21.89	3.42	9.04	56.9	41.3
2A33	0.60	22.27	5.06	7.75	57.5	34.8
B	0.60	21.41	5.09	7.55	59.0	35.3
C	0.60	23.98	5.20	8.04	55.2	33.5
D	0.60	21.90	5.05	7.26	56.2	33.7
2A43	0.75	22.33	6.41	6.36	57.2	28.5
B	0.75	20.71	6.40	6.16	60.6	29.7
C	0.75	21.94	6.31	6.49	58.3	29.6
D	0.75	23.10	6.19	6.53	55.1	28.3
2A53	1.05	---	---	---	---	---
B	1.20	21.75	10.53	2.83	61.4	13.0
C	1.20	20.88	10.29	2.62	61.8	12.5
D	1.20	21.68	9.98	2.47	57.4	11.4

[1] During this test the following temperatures were constant: Orifice - 960 F, ambient air - 85 F, and steam - 800 F. Static pressure at the orifice was 18 inches of water and h_w was 23 inches of water.