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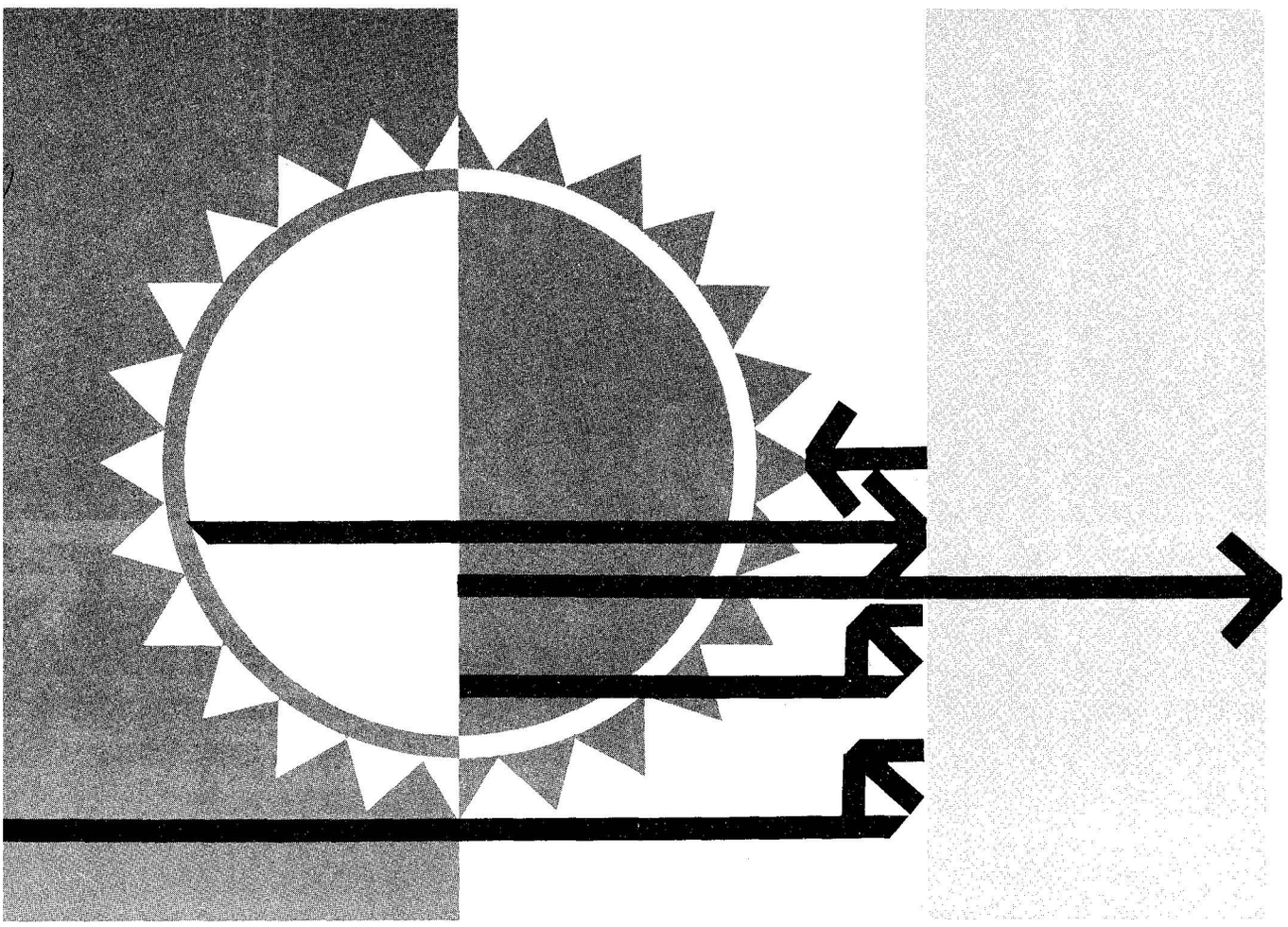
PARAMETERS FOR PREDICTING MAXIMUM SURFACE TEMPERATURES OF WOOD IN EXTERIOR EXPOSURES



ABSTRACT

Accurate predictions of maximum temperatures of wood products in exterior exposures have been of great interest to industries that manufacture the wood products or provide finishes or adhesives for them. This report presents information in tables, maps, and diagrams that can be used to predict maximum surface temperatures without lengthy or involved calculations.

This paper supplements a previous report entitled, "Predicting maximum surface temperatures of wood in exterior exposures," which appeared in the July 1965 issue of the Forest Products Journal.

PARAMETERS FOR PREDICTING MAXIMUM SURFACE TEMPERATURES OF WOOD IN EXTERIOR EXPOSURES

by

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FOREST PRODUCTS LABORATORY[1]

FOREST SERVICE

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INTRODUCTION

The wood, paint, and adhesive industries have long been interested in the maximumtemperatures attained by wood and wood products used outdoors. Extremely high temperatures can often be harmful to the durability and life of a product unless the product is specially designed to withstand such temperatures. Until a more thorough understanding of climatic conditions such as the daily surface temperature ranges is gained, it is difficult to establish realistic accelerated climatic testing methods for siding, sheathing, and other wood products as well as for finishes and adhesives that must endure weathering.

An earlier report (17)[2] described the relationship between the maximum surface temperature and atmospheric climatic conditions in terms of an energy balance. An equation based on the law of conservation of energy was developed to permit the determination of the maximum surface temperature of wood products. This equation, presented in a modified form, is:

$$(1 - \alpha)\, S_o + \epsilon L_o = \epsilon \sigma T^4 + h\Delta T \qquad (1)$$

The temperature of the surface was considered to be dependent upon certain energy gains and losses. The left side of the equation represents energy gains while the right side accounts for energy losses. The various terms are:

$(1 - \alpha)\, S_o$ -- The absorbed solar energy[3] term where α is the albedo (a measure of solar reflectivity) and S_o is the incident solar radiation (langleys per minute).

ϵL_o -- The absorbed longwave energy term where ϵ is the emissivity (a measure of longwave absorptivity) and L_o is the incident long-

[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Underlined numbers in parentheses refer to Literature Cited at the end of this report.

[3] Radiation is divided by .wavelength into two major categories: solar or shortwave (0.275 to 4.000 microns) and longwave (4 to 25 microns). Both forms of energy are commonly measured in langleys (gram calories per square centimeter) per time interval.

wave radiation (langleys per minute).

$\epsilon\sigma T^4$ -- The emitted longwave radiation term derived from the Stefan-Boltzmann Law where ϵ is the emissivity, σ is the Stefan-Boltzmann constant, and T is the surface temperature (°K).

$h\Delta T$ -- The convection term where h is the convection coefficient--0.020 langley per minute per OK (17),--and ΔT is the temperature difference (°K) between the surface (T) and the air (T_A) near the surface.

The total expression involves only five independent variables -- α, S_o, ϵ, L_o, and T_A-- which must be known in order to determine the surface temperature, T. The primary assumptions when using this equation for wood products are that condensation or evaporation in the product or at the surface and heat conduction through the product are negligible.

In an attempt to simplify the calculations and make it easy to obtain an approximate (±2° C.) solution for T, the relationships of the equation are presented in diagrammatic form in this report. In addition, characteristic values of albedoes for many paints and unfinished woods are presented. Values are also given for the maximum amounts of solar radiation received on horizontal surfaces and vertical surfaces that face south.

ALBEDO

The albedo, α, of a surface is defined as the ratio of the reflected solar radiation to the incident solar radiation. In equation (1), $(1 - \alpha)$ represents the percentage of solar radiation absorbed by the surface. Therefore, a white surface that has an albedo of 90 percent would absorb 10 percent of the incident radiation.

The albedo of a surface can be measured by two independent means. In both methods it is necessary to establish certain limitations on atmospheric and solar conditions, because wide variations in the spectral distribution of solar energy can occur and can drastically alter the results. The most straightforward method is to measure the incident and reflected radiation directly with a pyrheliometer or radiometer that is equally sensitive to energy of all wavelengths in the solar spectrum. Several studies have been conducted in this manner (1, 4, 9). The major problem with this method is obtaining proper instruments and experimental conditions.

Albedo can also be measured indirectly as described by Betz (3) by using a reflectometer and by approximating the spectral distribution of solar energy. In this case the albedo, α, is given mathematically by

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_2} R_\lambda S_\lambda \, d\lambda}{\int_{\lambda_1}^{\lambda_2} S_\lambda \, d\lambda}$$

where λ = wavelength

λ_1 and λ_2 = the lower and upper wavelength limits of solar radiation

R_λ = absolute reflection at λ

S_λ = intensity of solar radiation at λ

This method was used in determining albedoes for this report. However, because of instrument limitations, the integrals were solved by summation over small increments of wavelength. The total absolute reflectance of various painted and natural wood surfaces was measured at various wavelengths throughout the solar spectrum. Such measurements produced values of the percent of light reflected at various wavelengths. Assuming that the spectral distribution of sunlight is accurately given by Moon (13), for an optical air mass of two[4] then the reflectance at each wavelength is multiplied by the percentage of solar energy at each corresponding wavelength, the products summed and divided by the total energy of all wavelengths to obtain the albedo. In mathematical form

[4]The optical air mass number is a measure of the length of the path that light (in this case, sunlight) must travel through the atmosphere to reach sea level. An air mass of zero represents a path length of zero or a condition of no atmosphere. This cannot be achieved on earth. An air mass of one is the path length when the sun is at its zenith. An air mass of two is the path length when the sun is about 60° from its zenith.

$$\alpha = \frac{\sum_{\lambda = 300\mu}^{2000\mu} R_\lambda S_\lambda}{\sum_{\lambda = 300\mu}^{2000\mu} S_\lambda}$$

where α = albedo (percent)

λ = wavelength (millimicrons)

R_λ = absolute total reflectance at A (percent)

S_λ = solar energy at λ (langleys per minute)

Such calculations require that the reflectance at a particular wavelength actually be representative of the reflectance over a band of wavelengths. For example, the reflectance at 350 millimicrons for a particular surface may be 20 percent. Because readings of reflectance were made at every 10 millimicrons (i.e., ... 340, 350, 360, ...), the value of 20 percent at 350 millimicrons is assumed to be the value for the wavelength band from 345 to 355 millimicrons. The optical characteristics of the particular instrument used tend to validate this assumption. Likewise, S_λ represents the percent of solar energy in a wavelength band rather than at one particular wavelength.

The values of albedo for various woods and paints (tables 1 and 2) are intended as a guide for estimating albedoes of other surfaces. The two physical characteristics of the surface which influence the albedo are gloss and color. Higher gloss implies a higher albedo for a particular color, and lighter color implies higher albedo for a particular gloss.

SOLAR RADIATION

The amount of solar radiation, S_o of equation (1), incident on a surface must be known before calculations of maximum surface temperatures can begin. There are many instruments for specific measurements of solar radiation (5, 6, 12, 14), but for general purposes, Weather Bureau data of radiation on horizontal surfaces provide reasonably accurate values.

Until 1963, the Weather Bureau made virtually all of its determinations of solar radiation with models of an Eppley pyrheliometer that were less accurate than those that are currently being placed in use. Reduction of the raw data was performed manually. Such instruments and reduction methods lead to errors as great as 5 to 10 percent according to Bennett (2). Therefore, the solar radiation data presented here should be considered qualitative rather than quantitative. Nevertheless, this information should be sufficiently accurate to predict maximum surface temperatures of wood products for most purposes.

Horizontal Surfaces

A compilation of hourly values of solar radiation on horizontal surfaces was obtained from 40 United States Weather Bureau stations (16); a list of the stations is given on page 9 of this report. Data were supplied for the three most recent years (usually 1962 through 1964) for four months of the year (March, June, September, and December) for each station.

The data were analyzed to select the highest 5 percent of the hourly values at noon for a given month, year, and station. This procedure provided realistic hourly values of maximum solar radiation that occurred during the month. Transitory conditions may produce much higher momentary values but such occurrences are unpredictable and would be of little consequence compared with the effect of sustained radiation. The highest 5 percent of the radiation values for a specific month at a specific station for the 3 years were then averaged to obtain the maximum noontime solar radiation.

These average values with units of langleys per hour were then divided by 60 minutes per hour to convert to langleys per minute for use in equation (1). This division 'is valid because the solar radiation for clear days closely approximates a sine curve and in reducing maximum noontime hourly values to langleys per minute, the error introduced is no greater than 4 percent and is usually less.

The average monthly solar radiation values were plotted on outline maps of the United States and isopleths were drawn (figures 1-4). Values for some stations are based on 2 years' data (indicated by parentheses) because data for the

third year were not available. In some instances the 2-year average radiation value was greater than the 3-year value by 0.02 langleys per minute or greater (indicated by a "+" after the 3-year value). No value was plotted when only 1 year's data were available for a specific month.

Vertical Surfaces

Calculating the solar radiation received by vertical surfaces is somewhat more complicated than for horizontal surfaces. Very few direct measurements of solar radiation are made on nonhorizontal surfaces because most measuring instruments cannot be tilted without losing their accuracy. Direct conversions from radiation intensity on a horizontal surface to radiation on tilted surfaces, taking into account the elevation of the sun above the horizon, are usually quite inaccurate because solar radiation is not distributed uniformly throughout the sky. A very thorough discussion of this problem is presented by Kandratyev and Manolova (8) and by Liu and Jordan (11).

For the derivation of maximum solar radiation on vertical surfaces presented here, diffuse radiation must be considered a contributing factor. Diffuse radiation is radiation which does not come directly from the sun, that is, from the same angle as the elevation of the sun. It is caused by the scattering of the sun's light by the atmosphere and by atmospheric contaminants, Radiation which comes directly from the sun is called direct solar beam radiation. Diffuse radiation was also a factor in the solar radiation on horizontal surfaces but it was automatically considered by the measuring instrument.

Parmelee (15) has calculated the amount of diffuse radiation received on horizontal and vertical surfaces for various elevations of the sun. For the present study, Parmelee's data are incorporated in the derivation of noontime radiation values on vertical surfaces that face south The amount of diffuse radiation received on a horizontal surface was first subtracted from the values of total radiation (figures 1 to 4) to find the intensity of the direct solar beam on a horizontal surface. The intensity of the direct solar beam on a horizontal surface was then multiplied by the cotangent of the sun's elevation at noon to determine the intensity of the direct solar beam on a vertical surface. Parmelee's value of diffuse radiation on vertical surfaces that face south was then added to the direct solar beam value. These values were calculated for the 40 locations mentioned earlier and were plotted for 4 months of the year (figures 5 to 8).

Vertical surfaces also receive a small amount of radiation that is reflected from the ground. The intensity of this radiation depends upon the reflectivity or albedo of the ground and upon the amount of radiation received by the ground from the sun. If the radiation reflected from the ground is scattered with equal intensity in all directions, then for a vertical wall the incident radiation reflected from the ground would be $1/2\alpha S_o$, where α is the albedo of the ground and So is the intensity of radiation incident on the ground, which is considered as a horizontal surface, The albedo of various types of ground surfaces is given in table 3. The intensity of radiation received by the ground is given in figures 1 to 4.

The value of reflected radiation thus obtained is added to the previous sum of direct and diffuse radiation (figures 5 to 8) to arrive at a value of maximum radiation on a vertical surface that faces south

It should be noted that the wavelengthspectrum of solar radiation reflected from the ground is somewhat different than that of direct solar radiation. As a result, the portion of this incident energy absorbed by a wall cannot be predicted precisely by using the albedo values given in tables 1 and 2, because these albedo values pertain only to the solar spectrum. However, errors introduced in this way would be very small when the total radiation on a vertical surface is considered.

DIAGRAMMATIC REPRESENTATION

Having established parameters for the albedo and solar radiation terms of equation (1) certain generalizations and assumptions can be made about the remaining terms,

Longwave radiation, L_o, is emitted by all solids, liquids, and gases according to the Stefan-Boltzmann Law; the intensity of emission depends upon the temperature of the emitting subject, Thus, longwave radiation is received by a sur-

face from surrounding objects and affects the maximum temperature of the surface. A horizontal surface receives longwave radiation principally from the atmosphere above it at a rate of 0.30 langley per minute. This is a typical value for clear or mostly clear skies, For vertical surfaces, longwave radiation comes from surrounding objects and the ground. A close approximation of the magnitude of this energy can be obtained by assuming that the temperature of emitting objects is the same as the air temperature, T_A, and that their emissivity, ε is about 1.00. Based on these assumptions the incident longwave energy according to the Stefan-Boltzmann Law is σT_A^4 for a vertical surface.

To fulfill the requirements of equation (1) an accurate estimate of the temperature of the air, T_A, near the surface is needed. Weather Bureau information can again be used and will be accurate for small surfaces. However, for large surfaces such as a roof of a house, Weather Bureau temperatures may be several degrees lower than actual conditions and an actual measurement of the air temperature near the surface may be necessary.

The relationships of equation (1) were drawn in diagrammatic form (figures 9 to 12) to simplify the maximum surface temperature calculations. In these diagrams the maximum surface temperature is a function of solar radiation, surface albedo, and air temperature. Two conditions of emissivity, ε, were considered in drawing the diagrams; for painted surfaces ε is 0.95, and for natural wood surfaces ε is 0.85. Figures 9 and 10 represent the relationships for horizontally exposed painted and natural wood surfaces respectively. Figures 11 and 12 pertain to vertically exposed painted and natural wood surfaces. Although. the solar radiation values given previously are only for vertical surfaces facing south, figures 11 and 12 may be used for a vertical surface that faces any direction if the proper solar radiation values are known.

Examples of the use of the tables, maps, and diagrams are given at the end of this report.

SUMMARY

The albedoes, radiation values, and diagrams included in this report permit the determination of the maximum temperatures of natural and painted wood in horizontal or vertical exposures throughout the United States without having to make involved measurements or calculations. It should be recognized that the albedo values presented are intended as general guides and do not represent a constant value. As paints and woods age, they are known to change color and this would affect their albedo. Also, subtle differences in the color of paints or woods may affect the albedo significantly.

It should also be recognized that wide deviations in radiation values can be expected due to geographical variations such as mountains, large bodies of water, or atmospheric contaminants from large urban areas. For these reasons, and because isopleths on the maps are drawn through points of only approximately equal value, caution should be used in interpolating on the maps. Actual measurements of solar radiation should be made if more accuracy is desired.

Even with the various limitations imposed on the data and the maps, calculations of maximum temperature should be accurate to within a few degrees under the conditions stated.

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PREDICTING MAXIMUM SURFACE TEMPERATURES

Maximum surface temperatures attained by wood surfaces in exterior exposures can be predicted by knowing the conditions and by se-letting the appropriate diagram. Consider the following examples:

Horizontal Surface

A nearly flat horizontal roof is exposed during September in Nashville, Tenn. The roof is painted blue. The approximate albedo is 20 percent (table 2); solar radiation is 1.25 langleys per minute (figure 3); and air temperature is 30° C. (86° F.). With these conditions, figure 9 is the proper diagram for maximum temperature de-termination; the steps of this example are indi-cated by the dotted line in the figure, Locate the solar radiation value (1.25 langleys per minute) on the left margin and follow a diagonal line to the intersection with the albedo value (20 per-cent). From this point, follow a horizontal line to the intersection with the 30° C. (86° F.) air temperature (T_A) line. Proceeding up or down, the predicted maximum temperature is 52° C. (126° F.).

Vertical Surface

As another example, a wall that Paces south is exposed during December in southern Idaho. The wall has siding of natural western redcedar (albedo, 50 percent), Air temperature is 0° C. The ground is covered with snow several days old. The total solar radiation incident on the wall is 1.28 langleys per minute (figure 8) plus 1/2 times 81 percent (table 3) times 0.64 langley per minute (figure 4). The total radiation is 1.54 langleys per minute. Figure 12 is the correct diagram to use for this vertically exposed, natural wood surface. Using this diagram in the manner described earlier, the maximum surface temperature is 27° C. (80° F.).

Table I.--Albedo of wood

Wood	Color	Albedo
		Percent
Red gum, (heartwood, flatsawn)	Dark brown	48
Cedar, (heartwood, quartersawn)	Red	50
Yellow birch, (heartwood, flatsawn)	Brown	58
Douglas-fir, (heartwood, springwood, flatsawn)	Tan	61
Red oak, (heartwood, flatsawn)	Light tan	62
Yellow-poplar, (heartwood, flatsawn)	White-gray	65
Sitka spruce, (heartwood, vertical grain, quartersawn)	Light tan	67
Southern pine, (heartwood, springwood, flatsawn)	Yellow	70
Spruce, (heartwood, quartersawn)	Light yellow	72

Table 2.--Albedo of paint

Color	Pigment	Vehicle	Gloss	Albedo
				Percent
Black	Carbon black	Oil	Yes	7
Dark blue	Ramapo blue	Oil	Yes	14
Blue	Ramapo blue	Latex	No	22
Gray	Carbon black and titanium dioxide	Oil	Yes	23
Dark red	Iron oxide	Latex	No	26
Red	Iron oxide	Oil	Yes	32
Green	Green chrome oxide	Latex	No	33
Light green (7)				50
Light yellow (7)				55
Light cream (7)				65
White	White lead, P/NV = 0.15[1]	Oil	Yes	71
White	Zinc oxide	Oil	Yes	73
Light pink	Titanium dioxide	Oil	Yes	77
White	Titanium dioxide	Oil	No	79
White	Titanium-lead-zinc	Oil	Yes	81
White	Titanium dioxide	Latex	No	84
White	Titanium dioxide	Oil	Yes	85
White	Titanium, zinc	Oil	Yes	86
White	Titanium-lead primer	Oil	Yes	88
White	White lead, P/NV = 0.30[1]	Oil	Yes	91

[1] P/NV is the ratio of pigment to nonvolatiles.

Table 3.--Albedo of the ground[1]

Ground	Albedo
	Percent
Bare ground (dry)	10 - 20
Bare ground (wet)	8 - 9
Bare ground (moist)	9 - 12
Sand (dry)	18
Sand (wet)	9
Grass (dry)	15 - 25
Grass (wet)	33 - 37
Snow (old)	81
Snow (new)	90

[1] These values were obtained by List (10) from various sources.

Weather Bureau Stations that provided solar radiation data

Arizona, Page
Arizona, Tucson
California, Fresno
California, Inyokern
California, La Jolla
Colorado, Grand Lake
District of Columbia
Florida, Apalachicola
Florida, Gainesville
Florida, Miami
Idaho, Twin Falls
Illinois, Chicago
Kansas, Dodge City
Louisiana, Shreveport
Maine, Caribou
Massachusetts, Milton
Michigan, East Lansing
Michigan, Sault Sainte Marie
Missouri, Columbia
Montana, Great Falls
Nebraska, Omaha
Nevada, Ely
New Mexico, Albuquerque
New York, Ithaca
North Carolina, Cape Hatteras
North Dakota, Bismarck
Ohio, Cleveland
Oklahoma, Stillwater
Oregon, Medford
South Carolina, Charleston
Tennessee, Nashville
Tennessee, Oak Ridge
Texas, Brownsville
Texas, El Paso
Texas, Fort Worth
Utah, Toole
Washington, Friday Harbor
Washington, Pullman
Wisconsin, Madison
Wyoming, Laramie

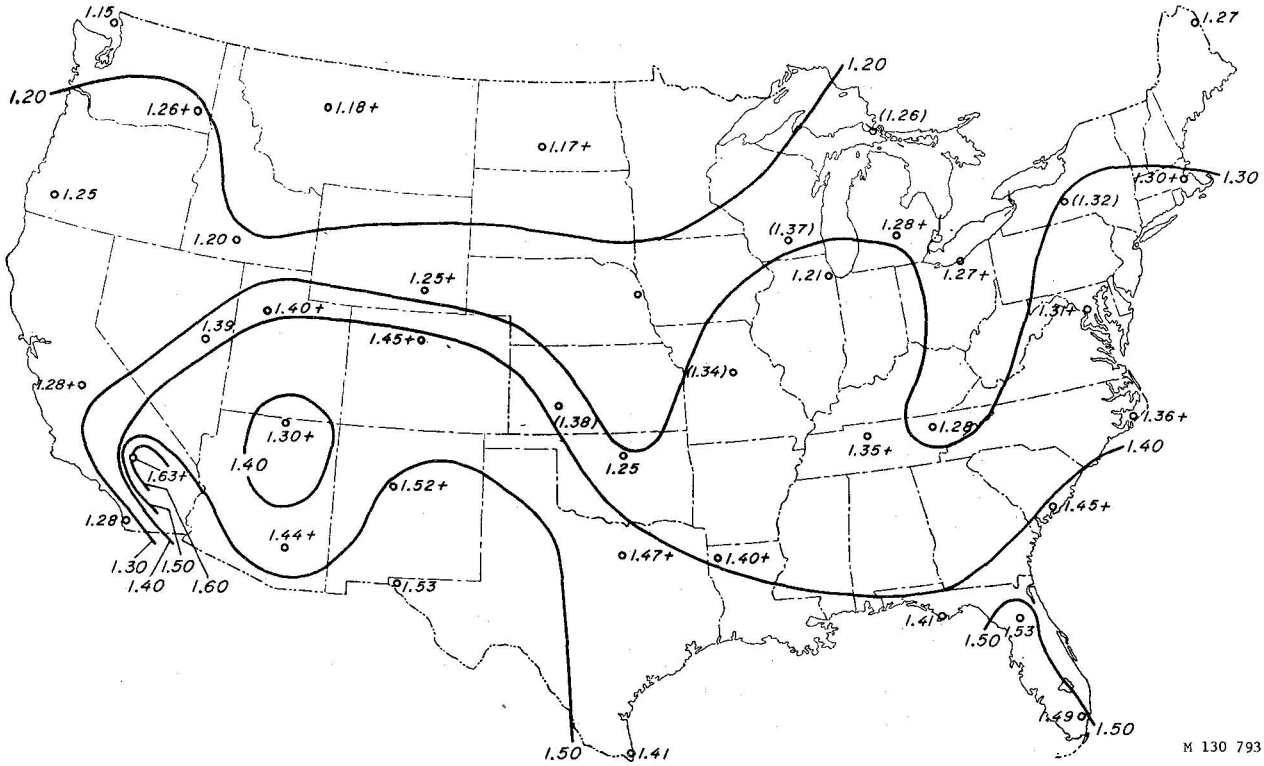

Figure I.--March: Maximum solar radiation received on a horizontal surface.

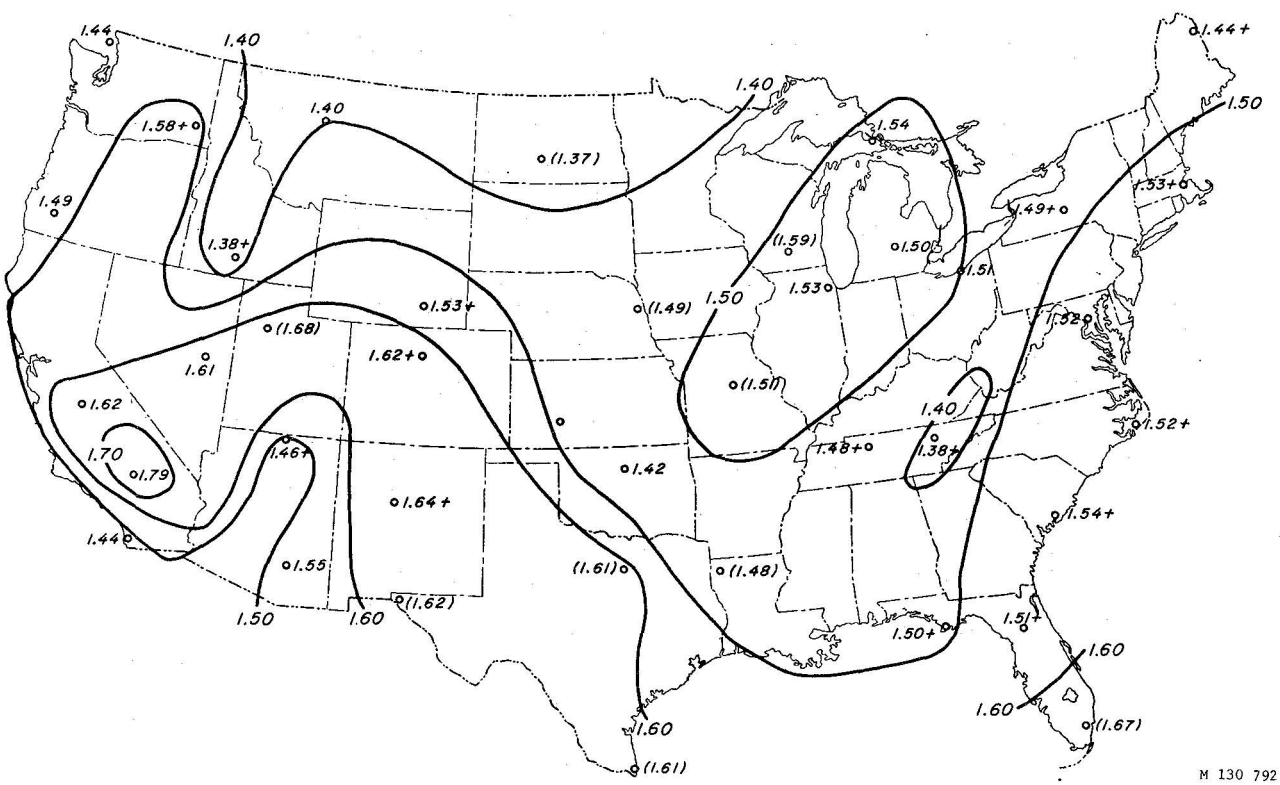

Figure 2.--June: Maximum solar ratiation received on a horizontal surface.

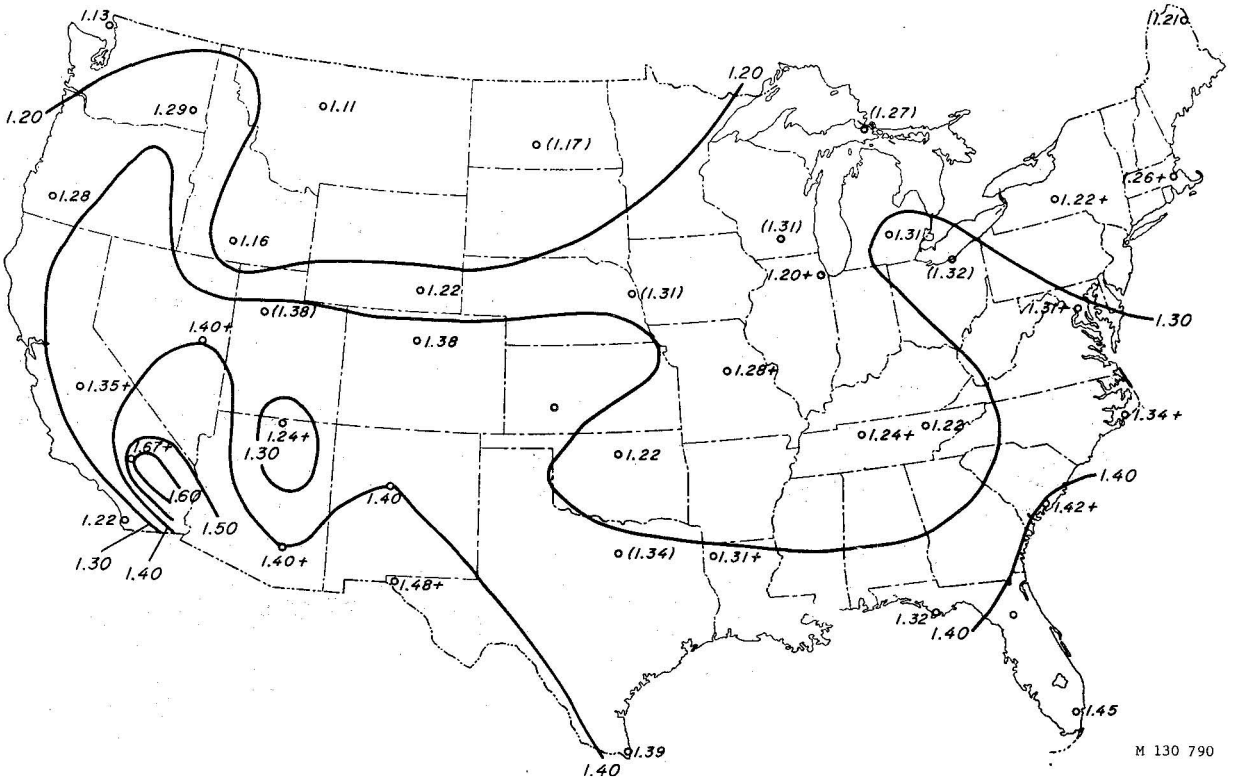

Figure 3.--September: Maximum solar radiation received on a horizontal surface.

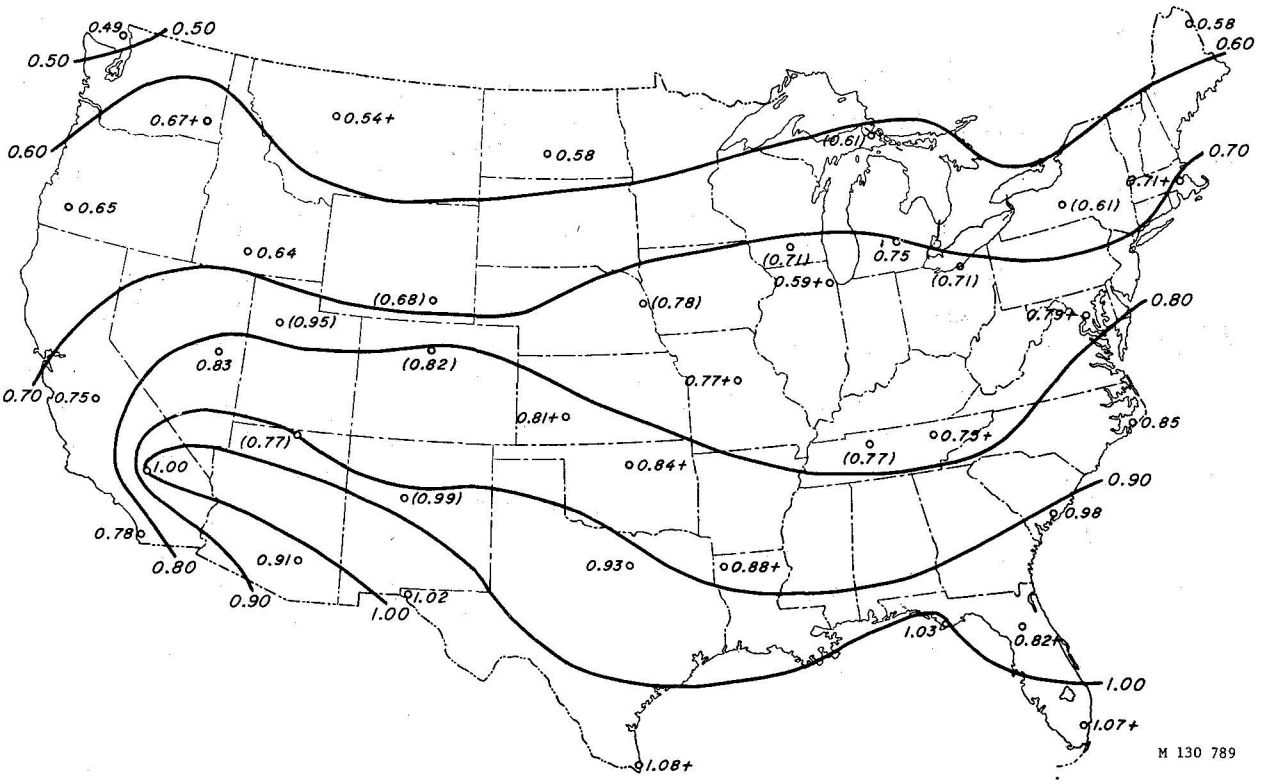

Figure 4.--December: Maximum solar radiation received on a horizontal surface.

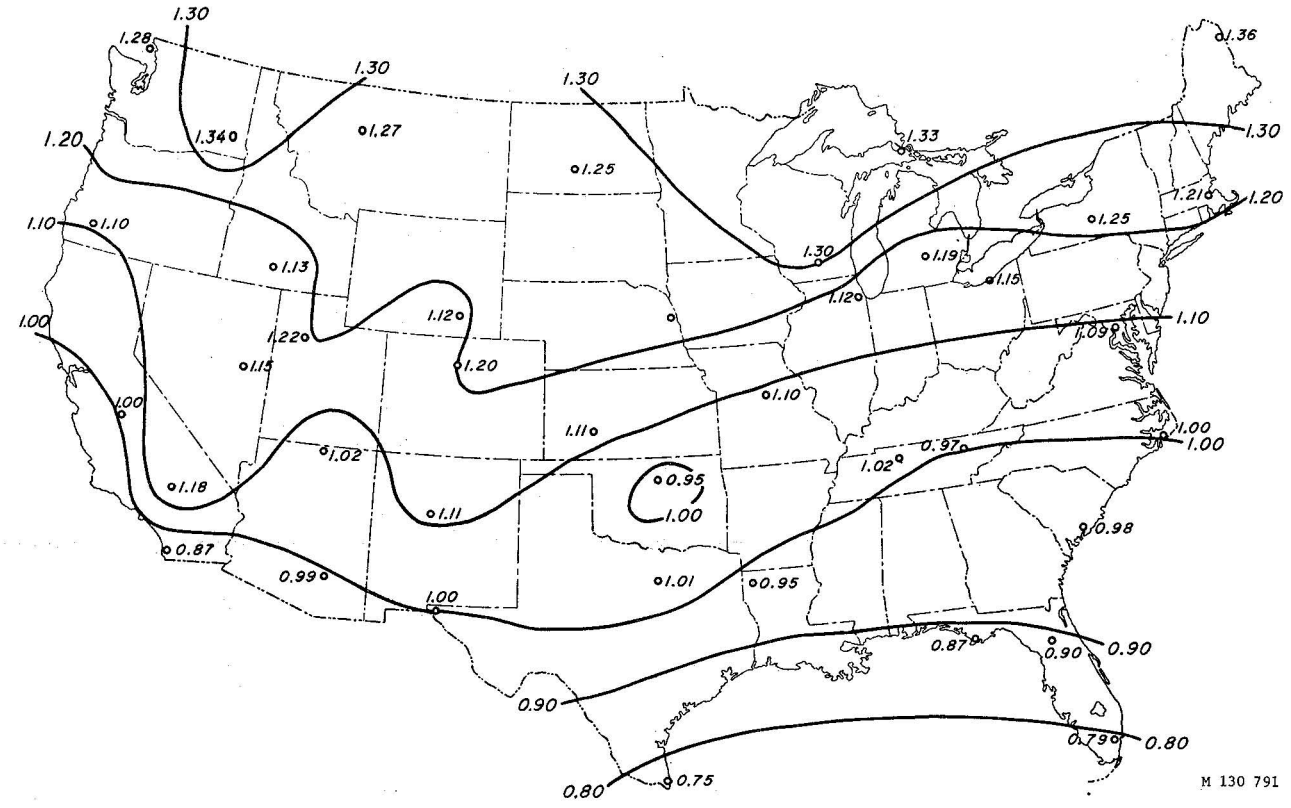

Figure 5.--March: Maximum solar radiation received on a vertical surface that faces south.

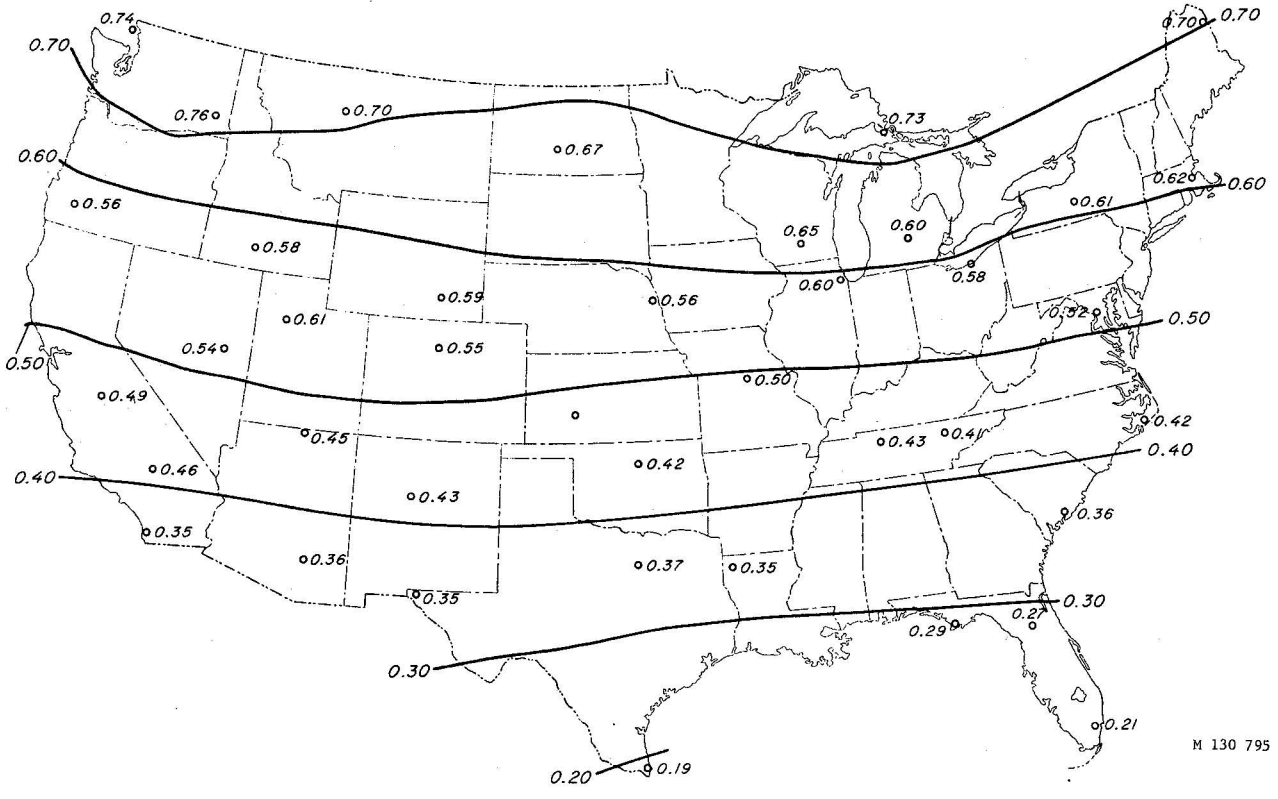

Figure 6.--June: Maximum solar radiation received on a vertical surface that faces south.

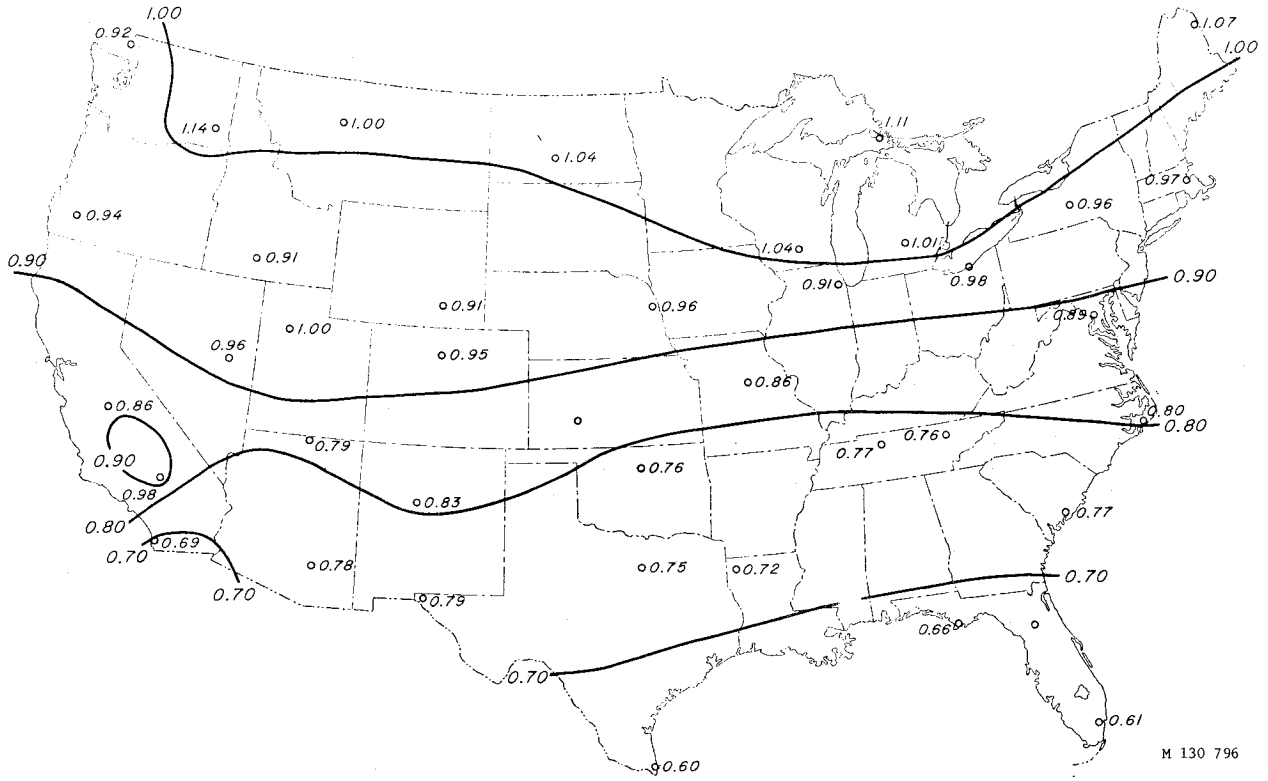

Figure 7.--September: Maximum solar ratiation received on a vertical surface that faces south.

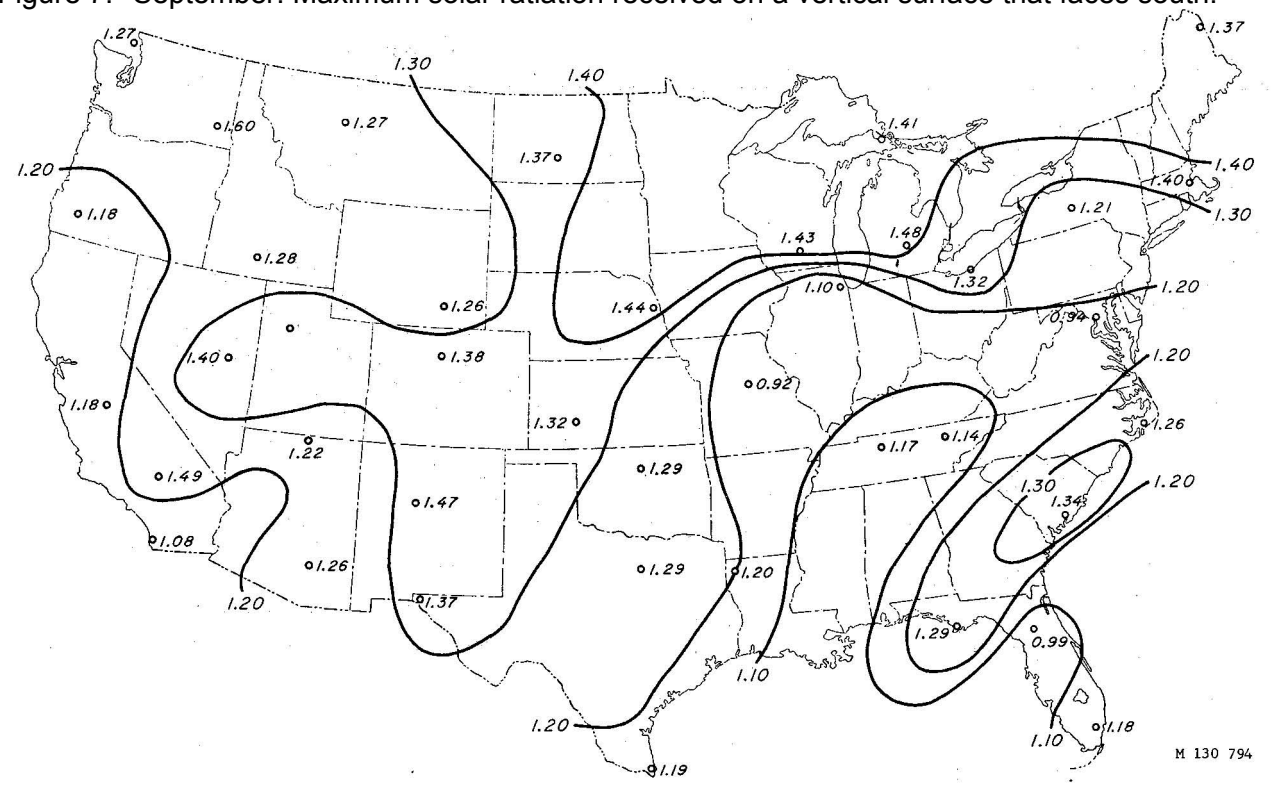

Figure 8.--December: Maximum solar radiation received on a vertical surface that faces south.

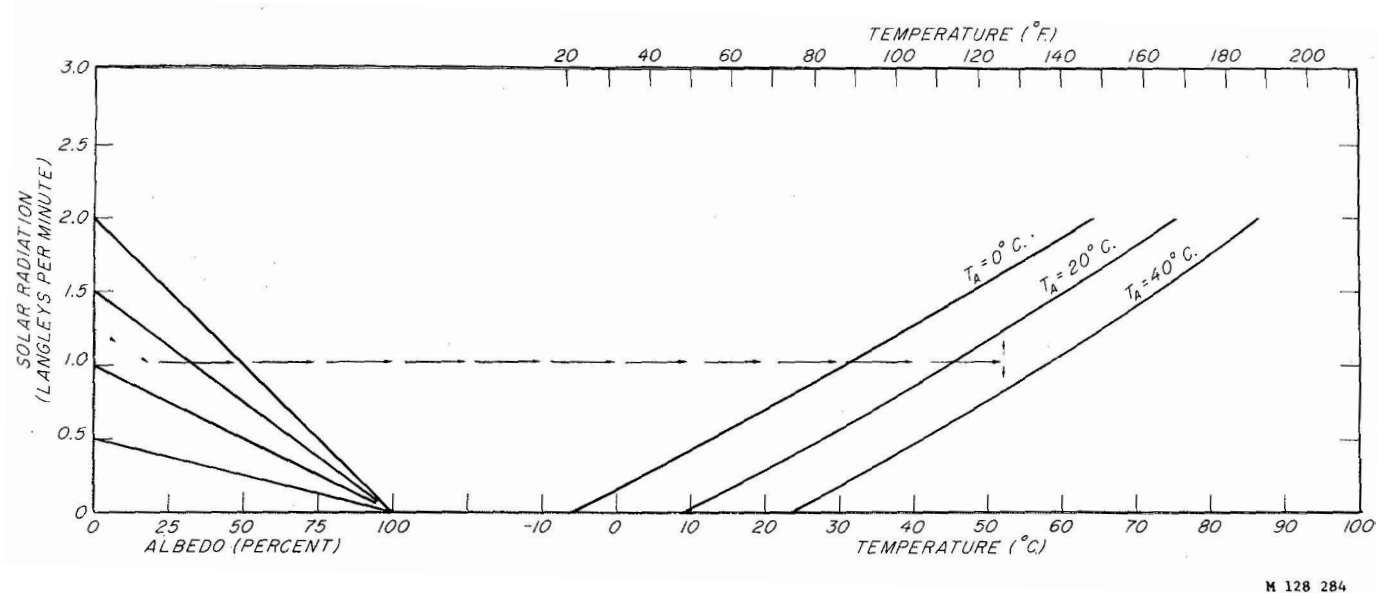

Figure 9.--Relationships to predict maximum temperatures on horizontal painted surfaces.

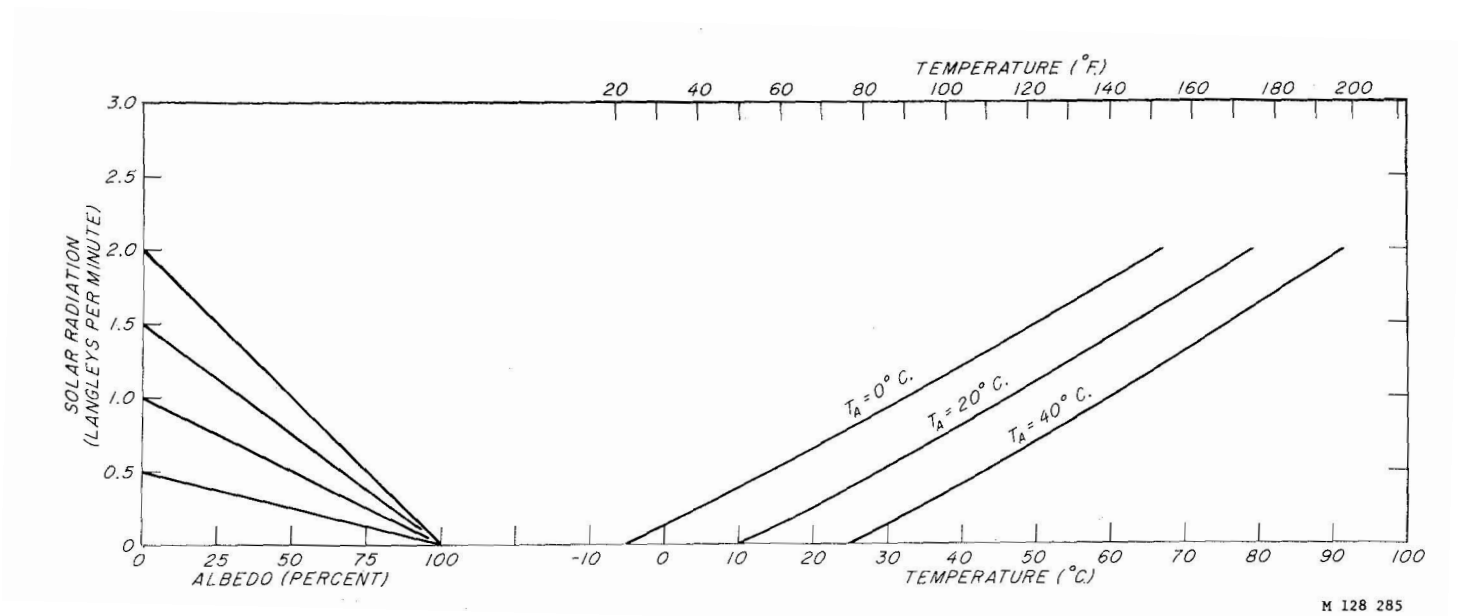

Figure 10.--Relationships to predict maximum temperatures on horizontal wood surfaces.

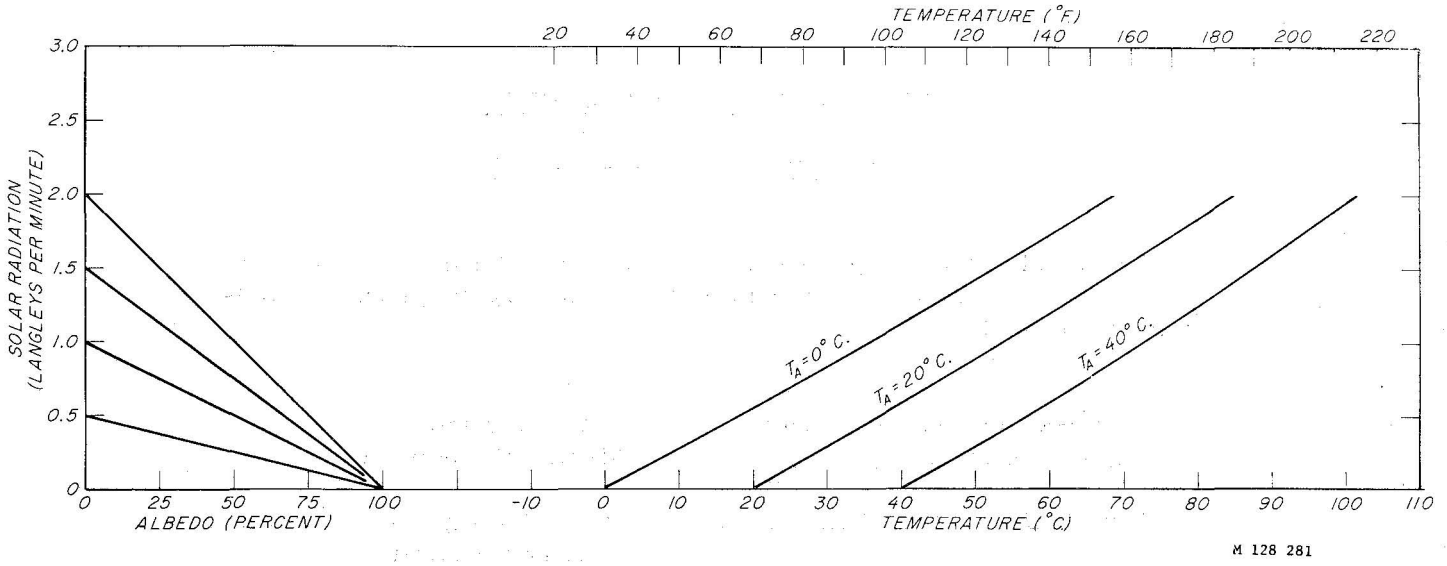

Figure 11.--Relationships to predict maximum temperatures on vertical painted surfaces.

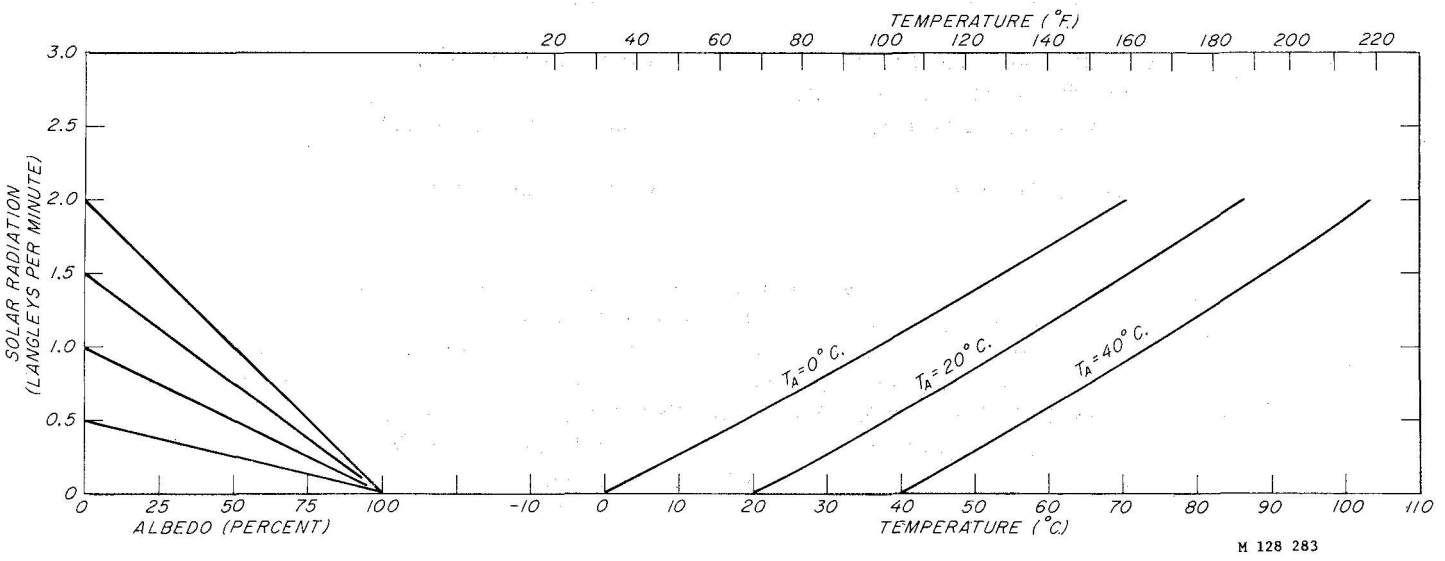

Figure 12.--Relationships to predict maximum temperatures on vertical wood surfaces.

PUBLICATION LISTS ISSUED BY THE

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The following lists of publications deal with investigative projects of the Forest Products Laboratory or relate to special interest groups and are available upon request:

Architects, Builders, Engineers, and Retail Lumbermen

Box, Crate, and Packaging Data

Chemistry of Wood

Drying of Wood

Fire Protection

Fungus and Insect Defects in Forest Products

Furniture Manufacturers, Woodworkers, and Teachers of Woodshop Practice

Glue and Plywood

Growth, Structure, and Identification of Wood

Logging, Milling, and Utilization of Timber Products

Mechanical Properties of Timber

Structural Sandwich, Plastic Laminates, and Wood-Base Components

Thermal Properties of Wood

Wood Fiber Products

Wood Finishing Subjects

Wood Preservation

Note: Since Forest Products Laboratory publications are so varied in subject matter, no single catalog of titles is issued. Instead, a listing is made for each area of Laboratory research. Twice a year, January 1 and July 1, a list is compiled showing new reports for the previous 6 months. This is the only item sent regularly to the Laboratory's mailing roster, and it serves to keep current the various subject matter listings. Names may be added to the mailing roster upon request.

The FOREST SERVICE of the U. S. DEPARTMENT OF AGRICULTURE is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, arid management of the National Forests and National Grasslands, it strives - as directed by Congress - to provide increasingly greater service to a growing Nation.