Specific Heat of Ovendry Spruce Pine Wood and Bark

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ABSTRACT. Wood and bark from 72 trees of *Pinus glabra* Walt. were evaluated with a Perkin-Elmer DSC-1B scanning calorimeter; a total of 6,696 observations was made in the temperature range 60 to 140°C. The samples were from Louisiana, Mississippi, and Alabama — the major commercial range of the species.

For wood representative of the trees, specific heat = 0.2651 + 0.001004 (temperature in degrees C.); heartwood appeared to have a higher specific heat than sapwood; latewood had a higher specific heat than earlywood. While latewood specific heat had a positive linear relationship with temperature, earlywood specific heat was a function of temperature and temperature squared, so that the curve was convex upward. Wood of maximum specific heat was latewood from trees in the eastern part of the major range, taken from the heartwood close to ground level.

For bark representative of the trees, specific heat = 0.3322 — 0.0002582 (temperature in degrees C.) + 0.000005137 (temperature squared); this curve is concave upward. Bark of maximum specific heat was from the tops of fast-grown trees in the southern part of the range. With all other factors fixed, specific heat of bark was negatively related to number of annual rings at the point of sampling.

THE FOREST PRODUCTS UTILIZATION RESEARCH PROJECT in Alexandria, La., is engaged in a systematic evaluation of southern pine wood as an industrial raw material. The specific heat of wood — that is, the heat capacity of a given mass of wood compared to the heat capacity of the same mass of water at 15°C. — is a fundamental thermal property and therefore of interest. Heat capacity of a material may be expressed as the number of calories required to raise 1 gram 1°C. in temperature. Because heat capacity of water at 15°C. is 1 calorie per gram per degree C., heat capacit and specific heat are numerically equal.

The design of this study was influenced b two factors. First was the knowledge th prior workers had reported mean specific he of large specimens averaged over rather wid temperature ranges. Second, availability c the relatively new scanning calorimeter pe mitted evaluation of very small specimens (to 20 milligrams) at precise temperature Since southern pine wood varies in many c its properties, it was thought probable th small variations also exist in the specific he of wood and bark.

In recognition of the problems faced by pr vious workers, the purpose of the present r search was to study variation exhaustive within a single species. Spruce pine (*Pin glabra* Walt.) was selected because it is compact population and therefore easi sampled.

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The specific objectives were:

1) To determine, for the major range of the species, the average specific heats for bark and wood, the averages to be stratified into three age classes and two growth rates.
2) To measure the variation in specific heat as a function of temperature in the range from 60 to 140°C. (140 to 284°F.).
3) To determine the variation in the specific heat of earlywood, latewood, and bark, with height in the tree, years from the pith, latitude and longitude, and specific gravity of specimens.
4) To compare the specific heats of sapwood and heartwood.
5) To determine, by regression relationships, which location in the tree provides the most accurate sampling point for predicting the tree average.
6) To develop regression relationships for predicting tree-average values from samples taken approximately 1 foot above ground level.

An additional aim was to review comprehensively the literature pertinent to moist as well as dry wood and bark, even though the research was restricted to dry material.

The report printed here is highly condensed. For those researchers who desire to investigate the subject further, the full literature review, explicit procedure, detailed results, and error analysis are available from the author.

The Literature in Brief

Specific Heat of Dry Wood

Dunlap (1912) is the major reference on the subject. With a modification of Bunsen's ice calorimeter he measured the specific heat of small cylinders of ovendry wood. The specimens weighed about 6 grams and were 1.7 centimeters in diameter and 3 to 9 centimeters in length.

From a total of 110 evaluations on 20 species ranging in specific gravity from 0.23 to 1.10, he determined that the true specific heat (c_p) of wood varies with temperature in the range from zero° C. to approximately 112°C., and that the relationship is expressed by a straight line: true specific heat $= c_p = 0.266 + 0.00116T$, where T is in degrees C. Because Dunlap was measuring mean specific heat ($\bar{c}_p$) over an interval from starting temperature (T_0) to endpoint temperature (T_1), his equation is more properly expressed:

$$\bar{c}_p = 0.266 + 0.00058\ (T_0 + T_1)$$

In Kiel in 1896, B. Volbehr wrote an unpublished doctoral thesis titled, "Swelling of Wood Fibers"[1]. He proposed an expression for the mean specific heat of wood over the range from zero to 100°C. with moisture content in the range from zero to 27 percent:

$$\bar{c}_p = 0.2590 + 0.000975m + 0.000605T_1 + 0.000015mT_1$$

where $\bar{c}_p$ = mean specific heat over the range in question

m = moisture content as a percentage of ovendry weight, *e.g.*, at 25 percent moisture content, $m = 25$.

T_1 = endpoint temperature, with starting temperature at zero° C.

With m equal to zero, and in terms of true specific heat at a particular temperature (T) in the range from zero to 100°C.:

$$c_p = 0.2590 + 0.001210T$$

This equation is similar in slope to Dunlap's equation for essentially the same temperature range, but has a slightly lower intercept.

Koljo (1950) reported the specific heat of dry wood to be 0.280 at zero° C.

While Dunlap reported no differences among species, Geiger (1942) observed that ovendry spruce had a mean specific heat of 0.323 (compared to 0.351 for beech) when cooled over the interval from 50 to —25°C. Narayanamurti and Jain (1958) evaluated ovendry wood of nine Indian species at 18°C. and found a range of values from 0.310 to 0.413.

Specific Heat of Wet Wood

Moist wood has a higher specific heat than the relative proportions of wood and water would suggest (Byram *et al.*, 1952).

Kelsey and Clarke (1956), in experiments on klinki pine (*Araucaria klinkii* Lauterb.)

[1]Original not seen. Information is from Beall (1968 and Narayanamurti and Jain (1958).

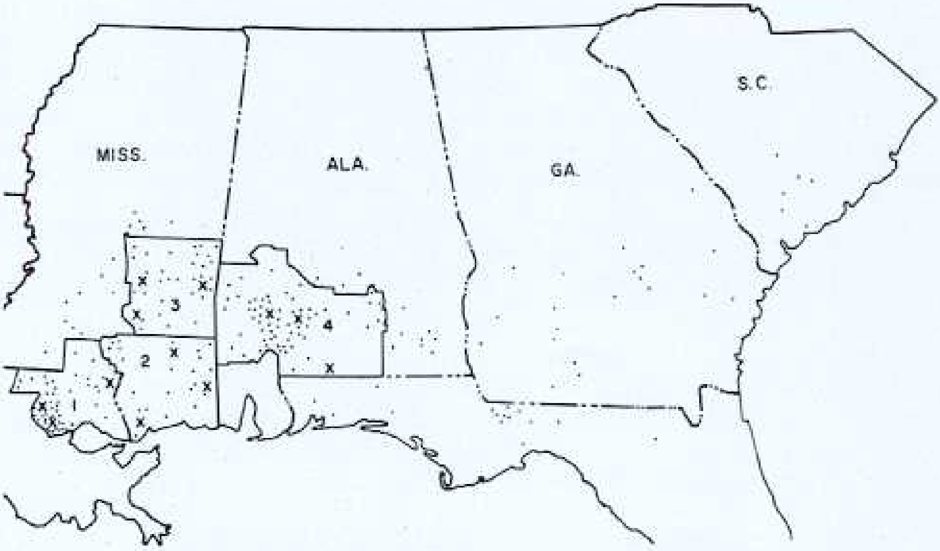

Figure 1. — The four areas from which spruce pine trees were sampled. Each X represents a replication comprised of six trees (three ages and two growth rates). Each dot represents a volume of 2 million cubic feet, as determined by the Forest Survey.

observed that at all moisture contents the apparent specific heat of sorbed water was either greater than or equal to that of free water. They also observed that the heat of sorption was negatively correlated with both moisture content and temperature. Heat of sorption decreased as moisture content increased. Within the range 27 to 46°C., heat of sorption at the lowest moisture contents was independent of temperature, but at moisture contents above 8 percent (dry-weight basis), the heat evolved on sorption decreased with increasing temperature. They concluded that the effect of temperature on the heat of sorption is adequate to account for the observed departure of the specific heat-moisture content relation for wood from that of simple mixtures.

Hearmon and Burcham (1956) concluded that Kirchoff's thermochemical equation can be applied to determine the specific heat of moist wood:

$$\frac{(-dw/dT)}{1+u} = c_{pu} - c_{simple\ mixture} = \Delta c_{pu}$$

where w is the heat evolved (calories per gram of dry material) in wetting the material from dryness to moisture content u (fraction of dry weight), and T is the temperature. c_{pu} is the true specific heat of the moist wood, an $c_{simple\ mixture}$ that calculated on the simpl basis of the relative amounts of wood an water. The elevation in specific heat of th moist wood — related to temperature depenc ency of the heat evolved in wetting the ma terial — is Δc_{pu} (found equal to 0.054 calori per gram of moist wood per degree C. whe measured at 50°C. on beech sawdust at 2 percent moisture content).

Kuhlmann (1962) measured the specif heat of dry and moist wood in the tempera ture range —60 to 80°C. Whereas the spec fic heat of dry wood was a straight-line fun tion of temperature, the graphs for moi wood were increasingly curvilinear (concav upward) with increasing moisture content.

Specific Heat of Dry Bark

Koljo (1950) determined the specific he of bark from spruce, pine, and birch tree For ovendry bark (at 22°C.) he recorded value of 0.320.

Martin's (1963) specific heat for ovendr bark from eight species (60 specimens) ave aged 0.329 at 56°C. The mean for his 1 specimens of shortleaf pine was also 0.32 Analysis of variance showed no significa difference between specimens or species.

Reifsnyder *et al.* (1967) evaluated the specific heat of ovendry bark from 90-year-old longleaf, 70-year-old shortleaf, and 40-year-old red pine trees. At 60°C., the variation between trees was significant, but not the variation between species:

Species	Specific heat	Number of trees	Total samples per species
Longleaf pine	0.303	5	20
Shortleaf pine	.322	5	20
Red pine	.323	4	15
Average of 55 samples	0.316		

Specific Heat of Wet Bark

Martin (1963) measured the elevation of specific heat — above that suggested by a simple mixture of water and bark — for bark at 27 percent moisture content and 56°C. He reported a value of 0.083 calorie per gram of ovendry bark per degree C. The elevation of specific heat had a positive linear relationship to moisture content between zero and 27 percent. Above 27 percent moisture content the value was constant at 0.083.

General Theory

Ward and Skaar (1963), in a study of the specific heat of moist particleboard, examined the 1819 empirical law of Dulong and

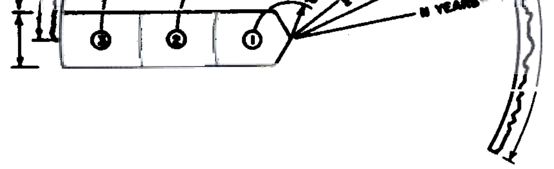

Figure 2. — Average value for specific heat of bark of each disk was determined from bark stripped from a 210° segment of the three disks taken from the top, bottom, and approximate midpoints of each bole. Identity of bark from each disk was maintained. Specific heat of earlywood and latewood was measured at sample points 1, 2, and 3 — *i.e.*, six specimens per disk.

Petit and discussed its inapplicability to wood-based material. Following a review of the more modern Debye theory, they used Dunlap's data and their own experimental data to estimate the atomic heat capacity at constant volume (equal to the specific heat at constant volume x atomic weight) of wood and moist particleboard. Both curves are functions of temperature. In the range zero to 100°C., their curve for dry wood falls very close to experimentally determined values for graphite. Moist particleboard was shown to have a slightly higher atomic heat capacity at constant volume.

Procedure

A stratified random sample of 72 spruce pine trees was cut in the area encompassing the major range of the species. Tree variables were:

1) Geographic location: four areas (Fig. 1).
2) Age of tree: 15, 30, or 45 years.
3) Rings per inch 1 foot above ground: either less than six or more than six.
4) Replications of trees: three.

The 72 trees were felled and cross-sectional disks were removed at 8-foot intervals beginning at 1 foot above ground level and ending at a 4-inch top. These disks provided wood and bark representative of each entire tree.

Three of the disks per tree — those taken at 1 foot above ground, at a 4-inch top, and halfway between — also provided wood and bark for analysis of within-tree variability:

1) Height above ground: at the three positions represented by the disks.
2) Radial position in the stem: 1/6, 3/6, and 5/6 of the annual rings from the pith (Fig. 2).
3) Cell type: earlywood and latewood.

Thus, the six-factor experiment required 1,296 solid-wood specimens: (four locations) (three age classes) (two growth rates) (three replications of trees) (three heights) (three radial positions) (two cell types). For each specimen, distance from the pith was recorded in both rings and inches; distance above the ground was measured in feet. These 1,296 solid specimens will hereafter be referred to as point wood. They were comprised of 18 specimens from each of the 72 trees (three disks per tree x six specimens per disk, as explained in Fig. 2). Half were latewood and half earlywood.

In addition, three other sets of samples were drawn:

Tree wood: 360 wood specimens prepared from pairs of opposed 30-degree wedges taken from disks at 8-foot intervals to a 4-inch top. The average value for each of the 72 trees was derived from five replications. Wedges were milled and screened to facilitate preparation of representative specimens.

Tree bark: 360 bark specimens prepared (by milling and screening) from wedges taken at 8-foot intervals to a 4-inch top. The average value for each of the 72 trees was derived from five replications.

Disk bark: 216 milled bark specimens, one from each of the three disks taken at top, bottom, and midpoint of each of the 72 trees.

Because each of the 2,232 samples was evaluated at three temperatures, a total of 6,696 observations was made.

The drying procedure for specimens had to be such that there would be no appreciable weight change (±0.05 milligram) during the total calorimeter scan. Wood specimens were dried for 8 hours in a vacuum oven at 103°C. Bark specimens were dried on the calorimeter at 152°C. Each specimen was weighed after as well as before it was run, and the averag weight was used in calculating the specifi heat.

Scanning Calorimeter

The instrument employed for evaluation c specific heat was the Perkin-Elmer DSC-1l differential scanning calorimeter (Fig. 3).

In this calorimeter, specimen and referenc material are subjected to increasing (or de creasing) temperature at a closely controlle rate. A monitoring system detects any differ ence between specimen and reference tem perature and simultaneously changes th amount of heat supplied to either specimen c reference in order to maintain both at th same temperature.

The instrument's actual measurement is nc the difference in temperature between spec men and reference; this always remains ve small. Instead, the measurement is the diffe ence in electrical power required to maintai specimen and reference at the desired ten perature. Thermal lags are minimized by u of very small specimens.

Because the recorder is arranged with di ferential energy as the ordinate and tin (hence temperature when programmed to specific rate of temperature rise) as th

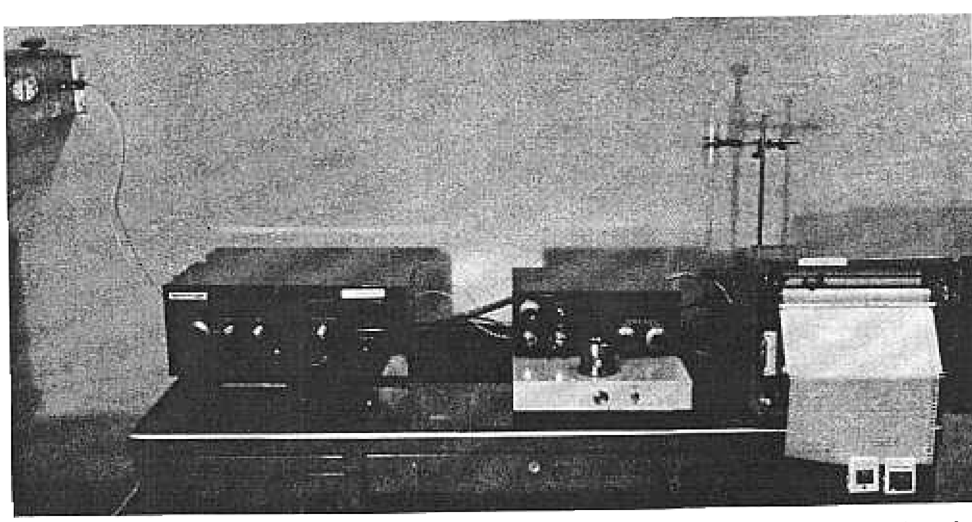

Figure 3. — Perkin-Elmer DSC-1B differential scanning calorimeter. Extreme upper left: valve to control purging nitrogen. Left: Temperature indicator and scan control. Center: Sensing head in which specimen and reference were subjected to increasing temperature at a closely controlled rate. Right: Chart to record the difference in electrical power required to maintain the specimen, as compared to the reference, at a programmed rate of temperature rise (in this case 10°C. per minute). Glass apparatus on back of table provided check on nitrogen flow rate.

abscissa, the ordinate readout is directly proportional to dH/dt; where H is heat and t is time.

In this study, the thermal quantity of interest is dH/dT; where T is temperature. For 1 gram of material, dH/dT is the specific heat (c_p) in calories per gram per degree C.

Typically, specific heat is a slowly varying function of temperature.

The readout

$$\frac{dH}{dt} = \frac{dH}{dT} \cdot \frac{dT}{dt} = c_p \cdot \frac{dT}{dt} = c_p\dot{T}$$

where $\frac{dT}{dt} = \dot{T} =$ the scanning rate — for example, 1/6°C. per second.

The ordinate displacement is proportional to $\dot{T}c_pm$, where m is the mass of the specimen in grams.

Essentials of the measurement procedure may be described briefly.

The sample pans were of aluminum, approximately 0.25 inch in diameter and 0.05 inch deep. Each pan had a flat aluminum lid, which fitted inside the pan directly on the sample. Cleaned pans and lids were weight-matched before loading. Pans could be sealed (not hermetically) with a crimping device, and powdered specimens (tree wood and all bark samples) were crimped to prevent spillage. Specimens of solid wood taken from the 1,296 sample points were merely deposited in the pans and the lids placed on top.

Table 1. — SPECIFIC HEAT OF OVENDRY SPRUCE PINE WOOD.

Stratification of trees	Specific heat of tree wood at 60°C.	100°C.	140°C.
15-year-old trees			
Slow-grown	0.3268	0.3670	0.4086
Fast-grown	.3212	.3629	.3993
30-year-old trees			
Slow-grown	.3242	.3655	.4038
Fast-grown	.3263	.3676	.4084
45-year-old trees			
Slow-grown	.3253	.3674	.4062
Fast-grown	.3263	.3670	.4055

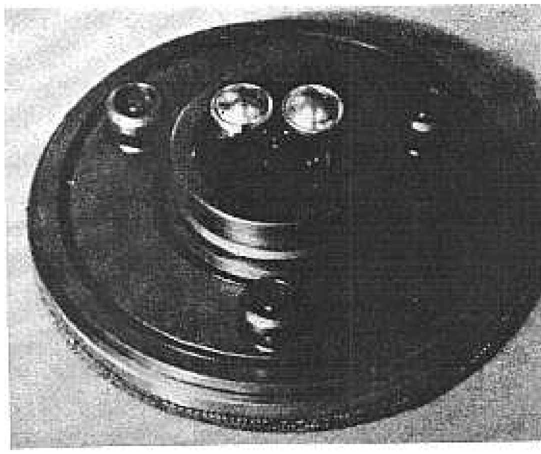

Figure 4.—View down into the nitrogen purged sensing head (top removed). Specimen and reference pans are under the two dome-shaped covers. Each pan rests on its individual heating element. The pans and covers were matched by weight. Weight-matching equalizes differential displacement due to the mc_p effect. The purpose of the domes was to maintain relatively constant radiation and convection behavior, and to minimize the effect of sample placement in the holder.

After the instrument had been calibrated, empty sample pans with lids were placed in both specimen and reference holders. Domed covers then were carefully placed over the lidded pans (Fig. 4). The temperature was dialed to 50°C. and held constant until the pen reached equilibrium and drew a flat line for at least half a minute. Scanning was then begun at the rate of 10°C. per minute and allowed to continue for 2 minutes. When the temperature reached 70°C., the scan was stopped and the pen again allowed to reach equilibrium and run flat for at least half a minute. This procedure was repeated for scans from 90 to 110°C. and 130 to 150°C. Then the temperature was dialed down to 50°C. and the blank pan removed. The head was cooled with a hand blower until temperature control was regained. A sapphire standard was next put in the sample pan, the lid dropped in place but not crimped, and the sapphire run in the same manner as the blank. From these two runs a constant was computed to be used in determining the actual specific heat of the wood and bark specimens. The wood or bark specimens, which weighed between 5 and 2C milligrams, then replaced the sapphire standard. The specific heat was calculated at the midpoints of the three scans, *i.e.*, at 60, 100, and 140°C.

The temperature program is not strictly linear over the whole range of interest. Thus, the ordinate calibration constant is, to some degree, a function of temperature. The use of a standard run under the same conditions as the unknown specimen eliminates this error. Since the specific heat of synthetic sapphire has been determined to five significant figures in the range zero to 1,200°K. by Ginnings and Furukawa (1953), and since sapphire could be obtained as small disks exactly fitting a sample pan, it was an excellent material for a standard.

In Figure 5, the baseline *ABC* is the scan made with empty sample pans and covers in both specimen and reference holders. The curve *AEC* is the scan of a sapphire disk used in an illustrative c_p determination. At any point in dynamic equilibrium on the curve, the ordinate deflection y is equal to $K\dot{T}c_pm$,

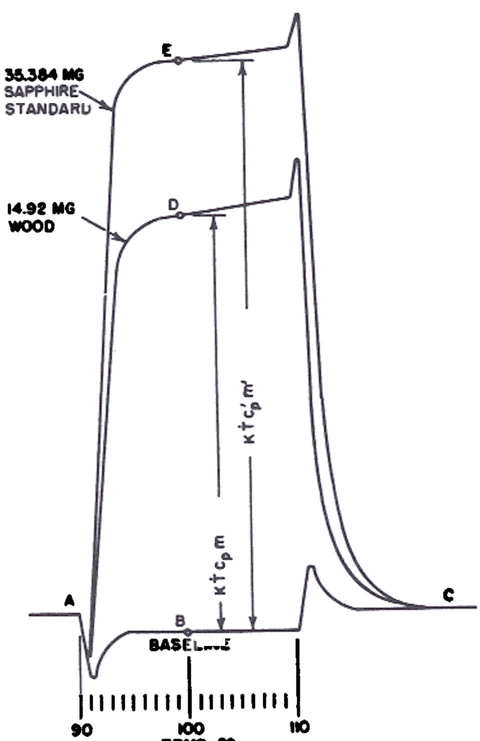

Figure 5. — Typical calorimeter plots for spruce pine wood in the range 90 to 110°C.; scanning rate, 10°C. per minute; full-scale chart deflection, 2 millicalories per second; chart speed, 1 inch per minte. Determination made at 100°C.

where K is the calibration constant. Thus,

for sapphire $\quad y' = K\dot{T}c_p'm'$,

and for the wood or bark sample $\quad y = K\dot{T}c_pm$,

therefore $\quad c_p \quad \frac{ym'}{y'm} (c_p'$

Because a single sapphire standard of known specific heat and mass was used during the entire experiment, the equation above was simplified to:

$$c_p = (constant)\cdot\frac{y}{y'm}$$

The principal source of error in the de termination of specific heat by this method i: uncertainty about the location of the no specimen baseline. Baseline error was reducec by scanning over a short interval (20°C.) anc by replicating the observations. Errors als occurred in measurements of the ordinate anc in weight determinations. The manufacture claims that, with good experimental tech nique, c_p may be routinely measured to withi ± 2 percent without replication. Runs wit one sapphire disk as the known material an another as the unknown appeared to confir this claim. Many of the errors occurred ran domly, and for the study as a whole it appear that individual values are, at best, accurat to three significant figures, *e.g.*, 0.332. Becaus observations were numerous, averages ar possibly accurate to four places, *e.g.*, 0.332 and are so recorded. Computer determinatio of standard errors applicable to specific curve required retention of additional places, as i dicated by the equations printed in the Re sults section of the text. Equations in th Abstract and the Discussion-Summary sectio have been rounded to four significant place

Results

Tree Wood and Species Average Values

The grand mean of specific heat at eac temperature was:

Temperature (°C.)	Specific heat of tree woc
60	0.3250
100	.3662
140	.4053

Table 2.—SPECIES AVERAGES FOR SPECIFIC HEAT OF OVENDRY SPRUCE PINE EARLYWOOD AND LATEWOOD.

Species stratification	Specific heat at 60°C.	100°C.	140°C.
15-year-old trees			
Slow-grown			
Earlywood	0.3231	0.3656	0.3985
Latewood	.3264	.3676	.4043
Fast-grown			
Earlywood	.3238	.3644	.3993
Latewood	.3255	.3638	.4019
30-year-old trees			
Slow-grown			
Earlywood	.3262	.3673	.4003
Latewood	.3261	.3657	.4027
Fast-grown			
Earlywood	.3219	.3649	.3984
Latewood	.3251	.3638	.4028
45-year-old trees			
Slow-grown			
Earlywood	.3215	.3637	.3975
Latewood	.3262	.3653	.4039
Fast-grown			
Earlywood	.3247	.3653	.3998
Latewood	.3277	.3657	.4041

Because trees were selected to fill certain age and growth-rate categories, these means cannot be said to represent the species truly.

The interaction of temperature x growth rate x tree age was significant by analysis of variance. The experimental design was such that specific heat values stratified by these three factors are species averages for the geographic range sampled (Table 1).

Since interactions of temperature x area and temperature x growth x area were significant by analysis of variance, stepwise multiple regression analysis was attempted. Factors considered were temperature, temperature squared, tree age, diameter inside bark at 1-foot height, growth rate at 1-foot height, specific gravity of wood (green volume and ovendry weight), latitude, and longitude.

At this intensity of sampling to establish the tree wood average (360 samples, *i.e.*, 72 trees replicated five times), none of these factors proved significant after temperature. The best equation accounted for 95.4 percent of the variation with a standard error of the estimate of 0.007243:

Tree wood specific heat =
0.2651253 + 0.0010039 (temperature, °C.)

This expression was determined for the temperature range 60 to 140°C. With 95-percent confidence, it can be said that the true value of the zero°C. intercept for these tree-wood values is within the range from 0.2620 to 0.2683.

Point Wood and Within-Tree Variation

The interaction of cell type x growth rate x age was significant. Species averages (in the geographic range sampled) for earlywood and latewood are shown in Table 2.

Of the 1,296 specimens of earlywood and latewood, 1,238 were in sapwood and only 58 in heartwood:

Specimen location	Specific heat at 60°C.	100°C.	140°C.
Heartwood (avg. of 58)	0.3284	0.3703	0.4080
Sapwood (avg. of 1,238)	.3247	.3650	.4008

From these data it would appear that sapwood has a lower specific heat than heart-

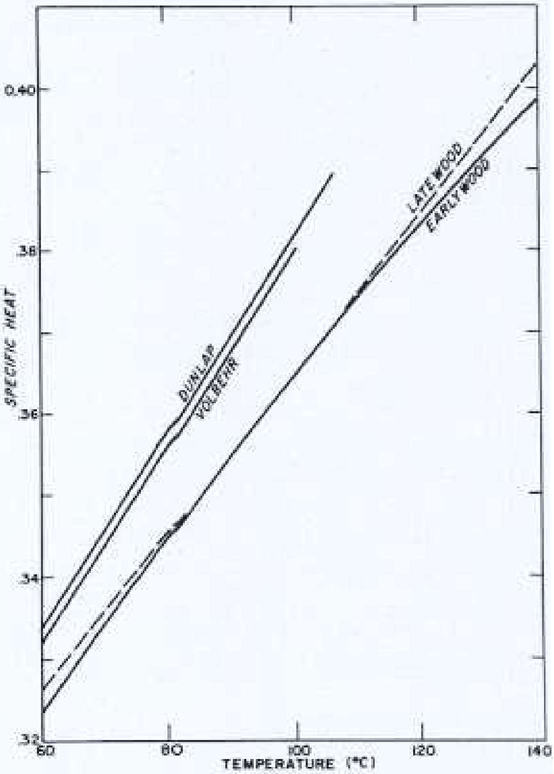

Figure 6. — Specific heat of latewood and earlywood as related to temperature. Curves are compared to data from Dunlap (1912) and from Volbehr's dissertation.

wood, but the unbalanced sample ruled out a rigorous statistical test.

Values for latewood and earlywood were analyzed by multiple stepwise regression to clarify interactions found significant by analysis of variance. The relationship of temperature to specific heat tends to mask the less potent variables of rings from pith, height in tree, specific gravity of point wood, latitude, and longitude. For this reason, a separate analysis was made at each of the three temperatures.

In these analyses, none of the foregoing factors proved significant for earlywood. Latewood specific heat at all three temperatures was negatively correlated with both height in the tree and longitude, but the relationships were very weak (R^2 of 0.03 or less):

Temperature (°C.)	Specific heat Earlywood	Specific heat Latewood
60	0.3235	0.3262
100	.3652	.3653
140	.3990	.4033

To show all relationships, including temperature, stepwise regression analyses were performed for all latewood, all earlywood, and pooled latewood and earlywood observations. Factors evaluated were temperature, temperature squared, rings from pith, specific gravity of point wood, height in tree, latitude, and longitude. For latewood, only temperature proved significant. The linear relationship was based on 1,944 observations, *i.e.*, 648 specimens x three temperatures. The equation (Fig. 6) accounted for 93.8 percent of the variation with a standard error of the estimate of 0.008128:

Specific heat of latewood =
0.2685083 + 0.00096392 (temperature, °C.)

With 95-percent confidence, it can be said that the true value of the zero°C. intercept for these latewood data is between 0.2674 and 0.2697. In the absence of data at lower temperatures, applicability of the equation is restricted to the range from 60 to 140°C.

For earlywood, temperature and temperature squared were the only significant variables. The earlywood curve of Figure 6 is also based on 1,944 observations. The equation accounted for 89.5 percent of the variation with a standard error of 0.010557:

Table 3. — SPECIFIC HEAT OF OVENDRY SPRUCE PINE BARK.

Stratification of trees	Specific heat of tree bark at 60°C.	100°C.	140°C.
15-year-old trees			
Slow-grown	0.3307	0.3541	0.3948
Fast-grown	.3361	.3602	.3957
30-year-old trees			
Slow-grown	.3369	.3566	.3963
Fast-grown	.3359	.3586	.3958
45-year-old trees			
Slow-grown	.3352	.3556	.3958
Fast-grown	.3366	.3615	.4022

Specific heat of earlywood =
0.2461675 + 0.0014370 (temperature, °C.) — 0.0000024692 (temperature squared)

Applicability of this curvilinear relationshi[p] for earlywood is limited to the range from 6[0] to 140°C.

When latewood and earlywood data wer[e] pooled to obtain the benefit of all 3,888 observations of pointwood, the factors of specifi[c] gravity (+), height (—), and longitude (—) entered the stepwise multiple regression expression. While significant, these relationship[s] were very weak and probably not of practica[l] importance.

No sampling point was located from whic[h] tree specific heat could be predicted with accuracy.

Tree Bark and Species Average Values

The grand mean of bark specific heat [a]t each temperature was:

Temperature (°C.)	Specific heat of tree bar[k]
60	0.3352
100	.3578
140	.3968

Because trees were selected to fill specif[ic] categories of age and growth rate, these mea[ns] are not necessarily representative of th[e] species.

The interaction of temperature x growt[h] rate x tree age was significant by analysis [of] variance. The experimental design was su[ch] that specific heat values stratified by the three factors are species averages for the geographical range sampled (Table 3).

In general, bark from slow-grown trees had lower specific heat than bark from fast-grown trees:

Tree growth rate	Specific heat; combined data for all temperatures
Slow (more than six rings per inch)	0.3618
Fast (less than six rings per inch)	.3648

To clarify interactions indicated by analysis of variance, regression analysis was made of the relationship between the specific heat of ovendry tree bark and the factors of temperature, temperature squared, latitude, longitude, specific gravity of bark, tree age, diameter of tree at 1-foot height, and growth rate at 1-foot height.

Growth rate (inches of diameter per year) entered the multiple regression expression as a significant factor (+), but from a practical standpoint it appeared that specific heat of tree bark could be expressed simply as a function of temperature and temperature squared (in the range of 60 to 140°C.). This simpler equation accounted for 94.5 per cent of the variation with a standard error of 0.006171 (Fig. 7):

Specific heat of tree bark =
0.3322344 — 0.0002582 (temperature, °C.) + 0.000005137 (temperature squared)

The relationship was based on 1,080 observations, *i.e.*, 72 trees *x* five replications *x* three temperatures.

Disk Bark and Within-Tree Variation

The three disks taken from each tree (near ground level, at a 4-inch top, and halfway between) provided bark that permitted a study of within-tree variation.

To show all relationships, disk bark data were studied by stepwise regression. Factors evaluated were temperature, temperature squared, age of disk, diameter of disk, growth rate of disk, specific gravity of disk bark, height in the tree, latitude, and longitude. All of these except diameter, longitude, and bark specific gravity proved significant. The equation accounted for 89.7 percent of the variation with a standard error 0.008455:

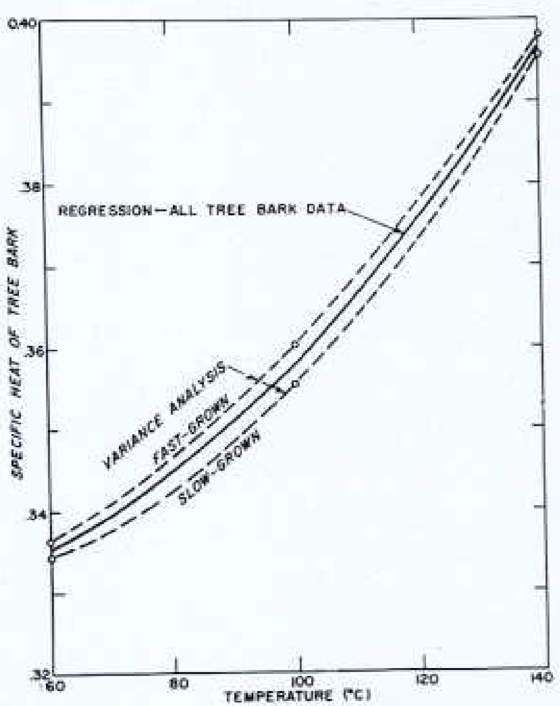

Figure 7. — Specific heat of tree bark related to temperature; regression curve based on 1,080 observations. The dashed lines connect category averages and illustrate the temperature X growth interaction.

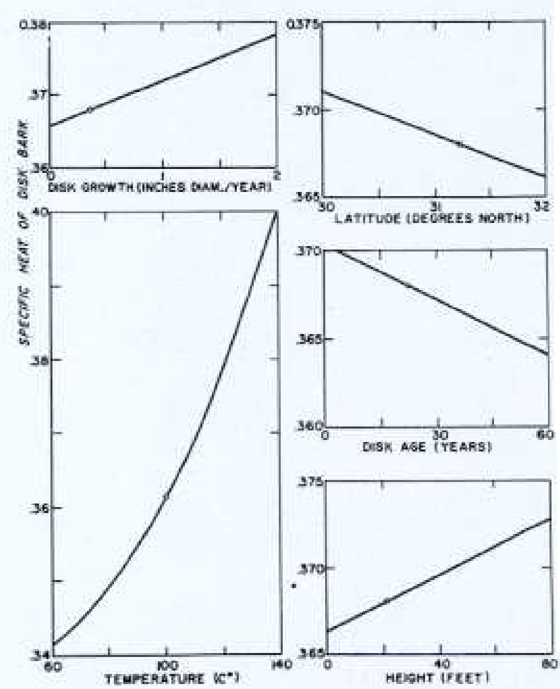

Figure 8. — Relationship of specific heat of disk bark to temperature, height in tree, disk growth rate, disk age, and latitude. Curves are based on 648 observations, *i.e.*, (72 trees) (three disks) (three temperatures).

Specific heat of disk bark = 0.4291753 —
0.0004518 (temperature, degrees C.) +
0.0000779 (height, feet) —
0.0001022 (age of disk, years) —
0.0026718 (latitude, degrees) +
0.00000595704 (temperature squared) +
0.0062364 (growth rate, inches of dia. per year)

Figure 8 shows the individual effects of the significant factors. The plots for each factor were made by holding all other variables constant at their average values.

No sampling point was found from which tree bark specific heat could be predicted with accuracy.

Discussion and Summary

A few new relationships were observed in this study. The conclusions stated below are applicable to ovendry spruce pine from the major geographic range (Fig. 1) and for material evaluated at temperatures between 60 and 140°C.

Wood

1) For wood representative of the trees, specific heat = 0.2651 + 0.001004 (temperature in degrees C.). Species values stratified by tree age and growth rate were established (Table 1).
2) Heartwood appeared to have a higher specific heat than sapwood.
3) Latewood had a higher specific heat than earlywood (Fig. 6).
4) Latewood specific heat had a weak negative correlation with height above ground and with longitude.
5) While latewood specific heat had a positive linear relationship with temperature, earlywood specific heat was a function of temperature and temperature squared (Fig. 6). The curve was convex upward.
6) Specific heat of pooled earlywood and latewood had a weak positive correlation with specific gravity.
7) No sampling point was located from which specific heat for wood of the entire tree could be predicted with accuracy.

For tree wood at the intensity of sampling stated (360 samples, *i.e.*, 72 trees replicated five times), in the range 60 to 140°C., the specific heat of spruce pine wood was validly expressed as a straight-line function of temperature only. The zero°C. intercept of this straight line fell very close to the zero°C. intercepts which Volbehr, Dunlap (1912), and Koljo (1950) determined for other species after observations from zero to 100°C:

	Intercept at 0°C.	Specific heat at 100°C.
Volbehr	0.2590	0.3800
Dunlap	.266	.382
Koljo	.260	——
Koch (spruce pine tree wood)	.2651	.3655

The slope of the line, however, was considerably less than that observed by either Dunlap or Volbehr. These data lend support to the position of Geiger (1942) and of Narayanamurti and Jain (1958) that specific heat may vary among tree species. The differences observed in this experiment between heartwood and sapwood and between earlywood and latewood, also suggest that there may be differences among species.

The relationships indicated that the material of maximum specific heat was latewood from trees in the eastern part of the major range, taken from the heartwood zone close to ground level. Presumably the observed variability in specific heat with position in tree and geographic location is mainly a result of variability in the proportions of cellulose, lignin, and extractives comprising the wood.

Bark

1) For bark representative of the trees specific heat = 0.3322 — 0.0002582 (temperature in degrees C.) + 0.00000513 (temperature squared). Species values stratified by tree age and growth rate were established (Table 3).
2) Specific heat of bark was a function of temperature and temperature squared (Figs. 7 and 8). The curve was concave upward.
3) Specific heat of disk bark was positively correlated with height above ground and negatively correlated with disk age and latitude (Fig. 8).
4) Bark from fast-grown trees had higher specific heat than bark from slow-grown trees (Figs. 7 and 8).

5) No sampling point was located from which specific heat of tree bark could be predicted with accuracy.

Much prior research on the specific heat of ovendry bark has been concerned with temperatures below the range 60 to 140°C. However, a few values for 60°C. are available for comparison:

	Species	Specific heat at 60°C.
Reifsnyder *et al.* (1967)	longleaf	0.303
Reifsnyder *et al.* (1967)	shortleaf	.322
Martin (1963)	loblolly	.329 (at 56°C.)
Koch (tree bark)	spruce pine	.3352

Although the wood of spruce pine trees evidently has lower specific heat than wood of some other species, these data suggest that bark may be comparatively high in specific heat. The major difference between the specific heat of bark and wood was found to be in the temperature relationship. The bark curve was a function of temperature and temperature squared and was concave upward (Figs. 7 and 8), while the curve for wood was a straight line or convex upward (Fig. 6).

Otherwise the values for tree wood and tree bark were quite similar:

Temperature (°C.)	Specific heat: Tree wood	Specific heat: Tree bark
60	0.3250	0.3352
100	.3662	.3578
140	.4053	.3968

For spruce pine disk bark in the range from 60 to 140°C., the relationships indicated that bark of maximum specific heat was from the tops of fast-grown trees in the southern part of the major range. With all other factors fixed, specific heat of bark was negatively correlated with number of annual rings at the point of sampling. It is probable that the observed variability in specific heat with position, location, and growth rate reflects a positive correlation between specific heat and the ratio of phloem to rytidome in bark.

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