United States
Department of
Agriculture

Forest Service

**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Note
INT-342

September 1984

Heat of Preignition of Three Woody Fuels Used in Wildfire Modeling Research

Ronald A. Susott[1]

ABSTRACT

Differential scanning calorimetry has been applied to three woody laboratory fuels studied in current wildland fire modeling research. The heat required to increase a fuel's temperature to ignition is an important modeling parameter affecting the rate of fire spread. Below 200° C, ground fuel-stick samples had similar heat requirements, but above 200° C the heat of preignition varied up to 19 percent among fuels. Therefore, these variations can affect fire spread rates similarly to variations in moisture content. A consistent set of data is provided for calculating the heat of preignition. Thermogravimetric analysis data are included to allow mass balance calculations.

KEYWORDS: specific heat capacity, pyrolysis, thermogravimetric analysis, fire models

Mathematical fire behavior models require the fuel preignition heat (Q_{ig}) as an input parameter (Rothermel 1972; Wilson 1982). This parameter is the total heat required to raise the temperature of unit mass of fuel to the ignition temperature. An ignition temperature of about 320° C is usually assumed. Frandsen (1973) describes a method for calculating Q_{ig} by integrating, over temperature, the specific heat capacities (C_p) of dry fuel and fuel moisture, and adding the heat of vaporization of moisture. Moisture's contribution to Q_{ig} has been assumed to be independent of the fuel burned.

The specific heat capacity of dry fuel, C_p (fuel), is a variable that depends on fuel composition. In general, C_p (fuel) should be determined for each fuel of interest, but in practice the equation for wood reported by Dunlap (1912),

$$C_p \text{ (average)} = 1.11 + 0.00486T \qquad (1)$$

has been used as an average value. C_p is the specific heat capacity (J/°C · g) and T is temperature (°C). This equation is expected to represent wood below 150° C, but may result in considerable error at higher temperatures where C_p data are not available. Heat capacity equations do not apply above the onset of thermal degradation where loss of products begins, but these higher temperature heat requirements are essential to fire behavior modeling.

Differential scanning calorimetry (DSC) has recently been applied to several fuels of interest to forest fire modelers (Susott 1982). That report provided a consistent set of Q_{ig} and weight loss data for packing excelsior (*Populus* spp.), ponderosa pine heartwood (*Pinus ponderosa* Laws.) from ½-inch (12.7-mm) lumber, and Douglas-fir (*Pseudotsuga menzeisii* [Mirb.] Franco) wood from ⅛-inch (3.2-mm) veneer, along with data on three samples of conifer needles and a sample of rotten Douglas-fir wood. The burning characteristics of the first three woody materials have been extensively studied to develop fire behavior models.

Current studies are aimed at extending fire behavior models to a wider range of fuel size, bed depth, packing ratio, and moisture content. These studies have added 1/16-inch (1.6-mm) sugar pine (*Pinus lambertiana* Dougl.) sticks and 1½-inch (38.1-mm) lumber of mixed species (mostly pine and fir) to the list of materials extensively burned. Q_{ig} data are not available on these latter two fuels nor on the ¼-inch (6.4-mm) ponderosa pine fuels burned for Rothermel's original study (1972) and Wilson's current study (1982).

The objective of this note is to provide complete Q_{ig} and weight loss data on the 1/16-, ¼-, and 1½-inch fuels used in fire behavior tests. Accurate data on Q_{ig} will allow a more detailed evaluation of relationships between other model parameters such as fuel bed depth, surface area-to-volume ratio, packing ratio, and moisture content. More complete data will also allow evaluation of new theories of how the heat sink characteristics affect fire behavior.

EXPERIMENTAL METHODS

Sample preparation.—The three wood samples were taken from lumber supplies used extensively for fire modeling (Rothermel 1972; Wilson 1982) at the Northern Forest Fire Laboratory. Small sections of

[1]Research chemist stationed at the Intermountain Station's Northern Forest Fire Laboratory, Missoula, Mont.

about 100 sticks were taken at random, ground to finer than 20 mesh, and combined into one homogeneous sample of each fuel type (sizes 1⁄16-, 1⁄4-, and 1½-inch).

Differential Scanning Calorimetry (DSC).—The DSC method used in this study has been described elsewhere (Susott 1982). The use of a microcomputer/controller facilitated the exact replication of the experimental method. Part of the value of these data is that they form a consistent set, obtained under identical experimental conditions, and should provide valid comparisons between fuels. As before, a 10-mg fuel sample was heated at 20° C/min in a 200 ml/min nitrogen purge. Four replicate runs were averaged for the final result.

A sapphire standard was used to calibrate the DSC heat flow rate. Data from four standard runs were combined and analyzed by polynomial regression resulting in the equation

$$E = 219.9 + 0.01489T + 0.000444T^2 \qquad (2)$$

where E is the DSC calibration coefficient (mW/V) and T is temperature (° C). The coefficient of determination, r^2, was 0.981. Equation 2 is in agreement with the previously reported calibration (Susott 1982) to within 2 percent over the range from 50° to 500° C. As before, all calibration runs were within 5 percent of equation 2. The accuracy of fuel sample measurements is expected to be within better than 5 percent.

Thermogravimetry (TG).—The experimental method used for TG has been described elsewhere (Susott 1980). Two runs at 20°/min were averaged and replicate runs generally agreed to within 1 percent. Sample size and thermal treatment were the same as for DSC runs.

Moisture contents were measured from the TG curves as weight loss at 140° C. TG and DSC data were calculated on a dry weight basis.

The time derivative of the TG curve (DTG) was calculated numerically as reported previously (Susott 1982).

RESULTS AND DISCUSSION

Figures 1, 2, and 3 show the DSC curves for ground samples from 1⁄4-inch ponderosa pine sticks, 1⁄16-inch sugar pine sticks, and the 1½-inch sticks of mill-run pine and fir, respectively. (Endothermic effects cause a positive DSC output.) The DTG curves are superimposed on the DSC to indicate weight losses once moisture is driven off. Both curves are based on dry sample weight.

The DSC curves were very similar among these three wood samples, as were the DTG curves. They are also qualitatively similar to the three sound wood samples (packing excelsior, 1⁄8-inch Douglas-fir wood, and ½-inch ponderosa pine heartwood) previously reported (Susott 1982). All samples showed the linear increase in C_p, predicted by equation 1, at least up to 200° C. (The small peak at 40° C is a measurement transient due to the start of heating.) The C_p values below 200° C shown in figures 1 to 3 are 5 to 10 percent lower than equation 1, but agree more closely with values given by Koch (1969) for spruce pine (*Pinus glabra* Walt.) wood. DTG curves show that pyrolytic weight loss begins in this region. The pyrolysis rate increases above 250° C, causing an exothermic peak at 325° C but changing to a sharp endothermic peak between 350° and 400° C. Above 400° C, the weight

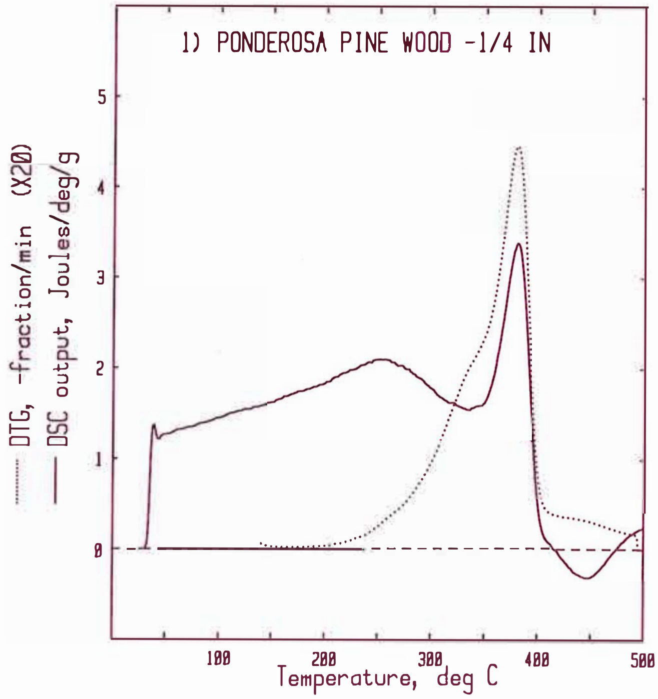

Figure 1. — DSC and DTG curves for ground ponderosa pine wood from 1⁄4-inch sticks.

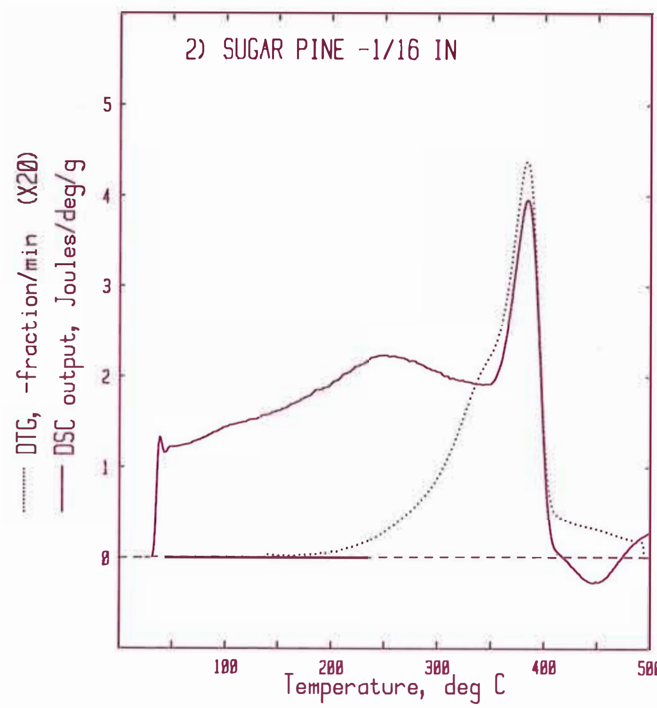

Figure 2. — DSC and DTG curves for ground sugar pine wood from 1⁄16-inch sticks.

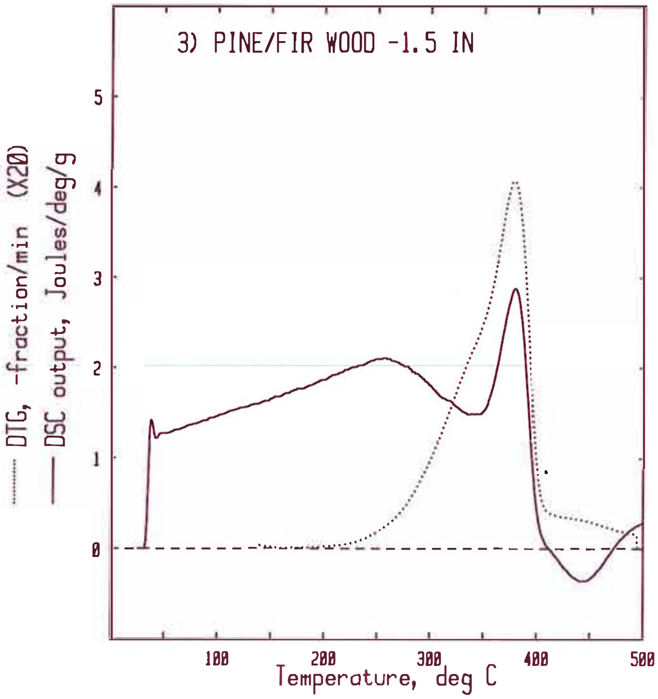

Figure 3. — DSC and DTG curves for ground wood of mixed species (mostly pine and fir) from 1½-inch sticks.

loss rate abruptly decreases and the DSC shows a broad exothermic peak at 425° C.

Quantitative comparisons are best made with the integrated DSC results in table 1. Table 2 gives the TG mass fraction remaining at temperatures above 140° C, following the moisture loss. Below 200° C, where C_p dominates the DSC curve, the total heat requirement averaged 270 ± 7 J/g for six woody fuels (three in this study combined with 271, 281, and 276 J/g from the woody fuels analyzed in the previous report). Equations given by Koch (1969) predict a value of 277 J/g for the integral from 25° to 200° C. This good agreement verifies the DSC calibration at low temperatures, and confirms that a constant contribution to Q_{ig} can be assumed for the wood samples analyzed. The value for 1⁄16-inch sugar pine was significantly lower than for ½-inch pine (5 percent level), but the difference was only about 7 percent. Within experimental error (about 5 percent), the wood samples used in combustion tests by Rothermel (1972) and Wilson (1982) have the same specific heat capacity up to 200° C.

These samples show larger differences in the DSC integral from 200° to 400° C. At 400° the 1½-inch sticks gave the lowest value of 649 J/g, compared to 712 J/g for 1⁄16-inch sugar pine, and 781 J/g for ⅛-inch Douglas-fir veneer in the previous report (Susott 1982). These differences were significant at the 5 percent level, showing a range of about 19 percent in the heat of preignition at 400° C. This range is comparable to the effect of a 5 percent range in moisture content.

Table 1.—Integral of DSC results (J/g) at temperatures up to 500° C

Temperature	Sample number		
	1	2	3
°C			
25	0	0	0
30	7	6	7
40	20	19	20
50	32	31	33
60	45	43	46
70	59	55	59
80	72	68	73
90	86	82	87
100	101	96	101
110	115	111	116
120	130	125	132
130	146	141	147
140	162	156	163
150	178	172	180
160	194	189	197
170	211	206	214
180	229	224	232
190	246	242	250
200	264	261	268
210	283	280	287
220	302	301	307
230	322	322	327
240	343	344	347
250	363	366	368
260	384	388	389
270	405	410	410
280	425	432	430
290	444	453	450
300	462	473	468
310	479	494	485
320	496	513	502
330	511	533	518
340	527	552	533
350	543	571	548
360	561	591	564
370	585	617	586
380	617	651	614
390	646	689	639
400	659	712	649
410	661	716	651
420	661	717	650
430	659	716	648
440	657	714	645
450	654	711	642
460	651	708	639
470	650	707	638
480	650	708	638
490	652	709	640
500	654	712	643

Note: Values are on a dry-weight, ash-included basis.
Integration from 25° to 40° C used dQ/dT at 40° C.

Samples: (1) Ponderosa pine wood, ¼-inch.
(2) Sugar pine, 1⁄16-inch.
(3) Pine/fir wood, 1½-inch.

Table 2.—TG weight (fraction remaining) at temperatures up to 500° C

Temperature	Sample number 1	2	3
°C			
140	1.000	1.000	1.000
150	.999	1.000	.999
160	.998	.999	.999
170	.998	.999	.999
180	.997	.998	.999
190	.997	.997	.998
200	.996	.996	.998
210	.995	.994	.997
220	.993	.991	.996
230	.990	.988	.994
240	.987	.983	.992
250	.981	.977	.988
260	.973	.968	.982
270	.963	.958	.974
280	.950	.945	.963
290	.934	.929	.947
300	.913	.909	.926
310	.885	.884	.898
320	.850	.853	.863
330	.807	.813	.819
340	.757	.766	.768
350	.701	.712	.709
360	.637	.652	.642
370	.556	.580	.559
380	.451	.486	.461
390	.352	.379	.369
400	.308	.313	.322
410	.295	.294	.307
420	.285	.283	.297
430	.276	.273	.288
440	.268	.264	.280
450	.260	.256	.272
460	.253	.249	.265
470	.246	.242	.259
480	.241	.237	.253
490	.237	.233	.249
500	.233	.228	.245

Note: Values are on a dry-weight, ash-included basis.
Samples: (1) Ponderosa pine wood, 1/4-inch.
(2) Sugar pine, 1/16-inch.
(3) Pine/fir wood, 1 1/2-inch.

CONCLUSIONS

Differential scanning calorimetry of six woody fuels gave good agreement in heat required for preignition below 200° C. Above 200° C, there is considerably more variation among fuels, especially from 300° to 400° C. These higher temperature contributions are not currently considered in modeling heat sink properties, but may be found necessary in new, improved fire models. The consistent set of data published herein allows evaluation of the effects of surface area-to-volume ratio and other variables on fire behavior in wooden cribs without the complication of an unknown Q_{ig} Data on more fuel types are needed to extend these models to include other wildland fuels such as grasses, foliage, small twigs, and bark. We are working on improving the accuracy of the DSC method to provide these data.

REFERENCES

Dunlap, Frederick. The specific heat of wood. Bulletin 110. Washington, DC: U.S. Department of Agriculture, Forest Service; 1912. 28 p. Forest Products Laboratory (Madison, WI) series.

Frandsen, William H. Effective heating of fuel ahead of spreading fire. Research Paper INT-140. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 16 p.

Koch, Peter. Specific heat of ovendry spruce pine wood and bark. Wood Science. 1: 203-214; 1969.

Rothermel, Richard C. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972. 40 p.

Susott, R. A. Effect of heating rate on char yield from forest fuels. Research Note INT-295. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 9 p.

Susott, Ronald A. Differential scanning calorimetry of forest fuels. Forest Science. 28(4): 839-851; 1982.

Wilson, Ralph A. A reexamination of fire spread in free-burning porous fuel beds. Research Paper INT-289. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 28 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1984-0-776-032/10,505