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HEAT OF COMBUSTION, HEAT YIELD, AND FIRE BEHAVIOUR

by C.E. Van Wagner



PETAWAWA FOREST EXPERIMENT STATION
CHALK RIVER, ONTARIO
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Heat of Combustion

The purpose of this Report is to present the heats of combustion of some forest fuels at Petawawa, and to discuss the reductions necessary to arrive at a practical heat yield suitable for calculating a fire's energy output rate.

The heats of combustion were determined with a Parr Peroxide Bomb Calorimeter by the method described in Parr Instrument Company's Manual Number 122. It was realized that an Oxygen Bomb Calorimeter would have been preferable, but a peroxide model was available at the time and resources were limited.

Each sample was air-dried to a few percent moisture and run four times with satisfactory repeatability. However, because the corrections necessary in the calculations were difficult to determine absolutely, a sample of one fuel, red pine litter, was sent away for determination by the oxygen bomb method. The ratio of this result to the peroxide value was 103.6, and this correction was applied to all the samples.

There were twelve samples in all, listed in Table 1 on the "high-heat" basis and corrected to zero moisture content. The units are calories per gram, which may be converted to Btu's per pound by multiplying by 1.8. Ash content was not determined and no allowance was made for it.

Some trends are evident. Living conifer needles have a higher heat of combustion (HC) than after they have fallen and partly decomposed into duff. Wood has a lower HC than foliage. Balsam fir needles have a distinctly higher value and aspen leaves are lower than the conifers. However, this list of possible materials is by no means complete, so that general conclusions cannot be made. Hough (1969) gives an excellent set of HC values for fuels in the eastern and southern United States, which are in fair agreement with these.

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Heat Yield

The HC as determined in an oxygen bomb calorimeter is a well-defined quantity. The beginning and end of the reaction are both at room temperature and all water is thus recondensed to the liquid state. Combustion is complete and there are no losses of sensible or latent heat. For forest fire work, however, this calorimeter value must be reduced in one or more ways.

The first deduction is for the latent heat absorbed when the water of reaction is vaporized. This quantity can only be calculated if the percent hydrogen in the fuel is known. Byram (1959) gives from more basic references the formula $C_6H_9O_4$ as the basic composition of wood. The nine H's combine with the four O's in the wood plus some O from the air to yield $4\frac{1}{2}$ moles of H_2O as the water of reaction from one equivalent weight of wood. That is, 1 g. wood yields $\frac{4.5}{145} \times 18 = 0.559$ g. H_2O . Since 1 g. H_2O absorbs 540 cal. when vaporized at 100 C, the deduction is $0.559 \times 540 = 302$ cal. per g. of wood, or, multiplied by 1.8, 543 Btu/lb. as given by Byram. The calorimeter result is called the high heat of combustion. When 302 cal/g. (or 543 Btu/lb) is subtracted, it becomes the low heat of combustion.

The deduction for fuel moisture content is similar to that for water of reaction, and consists of the latent heat plus a small increment to separate the water from its physically bound state. From two different sources, this deduction equals 5.72 cal. per MC point, or 10.2 Btu per MC point. (These values would be 5.40 and 9.72 respectively if the loss were latent heat at 100 C only).

Byram (1959) makes a further deduction for the radiation emitted by the flame and burning fuel. His heat yield, and the resultant fire intensity, thus represent convective energy only. There are two arguments for not making this deduction. First, the amount of radiant energy is not a characteristic constant, but depends on the flame's thickness, temperature, length, and shape; it is quite difficult to measure the total emitted radiation, and a uniform deduction could well be out as much as 20 percent in individual cases. Second, radiation is not really a "loss", but contributes greatly to fire behaviour; it therefore seems reasonable to deduct it only if some special purpose requires an estimate of convective heat output alone.

Another possible deduction is one for incomplete combustion. Certainly most forest fuel does not burn with the perfect combustion attained in the bomb calorimeter, so that any energy output estimate that makes no allowance for this is bound to be on the high side. On the other hand, the degree of completeness is undoubtedly quite variable and very difficult to measure. Byram's (1959) estimate of

this quantity (about 5 percent loss at 20 percent MC) is admittedly tentative and not based on any firm field data. Perhaps the recent work on smoke production and composition being done in the U.S. will produce some good guides for this item (e.g. Fritschen et al, 1970). Meanwhile, a deduction for incomplete combustion is mainly a matter of subjective judgement.

Some references (e.g. Hough, 1969) give an ash-free heat of combustion. If fuel weight consumed is determined in such a way that the ash is weighed as part of the residual fuel, then, strictly speaking, an adjustment is necessary. If ash content is not known, then 3 percent is probably a reasonable figure to use. This adjustment is the only one that actually increases the HC.

Chemical Composition

To check some of the above results, samples of fresh white pine and aspen litter, and the waxy resinous material from each extracted with boiling xylene, were sent out for C, H, and O analysis. Table 2 gives the results in comparison with the assumed formula for wood, both pure and assuming 3 percent ash; in addition the theoretical heats of combustion were calculated from basic data given by Steiner (1941, p. 91 and 92) for the separate combustion of carbon and hydrogen. Only the excess of hydrogen over the amount needed to form water with the oxygen was used in this calculation. Also listed is the latent heat of the water of reaction, the difference between high and low HC; for this item all the H was assumed to form water.

There are several inferences to be drawn from Table 2. First, trembling aspen and white pine litter are nearly the same as the assumed wood formula in C and H content; their O content, however, is distinctly less. This difference in O probably accounts in part for the higher HC of leaves over wood, since a larger proportion of the H in foliage is thus available to produce energy. Second, it is apparent that the waxy and resinous xylene-soluble material in foliage has a quite different composition and a much higher HC. Aspen and white pine leaves contain 5 to 10 percent of such material when alive, which contributes still more to their higher HC in comparison with wood.

Third, the latent heat lost in the water of reaction is a little higher for the foliage than for wood, about 320 cal/g as opposed to 302. This difference is not very important, however, since it only amounts to about $\frac{1}{2}$ percent of the total HC. The use of 302 cal/g. or 543 Btu/lb as a standard deduction for converting high-heat HC to low-heat HC seems therefore quite reasonable.

Fourth, the pattern of comparison of the theoretical HC's of Table 2 with the experimental values of Table 1 is not quite consistent.

Jack pine and aspen twigs yielded HC's about 300 points higher than theoretical, and fresh white pine litter about 250 points higher; fresh aspen litter, however, gave an experimental HC about 150 points lower than the theoretical value.

Conclusion

Considering the small number of data presented here, this work is obviously on an exploratory scale. Whether it should be pursued much farther is an open question that depends mainly on how much fire behaviour is likely to be affected by the observed differences in HC. Since most fires burn a combination of foliar fuel (live or dead) and wood, it is differences within each of these two main classes that is of interest. Duff, if it does burn, is an additional fuel. To judge from the present results and those in other references, the range of variation within each class is about 10% and the direct effects on the fire would presumably be to change the height and temperature of the flame. As for flame height, it is well established that any increase in the energy output by the burning fuel causes somewhat less than a proportional increase in flame height.

Regarding flame temperature, a rough calculation suggests that a 10 percent increase in HC would raise flame temperature by about 100 C. Philpot and Mutch (1971) found a seasonal variation of this same order in the HC of western conifer foliage, and speculate that this difference might have a marked effect on the pattern of crown fire incidence, since both trends peak in late summer. However, it remains to be shown whether the seasonal trend of fire weather in that region may simply override other factors in setting the crown fire pattern. They also found a trend in foliar moisture content with about 30 percent higher values in late summer than in spring. Another rough calculation suggests that the decrease in flame temperature caused by such a higher foliar MC should just offset the increase in flame temperature due to a 10 percent higher HC.

In view of all these considerations, the general conclusion drawn here is that variation in the heat of combustion among forest fuels is not a major factor in determining forest fire behaviour in Canada.

Acknowledgement

J.W. Bell collected the samples, ran the heats of combustion and processed the data for this Report.

Table 1. Heats of combustion of 12 samples of forest fuels at
 Petawawa, high-heat basis, moisture free.

<u>Material</u>	<u>Heat of combustion cal/g + standard error</u>
<u>Green needles</u>	
Balsam fir	5494 ± 18
Red pine	5216 ± 40
Jack Pine	5185 ± 19
<u>Leaf litter, fresh fallen</u>	
Red pine	5327 ± 22
White pine	5311 ± 35
Trembling aspen	4977 ± 29
<u>Needle litter, summer</u>	
Red pine	5069 ± 56
Jack pine	5067 ± 34
<u>Duff</u>	
White pine	4236 ± 21
<u>Bark</u>	
Jack pine slash	4827 ± 42
<u>Wood</u>	
Jack pine slash, $\frac{1}{2}$ in.	4585 ± 53
Aspen twig, dead	4475 ± 38

Table 2. Chemical composition, theoretical heat of combustion, and latent heat loss of four materials, compared with theoretical formula for wood.

<u>Material</u>	Chemical composition, %				<u>Ash</u>	<u>Theoretical heat of combustion, cal/g</u>	<u>Latent heat loss, cal/g</u>
	<u>Carbon</u>	<u>Hydrogen</u>	<u>Oxygen</u>				
Trembling aspen litter	49.5	6.5	36.9	6.7		5164	316
White pine litter	49.8	6.7	39.8	2.6		5044	324
Xylene extract of aspen litter	77.9	11.3	10.0	-		12967	550
Xylene extract of pine litter	82.8	10.3	6.5	-		15786	500
Ash-free wood $C_6H_9O_4$	49.6	6.2	44.1	-		4361	302
Wood $C_6H_9O_4$ 3% ash	48.1	6.0	42.8	3.0		4230	296

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