

Heat Evolved From Smoldering Peat¹

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Abstract. Smoldering ground fires can raise mineral soil temperatures above 300°C for several hours with peak temperatures near 600°C. Such temperatures can result in the decomposition of organic material and kill important soil organisms. The heat evolved per unit organic mass was investigated by monitoring the mass of oxygen consumed during smoldering. Organic bulk densities of laboratory samples were comparable to field observations and ranged from 90 to 180 kg m⁻³. Moisture and inorganic contents were expressed as mass ratios relative to the organic mass. Moisture ratios ranged from zero to 0.8 and inorganic ratios from near zero (natural peat inorganic ratio) to 4.0. Heat evolved per unit organic mass was independent of organic bulk density and inorganic ratio, and changed little with moisture ratio within the limits of combustion. The average value for all observations (N=190) was 14.2 MJ kg⁻¹ with an error less than 4.5%.

Keywords: Fire; Forest; Smoldering; Peat; Duff; Heat; Calorimeter; Oxygen consumption.

Introduction

Fire plays a significant natural role in the coniferous forests of the temperate zone. Boerner (1982) calls such forests oligotrophic ecosystems where nutrients are locked into live biomass and detritus, and where woody materials decay slowly. Fire rapidly releases such nutrients and cycles them back into the soil for root uptake. The heat released in the combustion process profoundly affects both biotic and abiotic components of the forest ecosystem. The purpose of the research described here was to determine the amount of heat generated in flameless smoldering combustion of fine, compacted materials of

the forest floor, collectively known as duff, and how the amount of heat was influenced by duff composition, specifically moisture content, organic bulk density, and inorganic content. Once ignited, smoldering duff can significantly affect the underlying mineral soil through the close proximity of high temperatures of long duration. Ultimately, this knowledge will enhance the capability of forest scientists and managers to predict the effects of smoldering combustion on forest ecosystems.

It is hypothesized that the heat evolved from smoldering organic material is unaffected by changes in either the organic bulk density, or moisture and inorganic content expressed as mass ratios relative to the organic mass.

Methods

Fuel Samples and Treatments

Canadian sphagnum peat moss was selected as a representative fuel for examining the behavior of smoldering duff. Peat moss has similar particle sizes and bulk densities as duff and is an important ground cover in the wet boreal forest that supports smoldering combustion (Wein 1983). Emulation of duff by peat is an approximation that provides a controllable medium for experimental investigation of smoldering ground fires. Until methods are available that allow field evaluation, this approach provides a first estimate of the heat evolved from smoldering duff realizing that the aggregated properties of peat are lost in sample preparation and confinement within a specified volume.

The lower and upper organic bulk densities of the fuel samples were selected to be 90 and 180 kg m⁻³. This corresponds to the range that is normally found in duff. Results are related to smoldering in the absence of wind and slope.

Moisture and inorganic contents were expressed as mass ratios relative to the organic mass. They are unitless

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but can be easily converted to densities by multiplying them by the organic bulk density. Moisture ratios, R_M , ranged from 0 to 0.8 at 0.2 intervals; inorganic ratios, R_I , from near 0 to 4 at intervals of 1. An inorganic ratio of 0 is not possible because of the inherent inorganic content of peat (0.04 and 0.08 ash content on dry weight basis). All combinations were sampled except those at moisture ratios and inorganic ratios that were not expected to sustain smoldering beyond the limit given by Frandsen (1987) (Fig. 1), as

$$R_M + (R_I/4) < 1.1 \quad (1)$$

Simply viewed, nonburning inorganic materials act as a heat sink occupying space that would otherwise be filled by organic material that supplies heat to sustain the combustion process. Moisture is an even greater heat sink requiring the heat of vaporization to drive off the

moisture before the organic material can burn. Both contribute to the limits of sustained smoldering.

Peat was moistened or dried to reach the selected moisture ratios. Inorganic material in the form of 240-mesh (0.056 mm particle size) powdered silica was added to the moist peat to obtain higher inorganic ratios. More detail on sample preparation can be found in Frandsen (1989). Silica was used to ensure that there would be the least amount of chemical interaction between the added inorganic material and the combustion process. Inorganic materials in peat and the presence of mineral soil may alter the rate of combustion. Calcium, magnesium, and other alkaline earth metals commonly found in soil can alter the propensity to smolder (Barker and Drews 1985). Shafizadeh and Sekiguchi (1984) reported that inorganic materials strongly enhanced or suppressed smoldering combustion by affecting the relative amounts of CO and CO₂ and their rates of produc-

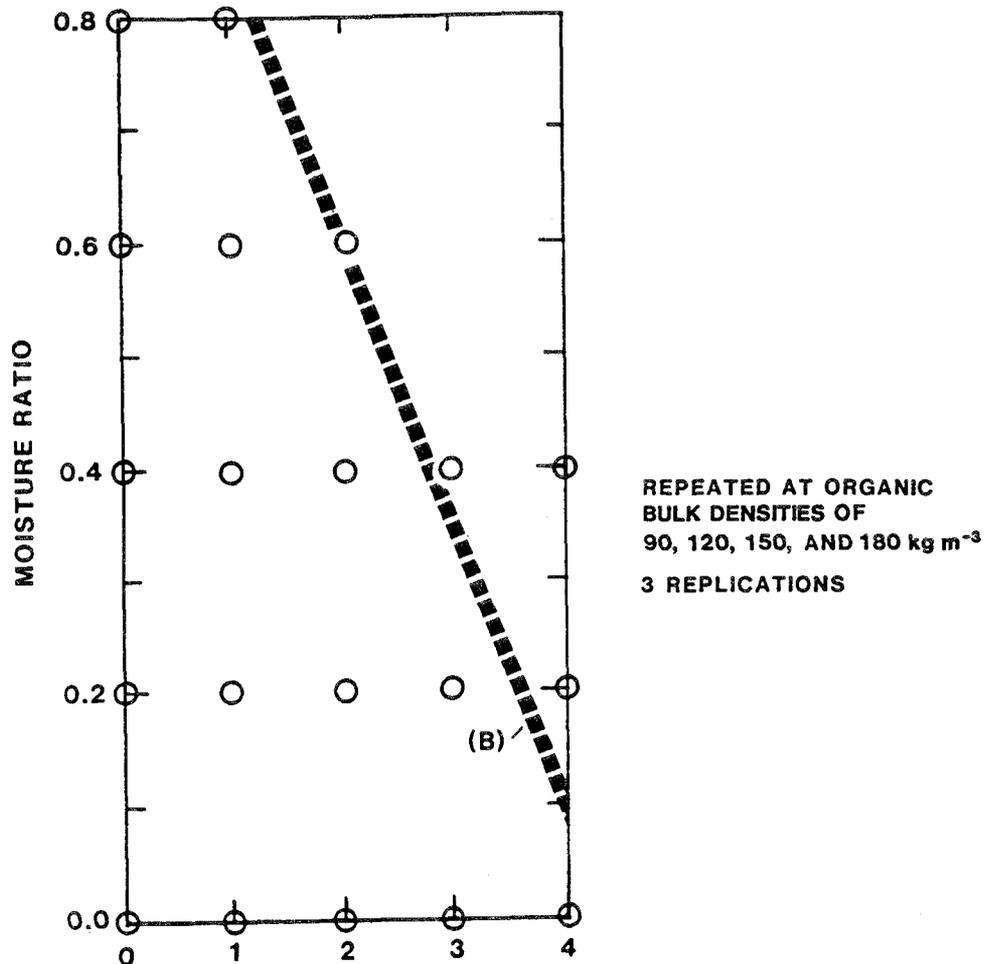


Figure 1. Sampling design. Each circle designates a sampling combination of moisture and inorganic ratios for each organic bulk density. Each combination was replicated three times. Few observations were attempted beyond the expected smoldering boundary, (B).

tion. The rate process of this study is covered in Frandsen (1991).

Experimental Design

The experimental sample of peat was contained within an open-top, nonburning, insulated box. The box, in turn, was placed in a glass cylinder. Both ends of the cylinder were sealed except for an inlet and exit to allow for a flow of air (Fig. 2). The sample volume within the insulated combustion box was 5 cm x 5 cm in cross-section and 4 cm deep. The insulating material was ceramic board with thermal properties similar to peat (Frandsen 1987). Consequently, the heat transferred to the walls is not greatly different from the heat transferred within the peat. This allows the burning peat to appear as part of an expanded volume. There was no excessive heat loss or cooling at the walls of the container, as evidenced by the absence of unburned peat adjacent to the walls when combustion was sustained.

The upper exposed surface of the peat was ignited by four rows of resistance coils heated to a red glow. The glowing area approximated the area of the peat surface and was held within 5 mm of the surface for 2 minutes. Prior experimentation indicated that 2 minutes was sufficient to ignite peat at all combinations up to the highest moisture and inorganic ratios. The amount of organic material consumed under enhanced burning during the ignition period is small compared to the total mass consumed. Based on measurements of the initial mass loss rate, 0.2 to 0.8 g of organic mass was consumed during the 2-minute ignition phase corresponding to 2% to 6% of the original organic mass.

The rate of heat production in the combustion box is related to the rate of oxygen consumption (Thornton 1917; Huggett 1980; Susott 1982; Parker 1984). The net difference in the oxygen mass flow in and out of the sealed combustion chamber is equivalent to the rate of oxygen consumption. Huggett (1980) found the heat conversion term to have a typical value of 13.1 MJ kg⁻¹ for conventional organic fuels found in a forest environment. This is based on the low heat value. Moisture vapor created in the combustion process is assumed to be lost from the combustion zone along with its associated heat.

Air from the exit port was sampled at 1.7x10⁻⁶ m³ s⁻¹ (0.1 ℓ min⁻¹) to determine its carbon monoxide and oxygen concentrations after passing through the combustion chamber. Dry ambient air at volume fraction 0.2095 (Weast 1967) entered the combustion chamber with the flow rate held at 5.8x10⁻⁵ kg s⁻¹ (3.5 g min⁻¹) and monitored for slight variations, an amount that was determined to be sufficient to maintain smoldering.

Traps were placed in the sampling stream (Fig. 2) to remove the gaseous products of smoldering combustion so that the final concentration after combustion was on the same basis as the incoming concentration. An ice water cold trap removed a major portion of the water vapor. Ascarite, whose major ingredient is sodium hydroxide, trapped carbon dioxide, forming sodium carbonate and water. Drierite, anhydrous calcium sulfate, followed ascarite and trapped the water produced in the ascarite trap, along with residual water vapor from the cold trap. Tars and particulates harmful to downstream instruments were also removed by these traps, aided by cotton swabbing used as spacers in the traps. Carbon

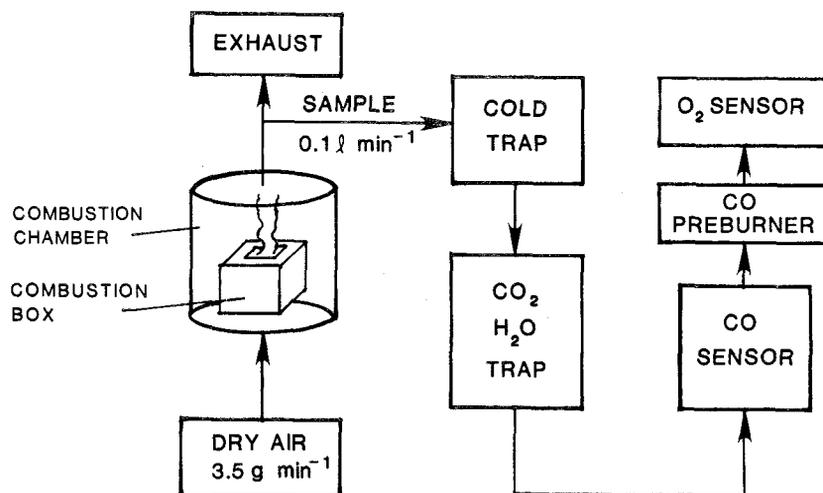


Figure 2. A process and gas flow diagram for measuring oxygen consumption in smoldering combustion. (3.5 g min⁻¹ = 5.8x10⁻⁵ kg s⁻¹, 0.1 ℓ min⁻¹ = 1.7x10⁻⁶ m³ s⁻¹).

monoxide could not be trapped. Its presence was accounted for analytically from its concentration measured by an infrared absorption gas analyzer in line with the sampling stream (Fig. 2). The sampling line terminated at the oxygen sensor after passing through a carbon monoxide preburner. The oxygen sensor was a solid electrolyte gauge operating at 1000° K (Kleitz and Fouletier 1976). The preburner ensured that the carbon monoxide did not burn in the oxygen sensor and thus destabilize the operating temperature of the oxygen sensor.

Method of Analysis

Parker's (1984) expression for the rate of heat production, \dot{H} (MJ min⁻¹), reduces to the following form after conforming to the present experimental setup where carbon dioxide was trapped out of the sample stream and no burner was used to burn the peat sample. Volumetric units are replaced with mass units.

$$\dot{h} = E \left(\frac{M_{O_2}}{M_a} \right) F_{ma} X_{O_2}^o \left[1 - \frac{X_{O_2}}{X_{O_2}^o} \left(\frac{1 - X_{O_2}^o}{1 - X_{O_2}^o - X_{CO}} \right) \right. \\ \left. \times \left(1 + \left(\frac{E_{CO} - E}{2E} \right) \frac{X_{CO}}{X_{O_2}} \right) \right] \quad (2)$$

where

- E = Heat produced per unit mass of oxygen consumed assuming that carbon goes to carbon dioxide ($E = 13.1$ MJ kg⁻¹)
- E_{CO} = Heat produced per unit mass of oxygen consumed assuming that carbon goes to carbon monoxide ($E_{CO} = 17.2$ MJ kg⁻¹)
- M_{O_2} = Molecular weight of oxygen
- M_a = Molecular weight of air
- F_{ma} = mass flow rate of air (set at 3.5×10^{-3} kg min⁻¹ and recorded for evaluation of heat release rate)
- $X_{O_2}^o$ = Volume fraction of oxygen in incoming air ($X_{O_2}^o = 0.2095$)
- X_{CO} = Volume fraction of carbon monoxide in air flowing from combustion chamber
- X_{O_2} = Volume fraction of oxygen in the sample stream ahead of CO preburner.

The following relationship was derived from the stoichiometry of the combustion of carbon monoxide in the presence of oxygen.

$$X_{O_2} = X_{O_2}^* + X_{CO} (1 - X_{O_2}^*) / 2 \quad (3)$$

where

$X_{O_2}^*$ = Volume fraction of oxygen in the sample stream after the CO preburner (Fig. 2).

The sampling frequency for monitoring sensors was once every minute. The greatest delay in sensing an event was associated with the passage of gas from the combustion chamber to the oxygen sensor at the end of the sampling line, a delay of approximately half a minute—well within the sampling interval. Except for a small fraction of the observations with smoldering durations near 78 minutes, sampling durations were greater than 100 minutes, extending up to 257 minutes. Consequently, the resolution in time was most often less than 1% of duration of smoldering. Each combustion event was evaluated from the moment of ignition, 2 minutes after recording began, until the end of smoldering as indicated by the absence of carbon monoxide in the sampling stream (carbon monoxide volume fraction < 0.0005). The analog outputs of the sensors were directly converted to physical values and stored for later analysis. The heat release rate was evaluated from these stored values and numerically integrated over the duration of smoldering to obtain the total heat evolved.

Results and Discussion

A total of 190 observations of the heat evolved from smoldering were obtained. The experiment was designed for four organic bulk densities and three replications at each of the 19 combinations of inorganic and moisture ratios marked in figure 1 for an expected total of 228 observations. However, some ignitions were not sustained at the higher inorganic ratios and bulk densities and became more pronounced with higher moisture ratios. The following successful observations were made: 56 of the 60 expected at 0 moisture ratio, 44 of the 60 at 0.2, 30 of the 48 at 0.4, 21 of the 36 at 0.6, and only 4 of the 24 at 0.8 moisture ratio. None of the burns at moisture ratio 0.4 and inorganic ratio 3 were sustained. Extra burns made to test the replacement peat discussed later under sample variation added 17 observations at 0 moisture ratio, 3 at 0.2, 12 at 0.4, and 3 at 0.6 moisture ratio. All extra burns were at the lowest bulk density and the two lowest inorganic ratios. A table itemizing successful observations is found in Frandsen (1989).

Multiple linear regression analysis was applied to examine the relationship of the heat evolved to the basic explanatory variables: organic mass, m_o , inorganic mass, m_i , water mass, m_M , and the volume of the combustion box. The treatments were combinations of nondimensional ratios, R_i and R_M , and the organic bulk

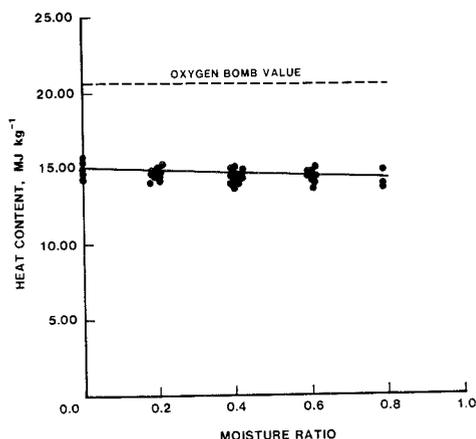


Figure 3. The observed smoldering heat per unit organic mass, Q_s , of peat versus the moisture ratio. A line, estimated from the multiple linear regression model, is superimposed on the peat observations. The oxygen bomb value, 19.4 MJ kg⁻¹ (low heat value), is shown for comparison.

density which were evaluated from these variables.

Total Heat Evolved

The analysis indicated that there was no significant dependence on the volume or the inorganic mass ($P \gg 0.05$) (Fig. 5). The heat depends only on the water mass and the organic mass.

$$H = a m_M + b m_O \text{ kJ} \quad (4)$$

The expression for H has been forced through the origin. If $m_O = 0$, then $H = 0$, i.e., when there is no organic mass, there can be no heat evolved. Furthermore, there can be no moisture mass, m_M , if there is no organic mass, m_O , to absorb the moisture. Forcing the regression through the origin does not detract from the ability of the resultant expression to fit the observed data. Both masses are significant ($P < 0.05$) and their coefficients are

$$a = -0.78 \text{ MJ kg}^{-1} \text{ and } b = 14.51 \text{ MJ kg}^{-1} \text{ (S.D.} = 5.28 \text{ kJ)}.$$

Heat Evolved Per Unit Organic Mass

Dividing equation (4) by the organic mass, m_O , gives a simple linear relationship between the smoldering heat evolved per unit organic mass, Q_s , and the moisture ratio, R_M .

$$Q_s = a R_M + b \text{ MJ kg}^{-1} \quad (5)$$

This simplified expression indicates that smoldering heat per unit organic mass is independent of the organic bulk density as well as the inorganic ratio. Based on

probable error-analysis (Fritschen and Gay 1979), the percent error is no greater than 3% for the three sampling variables: moisture ratio, inorganic ratio, and the organic bulk density (Appendix E of Frandsen 1989).

A graph of the smoldering heat per unit organic mass shows very little dependence on the moisture ratio, R_M (Fig. 3). The average value for all observations is 14.2 MJ kg⁻¹ (low heat value) with a standard deviation of 0.42 MJ kg⁻¹. The resultant coefficient of variation is 0.030 or 3.0%. However, this considers the organic mass, m_O , to which the evolved heat is normalized, to be without variation. As with the variables above, probable error analysis was used to evaluate the total variability of the smoldering heat per unit organic mass by including the variability of the organic mass. Results indicate that the percent error ranges from 1.9% to 3.6% at zero moisture ratio for organic bulk densities from 180 kg m⁻³ to 90 kg m⁻³ and from 2.7% to 4.5% at 0.8 moisture ratio over the same organic bulk density range (Appendix E of Frandsen 1989). The effect of the organic mass on the percent error is seen above in the doubling of the error by cutting the organic bulk density in half. This analysis suggests that the percent error in the smoldering heat per unit organic mass is certainly no greater than 4.5%.

Sample Variation

Two commercial varieties of peat were used as the sample fuel: Green Thumb (GT) and Sunshine (SS)¹. GT peat (0.04 ash content) was the original choice and was used for all pilot experiments and initial observations. When additional peat was needed, GT peat was not available. SS peat (0.08 ash content), after sifting, was comparable to GT peat in smoldering behavior at organic bulk density of 90 kg m⁻³. The particle size distribution of GT and SS peat was obtained by sifting through a series of different size mesh screens. The mass fraction of SS peat within the mesh number range 6-20 (3.4 mm to 0.85 mm) is more than twice the mass fraction of GT peat (Fig. 4). In contrast, the mass fraction of SS peat is about half that of GT peat in the smaller mesh number ranges 30-40 (0.60 mm to 0.43 mm), 40-60 (0.43 mm to 0.25 mm), and 60-100 (0.25 mm to 0.15 mm). The average particle diameter weighted by mass fraction is 0.7 mm for GT peat and 1.2 mm for SS peat. We may conclude from the small percent error, no greater than 4.5% for the smoldering peat per unit organic mass in

¹Both Green Thumb and Sunshine are Canadian sphagnum moss. Sunshine is available throughout northwestern United States and is distributed through the Fison Corporation. Sunshine, at the time of this writing, is being taken from the same bog that was the source of the Green Thumb peat purchased earlier.

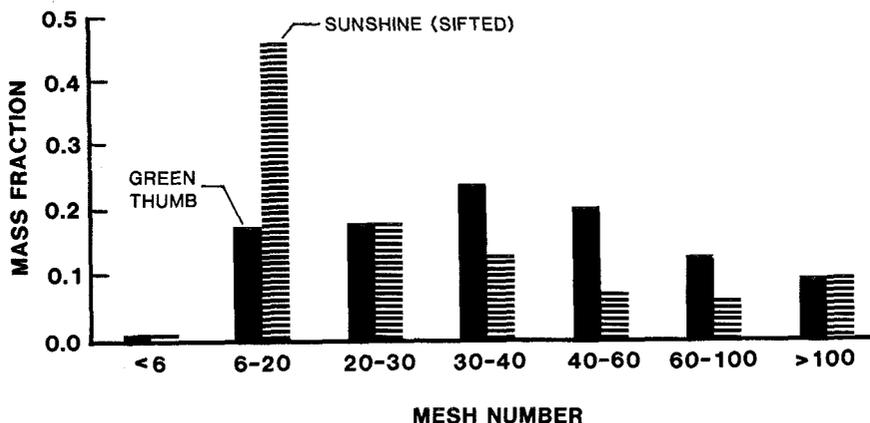


Figure 4. Particle size distribution by mass of Green Thumb peat compared to sifted Sunshine peat.

spite of the use of two different peat types, that the final result is, for the most part, independent of the size of organic particles for the two types of peat used.

Oxygen Concentration

Two likely products of smoldering combustion may alter the concentration of oxygen in the sample air stream, but are not expected to severely affect the final result: nitrogen and gaseous hydrocarbons. The upper limit on the concentration of nitrogen in peat is 2% (Fuchsman 1980) and the upper limit on the average rate of burning from this study is $2.5 \times 10^{-6} \text{ kg s}^{-1}$ (9 g h^{-1}). This translates to an average release rate of $5 \times 10^{-8} \text{ kg s}^{-1}$ (0.18 g h^{-1}) of nitrogen. Assuming that all of the nitrogen is released as molecular nitrogen, and applying the ideal gas law, $4.0 \times 10^{-8} \text{ m}^3 \text{ s}^{-1}$ ($2.4 \times 10^{-3} \text{ l min}^{-1}$) of nitrogen could be released into the flow of air through the combustion chamber. The air flow rate is near $5.8 \times 10^{-5} \text{ m}^3 \text{ s}^{-1}$ (3.5 l min^{-1}) of which 80% is nitrogen, giving a nitrogen flow rate of $4.7 \times 10^{-5} \text{ m}^3 \text{ s}^{-1}$ (2.8 l min^{-1}). Consequently, the nitrogen production rate is insignificant compared to the fixed flow of nitrogen through the combustion chamber and therefore does not significantly alter the concentration of oxygen in the sampling air stream.

Ward and Hardy (1984) have recorded the evolution of hydrocarbons and carbon monoxide from the smoldering phase of prescribed fires. The mass ratio of total hydrocarbons to carbon monoxide was 0.05. The molar ratio is 0.03 assuming that the hydrocarbons are represented by C_3H_8 (Nelson 1981). A modified heat release rate can be estimated by allowing C_3H_8 to be included in the analysis of the heat release rate.

The addition of hydrocarbons into the sampling stream will both decrease the oxygen content and increase the base volume of nonoxygen gases with carbon dioxide and water when the sampling stream passes through the CO preburner ahead of the oxygen sensor

(Fig. 2). Both trends indicate a decrease in the evaluated heat release rate. The recalculated rate using the recorded oxygen and carbon monoxide concentrations with the modified analysis gives an average reduction in the heat release rate of 5%. Consequently, with this limited bit of information, we might expect an error of -5% in the final smoldering heat per unit organic mass.

Oxygen Supply

The smoldering heat per unit organic mass is not dependent on the organic bulk density or the packing of inorganic material up to four times that of the organic bulk density ($0 < R_1 \leq 4$, Fig. 5) suggesting that smoldering is independent of oxygen supply if it is altered by changes in packing. Ohlemiller et al. (1979) writes on flexible polyurethanes: "the smolder process is flexible enough to adapt to a wide range of oxygen-supply levels, including extraordinarily low levels." These arguments allay any concerns that uneven sample fuel packing altered the resulting smoldering heat per unit organic mass.

Heat from CO Production

Frandsen (1989) obtained an average smoldering heat per unit organic mass of 14.8 MJ kg^{-1} over the same moisture ratio range (0 to 0.8). He assumed that the heat evolved producing CO, E_{CO} , was equivalent to the heat evolved producing CO_2 , E ; thus eliminating the contribution from that portion of equation (2) containing E_{CO} . The standard deviation, 0.20 MJ kg^{-1} , is less than the present deviation, 0.42 MJ kg^{-1} , but is still in reasonable agreement. Apparently, the error introduced by this assumption under the conditions of smoldering combustion is not great but does increase the value of the smoldering heat per unit organic mass by 4%.

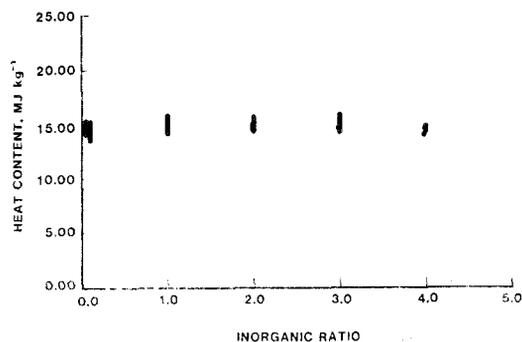


Figure 5. The observed smoldering heat per unit organic mass, Q_s , of peat versus the inorganic ratio.

Smoldering Combustion Efficiency

A comparison of the smoldering heat per unit organic mass obtained in this study, 14.2 MJ kg^{-1} , with the low heat value of the oxygen bomb calorimeter, 19.4 MJ kg^{-1} , that completely oxidizes the peat, indicates that only 73% of the heat is released under the conditions of this study—conditions that were designed to approach field conditions. (The low heat value is derived from a high heat value of 20.7 MJ kg^{-1} , and a peat hydrogen content of 5.5% (Fuchsman 1980).) This suggests that 27% of the heat was retained in unburned residues evolved from smoldering. Combustion was complete as evidenced by a residue of white fluffy ash. Further ashing shows no further loss in mass. Consequently, the unburned material must be in the form of volatile products of combustion such as tars. Tars coating the inside of the combustion chamber are evidence supporting the loss of heat to unburned products of combustion.

Conclusion

The heat evolved from smoldering peat is significantly related to the water and organic mass of smoldering peat samples as shown in equation (4) ($P < 0.05$) leading to equation (5). The fact that we are able to see small changes in the heat evolved per unit organic mass over the full range of moisture ratios testifies to the precision of the experiment.

The oxygen consumption technique is the most advanced method of measuring the heat evolved from smoldering. It is not easily adapted to measurements in the field. A serious drawback to the laboratory experi-

ment was the inability to maintain the integrity of a field sample. In defense of this method it would have been very difficult, if not impossible, to cover the range of conditions with field samples, not to mention their greater variability. The upper limits may be above the limits that would be found in the field. However, this ensures that the range of possible field conditions have been covered.

Future methods may open the way for "in situ" measurements of the heat evolved from smoldering. In the meantime this serves as a useful estimate and a valuable insight into the relationship between the heat evolved from smoldering and the bulk properties of smoldering material.

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