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Forced Smolder Propagation and the Transition to Flaming in Cellulosic Insulation

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

PREFACE

This report is one of a series documenting NBS research and analysis efforts in support of the Department of Energy's Building Thermal Envelope Systems and Materials Program, managed by the Oak Ridge National Laboratory. The multi-year effort reported in this document was supported first by DoE/NBS Interagency Agreement No. DE-AI01-76PRO6010, Task Order A008, culminating in Modification A037 (formerly IA No. EA77-A-01-6010). The concluding work and report preparation were supported by IA No. DE-AI05-850R21513, Modification No. A001, Task D-85/1 -- Assessment of Smolder-to-Flaming Tendancy in Cellulosic Insulation.

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FORCED SMOLDER PROPAGATION AND THE TRANSITION TO FLAMING IN CELLULOSIC INSULATION

Thomas J. Ohlemiller

Abstract

It is well known that a smoldering fuel responds to an increased oxygen supply by becoming faster and hotter until, eventually, flames erupt. This sequence is examined quantitatively for thick horizontal layers of a permeable fuel, i.e., cellulosic insulation. Two configurations are possible, forward and reverse smolder; both are investigated experimentally. The influence of combustion retardants is also examined; these include boric acid, a smolder retardant, and borax, a flaming retardant. Both prevent the transition to flaming in the absence of adjacent flammable material but are less effective in its presence. The overall response of these various fuel mixtures and configurations suggests that both kinetics and oxygen supply rate (not the latter alone) play substantial roles in dictating smolder response to an air flow.

Keywords: air flow, cellulosic materials, flaming, insulation, retardants, smoldering.

1. INTRODUCTION

This report summarizes the last phase of a study of the smoldering combustion characteristics of cellulosic insulation. In previous work smolder initiation [1,2,3] and smolder propagation [2,4,5] in these materials have been investigated.

Cellulosic insulation of the type investigated here is made from recycled paper products, mostly newsprint. When properly ground to a finely fibrous form, such products become an excellent thermal insulation. The inherent combustibility of the base material (essentially wood) must be controlled, however, by the addition of combustion retardants and by adherence to installation practices that keep the insulation away from heat sources.

Meaningful combustibility test methods are needed by the manufacturers and by regulatory agencies as a means of assuring continuing control of potential flaming and smoldering tendency. Cellulosic insulation currently must pass a radiant panel test which measures the minimum external radiation flux a given sample requires to sustain flame propagation over its exposed surface. It also must pass a smoldering test in which a lit cigarette is imbedded vertically in a layer of insulation. Smoldering of such materials is most likely to be encountered as a result of improper installation that places the insulation in contact with large area, relatively low temperature heat sources such as recessed light fixtures. Substitution of a cigarette as the heat source obscures the causal chain in the smolder initiation process. This led to the suggestion for an improved smolder initiation test method based on the use of an extended area, electrically heated source [2,3]. It was shown that such a test method can quantify the impact of smolder retardants on smolder initiation tendency by measuring the minimum heat source temperature required to start smolder in a given layer of material. The test method also showed, however, that this impact is not very great, e.g., the addition of 25% boric acid raises the minimum heat source temperature for smolder initiation by only 20-25°C [2].

In view of this inability of smolder retardants to prevent smolder initiation, it was desirable to look at subsequent stages (propagation, transition to flaming) of the smolder process to see if they are more susceptible to intervention. Self-sustained smolder propagation in horizontal insulation layers was examined in detail [4,5]. It was found that high levels of boric acid only slow the rate of propagation in layers of realistic thickness. Slower propagation represents no reduction in hazard level so a propagation rate test method was not pursued.

Smoldering insulation becomes an immediate life threat when and if it undergoes a transition into flaming combustion. For the usual attic type of installation, this is most likely to be caused by air flowing over or through the smoldering combustion zone as a result of winds impinging on the structure. Such winds may directly penetrate various attic vents or induce flow to/from rooms below the attic via ceiling holes around devices such as recessed light fixtures, vent fans, etc. It is clearly desirable to lessen the tendency of a smoldering insulation material to transition into flaming in such a manner.

There have been two previous studies of smoldering horizontal fuel layers in the presence of flowing air with some observations on the appearance of flaming. Palmer [8] examined the behavior of wood and grass dusts in layers up to 6 cm thick with air velocities up to 8 m/s; the configuration was quite similar to that used here but the bulk densities were 2-3 times higher except for the case of cork dust. The presence of flaming was noted but not examined in any detail. Leisch [9] examined the behavior of grain kernel fragments, grain and wood dust in 20 cm layers at air velocities up to 19 m/s. In this case the fuel layer was set into the bottom of the flow tunnel so that its top surface was initially flush with the tunnel floor. Flames were noted, under some conditions, to appear and to be trapped in the surface depression left by the smoldering process.

The present study was undertaken to look at the impact of both smolder and flaming retardants on the forced flow smolder and flaming transition process. A second objective was to assess the feasibility of developing a test method to rate transition tendency. After some preliminary experiments (discussed briefly below) on a smoldering bed of insulation with air forced through it, the work focussed on a horizontal layer of smoldering insulation with air flowing over the top of the layer. In this latter configuration, the ultimate point of interest is the flow velocity at which transition to flaming occurs; this provides a quantitative measure of transition tendency. As will be seen, this velocity varies with the nature of the combustion retardant additive and also with the presence or absence of wood adjacent to the insulation. In order to gain some insight as to how the air flow brings about flaming, its effect on the smolder process was examined over a substantial range.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Initial Experiments with Flow Through the Smoldering Insulation

The air flow in the real hazard scenario is potentially either through the insulation or over surface of the insulation. A simplified version of the former was pursued initially. A 25.4 cm diameter by 25.4 cm deep bed of unretarded insulation (bulk density 0.051 g/cm^3) was encased in a thin-walled (1 mm) stainless steel cylinder and subjected to a uniform downward flow of air (see Fig. 1). Uniform initiation of smolder on the top surface of the bed was achieved with an air permeable, electric heater; the igniter was removed after self-sustaining smolder was achieved and the desired air flow was continued.

This mode of smolder propagation, in the same direction as the air flow, is termed forward smolder. Reversal of the air flow with the same igniter placement would have yielded reverse smolder. Both configurations have been studied previously in a smaller apparatus [6]. Only forward smolder brings together the air and the hottest part of the smolder zone in an open space external to the fuel bed. Thus it was deemed more likely to yield flaming; reverse smolder was not examined here.

A total of nine smolder propagation experiments was run in this manner with two different unretarded insulations. The superficial air flow velocity (NTP volumetric flow rate divided by the bed cross-sectional area) was varied from 0.09 to 1.1 cm/s. Flaming was never encountered. Except at the lowest air flow velocity, the smolder front always propagated in an unstable manner which eventually led to a "wormholing" effect. All of the flow appeared to channel into a region that occupied roughly 10% of the cross-sectional area which then quickly smoldered to the bottom of the fuel bed. The position of such a "wormhole" was not consistently in one section of the fuel bed nor could its occurrence be precluded by extra care in packing the fuel bed. Egerton, et al. [7] first reported such instabilities in forward smolder of cigarettes; they occur there at much higher flow velocities. Egerton, et al.

attributed the instability to the lessening local flow resistance when the smolder wave gasifies part of the solid thereby allowing still more flow into this local region which gasifies more of the solid, etc. An attempt was made to dampen this mechanism by placing the fuel bed atop a bed of sand having a flow resistance ten times that of the fuel bed; one would expect this to greatly inhibit the channeling tendency since the channel could only provide a 10% decrease in total flow resistance rather than 100%. However, it was not effective. Furthermore, the channeling behavior was never very reproducible. Sometimes as many as three channels were initiated though only one would fully penetrate the fuel bed.

Since this behavior could not be fully controlled and also since it could be dependent on subtle aspects of the apparatus design, this type of forced flow smolder was deemed unsuitable for further development as a means of measuring tendency for transition to flaming.

2.2 Flow Over a Horizontal Smoldering Layer

A flow tunnel, illustrated in Fig. 2, was constructed for the purpose of examining the behavior of a smoldering insulation layer subjected to a flow of air over its surface. The tunnel provides a straight test section 115 cm long, 20.3 cm wide and 56 cm high; it is constructed from Marinite board. Air is drawn through the tunnel by a centrifugal fan at the downstream end; the speed of the fan can be varied to give flow velocities from 0.3 to 5.0 m/s. The combination of the inlet fairing and a honeycomb flow straightener (5 cm thick; 0.64 cm wide cells) provides a flow that is uniform over the central cross-section of the tunnel to within ± 2%, as measured by an air velocity probe. There is a slow, time-dependent fluctuation (~ 1 cps) of comparable magnitude. Side wall boundary layer effects do not appear to influence the central 50% of the tunnel over the majority of the length of the region where the insulation layer is placed. The sample thus behaves, to a large degree, as though it is in a steady wind blowing parallel to its top surface. The boundary layer on the top surface of the sample grows from the tunnel inlet. From the peak flow velocity and the longitudinal distance to the downstream end of the bed, one would infer that the boundary layer is laminar in all cases. However, the fuel bed surface is rough due to its particulate nature and to its uneven shrinkage during smoldering; this introduces local separation in numerous places and, in effect, causes a mildly turbulent boundary layer. This can be seen when smoke is being generated by the smolder process.

The leading and trailing edges of the insulation bed are ramped at an angle of 35° to lessen flow separation effects. The intersection of the upstream ramp with the top surface is always smoothed and rounded before a test by pressing down the insulation. The downstream intersection was not so treated and the flow is always fully separated from there onward (downstream).

Flow velocity is measured continually during a test with a Sierra Instruments Model 615 MHT air velocity meter*. The placement of the meter probe is ahead of the sample bed where the tunnel cross-section has its full 56 cm height. The sample bed is typically 10.2 to 10.8 cm deep before smoldering so the flow velocity over the top of the bed is about 20% higher

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*Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

than that recorded by the meter. The velocity values reported here are for the full cross-section height. The local cross-section above the sample varies as it smolders and shrinks; the tunnel was made 56 cm high to keep the corresponding variation in flow velocity within 20%.

Unretarded insulation from a commercial manufacturer is fully conditioned to 50% relative humidity at 21-24°C. It is weighed out and then fluffed by hand within a plastic bag to remove all clumps. It is packed in two stages, as uniformly as possible, into a pan that imposes the shape and size shown in Fig. 2. Preliminary experiments showed that bulk densities in the range of commercial insulation installation practice (.025-.035 g/cm^3) give erratic results; there is a distinct tendency for portions of the partially consumed, charred insulation to blow downstream. The bulk density was therefore raised to the maximum achievable with hand packing, 0.08-0.10 g/cm^3; this spread of values results from a varying tendency of the material to expand upward after it is removed from the packing pan. The same range of bulk density for the organic portion of the insulation is used when the material is retarded. Bulk density affects smolder velocity and it may affect the minimum air velocity needed to cause the transition to flaming; this has not been evaluated.

The combustion retardants (boric acid and 10 mol borax) were usually reagent grade but NF grade was used in a few tests. In all cases the material is through 200 mesh. It is mixed with the insulation in sufficient quantity to give a final product that is 15% by weight retardant. Uniform dispersion is achieved by two hours of mixing on a roller mill. Thereafter all procedures are the same as with the unretarded material.

After placement in the flow tunnel, the vertical sides of the insulation bed are in contact with either 1.27 cm Marinite board or 1.27 cm white pine board. The sample width is thus reduced to 17.8 cm. The bottom of the sample is always in contact with 1.27 cm Marinite board.

Thermocouples (chromel/alumel in a 0.050 cm diameter stainless steel sheath) are inserted laterally into the insulation bed so that the junction is at centerline mid-depth; three thermocouples are used, symmetrically placed about the sample center with a nominal separation of 10 cm from one to the next. The thermocouples are supported for about half of their immersed length with a 0.080 cm ceramic tube. This provides an optimum compromise between the need to position the thermocouples at precisely known spacings and the tendency of a rigid rod to disrupt the smolder bed when the bed shrinks.

The insulation layer can be ignited to smoldering on either end to produce propagation in the same direction as the air flow (forward smolder) or in the opposite direction (reverse smolder). The igniter is a 1.3 mm diameter electrical heater formed into a zig-zag pattern 8 cm long x 13 cm wide so that it uniformly ignites the full width of the insulation bed. It is slipped under the desired end of the bed, raised to 375°C and left in place for up to one hour. Its subsequent removal is somewhat disruptive to the end of the insulation bed so a thin sheet of stainless steel is laid across the first two inches of the bed (at the bottom of the ramp) to keep the flow smooth. During ignition the air flow velocity through the flow tunnel is 0.15-0.30 m/s; it is raised to the desired test value (and subsequently held constant) only after the smolder front on the top surface of the bed approaches the top end of the ramp portion.

It should be noted that even though the insulation bed is permeable, its flow resistance is several orders of magnitude greater than that for free flow over the layer; thus the flow does not appreciably penetrate the fuel layer and the oxygen influx is mainly diffusive.

The progress of the smolder front is easily visible on the top of the bed since it changes the insulation from a light gray to a dark black color. A motor-driven, 35 mm camera, viewing the top of the bed through a window in the top of the flow tunnel, monitors the smolder front progress by taking pictures at precisely-timed intervals (typically 10 min.). It also views ruled index marks of 1.27 cm spacing on both sides of the bed. The photos are magnified after a test and used to compute the smolder front velocity along the top of the bed. Smolder velocity at mid-depth is inferred from the thermocouples via their spacing and the time between 250°C isotherms.

The top of the bed is also monitored visually through side windows on the flow tunnel and by a visible/near-infrared TV camera placed next to the 35 mm camera. The IR capability (to 2.6 μm) picks up self-emission above 250°C and adds significantly to qualitative diagnosis of smolder behavior, enhancing the perceptibility of some pre-flaming phenomena. The appearance of flames was easily perceived by eye and on the IR TV.

3. RESULTS AND DISCUSSION

Table 1 summarizes all of the experimental conditions and results. The unretarded material is examined first; it provides a baseline for comparison of the effects of a smolder retardant (boric acid) and a flame retardant (borax).

The smolder velocities given in the following figures are all derived from the successive photos of the top surface of the fuel bed. The average value derived from the three imbedded thermocouples generally agreed with this value within 5 to 10% (and frequently closer). However, the two successive values derived from the thermocouples almost always showed some acceleration of the smolder front at the mid-depth of the bed. In contrast, the top surface photos rarely showed any clear-cut acceleration or deceleration. Evidently the smolder front was slowly changing shape as it moved through the bed; this effect was not large enough to obscure any of the trends discussed here.

3.1 Behavior of Unretarded Insulation

Reverse smolder tests (propagation in direction opposite to air flow) were run with two different batches of unretarded material. Figure 3 shows the measured smolder velocity as a function of air flow velocity. There is no significant difference in smolder velocity behavior between these two batches of material for this smolder mode. Both exhibit only the same weak acceleration of the smolder rate with increased air flow velocity; the smolder velocity increases by 67% as the air velocity goes from 0 to 5 m/s.

The batch 1 material exhibited a type of localized flaming phenomenon also seen with this material in forward smolder; here it appeared at air flow velocities greater than 4 m/s. The passing smolder front left some incompletely consumed char that formed a very low density layer on top of the fuel bed; the thickness of this layer increased with time at any given point as the smolder wave moved forward. At random intervals, localized portions of this char could be seen to grow gradually hotter over a period of 2-3 minutes as indicated by increasing light emission. As the char reached a bright orange color, flames (typically light blue, probably due to CO burning) appeared in the localized hole that the char consumption generated. This combination of glowing char and blue flames lasted up to 2 minutes and spread up to 10 cm through the residual char before extinguishing. It never spread up to the leading edge of the smolder front on the top surface of the bed where flaming based on pyrolysis products rather than CO could be established. The flames were always confined within the holes generated in the char. For these reasons, this flaming phenomenon was not viewed as a true transition from smoldering to flaming.

Thus, no true transition occurred in reverse smolder over the range of air velocities achievable with the present apparatus. For this reason, coupled with the relatively weak response of smolder velocity to air velocity in reverse smolder, it was concluded that the reverse smolder mode represents a distinctly lesser hazard than forward smolder (see below); it was not pursued further with regard to combustion retardant effects nor is it viewed as a good mode for rating smolder-to-flaming transition tendency.

Figure 3 also shows the forward smolder behavior of the same two batches of unretarded insulation material. Here the differing batches exhibit a qualitatively similar smolder velocity response but there are significant quantitative differences. Most of the quantitative differences in forward smolder velocity between batch one and batch two material are probably due to differences in bulk density (see Table 1); the batch two material was, in most cases, packed to a bulk density about 20% greater than for batch one. From stoichiometric considerations with an oxygen supply rate-limited process [4], one expects an increase in bulk density to cause a comparable decrease in smolder velocity. In addition, above a critical air flow velocity, batch 1 exhibited the CO flames in confined holes in the char, as discussed above; batch 2 did not.

Both batches, at air flow velocities between 2 and 2.5 m/s, exhibit a true transition to flaming combustion in that flames appear which move onto virgin fuel, consuming self-generated pyrolysis vapors. The CO flames in the char are not a necessary precursor to the initiation of pyrolysis vapor flames since they did not occur with batch 2 material. The pyrolysis-vapor flames typically originated in a cavity-like depression or step formed just to the char side of the leading edge of the smolder front on the top surface. Such a depression was formed rather erratically, evidently by the combination of char shrinkage and consumption. The interior surface of such cavities could be seen to glow just prior to flaming ignition. Evidently the concave structure facilitated locally higher temperatures due to decreased radiative losses; these structures may also have facilitated flaming ignition by allowing local build-up of a flammable gas mixture and by providing a flame-holding region. These details imply that modeling of the transition process will be difficult at best.

The pyrolysis-vapor flames originated at a local region (1-2 cm wide) along the leading edge of the smolder front, spread laterally across the leading edge quite quickly, then spread downstream over the virgin portion of the fuel bed. The spread is spatially erratic and transient. Since the cellulosic insulation material is made ultimately from wood, it is a good char former. Thus, a flame cannot be permanently stabilized on the exposed top surface of the insulation bed; the build-up of only 2-3 mm of char slows the evolution of pyrolysis vapors to the point where the flame blows off. This presumably is a result of the char insulating the pyrolysis region. The flame thus at first spreads rapidly over a large area of the virgin fuel then falls back to regions that provide a flame holder function. Slight depressions in the top surface of the virgin fuel area where flow separation occurs provide temporary anchor points until the char again becomes too thick (after about 1-2 minutes); the flame then dies but it frequently will have initiated smoldering in the local region where it temporarily persisted. The longest-lived flames (up to about 5 min.) are anchored at the original leading edge of the smolder front where the smolder process provides pre-heated fuel and a supplementary source of pyrolysis vapors. Since the smolder process consumes fuel at a much slower rate than the flames, it too ultimately becomes inadequate as an anchor and the flames extinguish. The smolder process continues, its geometry distorted by new initiations downstream; after a variable time interval, the whole process of flaming ignition, spread and extinction is repeated with spread occurring only on areas of fuel not previously charred.

The transient nature of these flaming episodes does not lessen the danger they represent. They persist for a time that is more than adequate to pose an ignition threat to any adjacent flammable structures that exist in a real cellulosic insulation installation. The presence of adjacent wood has further consequences, particularly for retarded insulation, as discussed below.

The differing responses of forward and reverse smolder to increasing air flow pose interesting mechanistic questions. It has not yet been possible to explore these in great depth but some information has been obtained. It should be noted that Palmer [8] also saw such differences though he did not pursue their cause.

Once a smoldering process is past the initiation stage, it has generally been accepted that its rate is controlled by the rate of oxygen supply [8,10, 11,12]. Here again there would seem to be room for such an interpretation. In forward smolder the air flow impinges on the upward ramping surface of the char (Fig. 4); in reverse smolder the flow over the char is separated, as is apparent from the smoke behavior. While there does not seem to be any information in the literature on heat or mass transfer to surfaces very similar to those encountered here, reference to the local transport behavior on cylinders [13] shows that, over a substantial range of Reynolds numbers (20-20,000 based on diameter), the transport of the upstream portion of the surface does indeed exceed that on the separated downstream surface.

In view of the considerable surface roughness here and the ambiguity as to the most pertinent Reynolds number, it was decided that direct measurements of the local mass transfer rates were desirable. The technique chosen, evaporation of a subliming solid (camphor), has been used in the past mainly to infer local heat transfer rates from local mass transfer rate measurements [14]. Unretarded cellulosic insulation beds were smoldered in both forward and reverse configurations (1.95 m/s air flow velocity) and then quickly extinguished with nitrogen after the top of the smolder wave progressed over about two-thirds of the length of the fuel bed. The resulting profiles are those shown in Fig. 4. Pre-weighed flakes of camphor (approximately 1 cm square, $1\frac{1}{2}$ - $2\frac{1}{2}$ mm thick, with tape covering the bottom surface) were placed at several lateral and longitudinal positions on the top surface of the char. A given set of camphor flakes was exposed to a fixed air flow velocity over the extinguished fuel bed surface for a period up to four hours; the weight loss from each flake was then sufficient to permit a weighing accuracy of 1-2%. From the weight loss, the flake area and the vapor pressure of camphor, one can compute the effective local mass transfer coefficient [14].

The variation with position on the char surface is not very great ($\leq$ 35% on the forward smolder case from approximately 23 cm behind the leading edge of the smolder front to approximately 6 cm in front of it). This variation was not pursued extensively because it is small enough to be of secondary importance. Of greatest interest is the behavior near the leading edge of the smolder front; this has the greatest bearing on smolder propagation rate. Figure 5 shows the measured mass transfer coefficient as a function of air flow velocity for a position 2 1/2 cm behind the leading edge of the smolder front (i.e., on the char side for both forward and reverse smolder). The values of the mass transfer coefficient are 5-10 x higher than what one would get for a smooth flat plate parallel to the same flow velocity; the velocity dependence (transport coefficient ~ square root of air flow velocity) is the same as for a flat plate [15].

Comparison of Fig. 5 and Fig. 3 leads one to conclude that oxygen transport alone cannot account for the differences between the forward and reverse smolder propagation behavior. The difference in mass transfer coefficients is only about 25-30% whereas the smolder velocities can differ by a factor of two. In addition, smolder in the two configurations shows differing air velocity dependencies while the dependency of the mass transfer coefficient is essentially independent of configuration. Furthermore, despite the slightly larger coefficient in the forward configuration, depletion of oxygen in the boundary layer over the preceding char probably leads to a slower oxygen transport rate near the leading edge in the forward case; the reverse case does not exhibit this oxygen depletion.

The leading edge region of the smolder front is subject to the greatest heat losses (see Fig. 4). It loses heat by conduction and radiation into surrounding virgin fuel; it also radiates from its top surface to the cold surroundings. In reverse smolder this region also may suffer a net convective heat loss to the air flowing over the surface, in spite of the flow separation. (Note that the convective heat transfer coefficients will behave the same as the mass transfer coefficients in Fig. 5.) Certainly the virgin fuel just ahead of the leading edge of the reverse smolder front (prior to flow separation) suffers a convective heat loss because the air passing over it is at room temperature. In contrast, forward smolder provides a configuration that preheats the air flow as it approaches the leading edge of the smolder front; one expects a net convective heat input to the char just upstream of the leading edge of the smolder front as well as to the downstream virgin fuel not yet charred. In fact the top surface temperature profile at 2 m/s shows that in the forward smolder case, the drying of water from the insulation is pushed several centimeters ahead of the smolder reaction zone by the convective heat input. Drying is immediately in front of the reaction zone for reverse smolder.

In view of these considerations and the observed smolder behavior, we hypothesize that the leading edge region of the smolder front is kinetically-limited, particularly with regard to char oxidation, not oxygen supply rate-limited (the remainder of the smolder front is oxygen supply rate-limited, as is usually assumed). In this sense it is analogous to the flame holder region of a diffusion flame (the analogy is strongest for reverse smolder). A kinetically-limited region will be highly responsive to temperature (and additives, see below) and thus to the net heat flux; it will be only weakly responsive to an enhanced oxygen flux.

Consider the forward smolder case first in view of this hypothesis. An increased air flow directly increases the heat transfer coefficient from the char-heated air to the leading edge region causing some acceleration there. Furthermore the increased air flow first impinges on the oxygen supply rate-limited portion of the char oxidation zone upstream of the leading edge region. There it accelerates the char oxidation rate, raising the local surface temperature and thereby heats the air further. This hotter air in turn transfers more heat to the leading edge region enhancing its acceleration. This occurs in spite of the fact that the enhanced char oxidation depletes more oxygen from the heated air in the boundary layer (which probably overrides the increased mass transfer coefficient). If the leading edge of the smolder front can thus move forward more and more rapidly, the remaining portion of the smolder front (the oxygen supply limited portion) can keep up by adjusting its shape to assure that the oxygen supply rate per unit length of smolder front is just sufficient.

This accelerating char oxidation closer and closer to the leading edge of the smolder zone puts a heat source of increasing strength and temperature in closer proximity to the virgin fuel. The top surface temperature profile at

2 m/s shows that the forward smolder mode supports a temperature gradient parallel to the surface that is 2 1/2 x greater than in the reverse smolder case. Ultimately the accelerated char oxidation at the leading edge leads to the development of the concave structures, described above, which ignite pyrolysis vapors to flaming.

The reverse smolder case might at first be expected to go slower with increased air velocity on the basis of the preceding heat transfer considerations. In fact, Palmer [8] did find one material (cork dust) that smoldered more slowly with increased air velocity above about 3 m/s in the reverse smolder configuration; many of his materials showed a constant reverse smolder velocity with increased air flow velocity above about 1 to 2 m/s, though they accelerated at lower air velocities. Here, Fig. 3 shows only a slow but steady acceleration of reverse smolder velocity. Evidently the increased convective heat loss from the leading edge region is more than compensated by other changes. The region beyond the leading edge (downstream) responds to the increased oxygen supply by getting hotter as in the forward smolder case. The separated flow, with its attendant flow reversal, helps move some of this heat up toward the leading edge. Conduction and radiation through the fuel bed do so also. Furthermore, as comparison of Fig. 4(a) and 4(b) shows, the leading edge char zone is 50% thicker in the reverse case, lessening heat losses. The net summation of the increased inputs of heat to the leading edge region is evidently sufficient to outweigh the increased convective loss from the top surface. A further factor that probably aids acceleration of the smolder process in this case (and less so in the forward case) is an improved oxygen supply to the oxidative pyrolysis zone comprising the front portion of the blackened region in Fig. 4. This exothermic processs (see Fig. 7) was previously inferred to contribute significantly to smolder propagation in the absence of air flow [4,5].

These arguments provide a plausible qualitative explanation of the strong response of forward smolder to increased air flow and the weak response of reverse smolder. They do not explain the quantitative details such as the breaks in slope in the forward case (Fig. 3); these await a detailed mathematical model. The present arguments suggest that this model must describe the gas phase above the fuel as well as the fuel bed itself, since their coupling is a key feature of the observed behavior.

3.2 Behavior of Retarded Insulation

It is apparent that, in the transition from smolder to flaming, both smolder and flaming inhibitors could have an impact. Both boric acid, a smolder inhibitor, and borax, a flaming inhibitor, were tested separately for their influence on forced flow smolder (forward configuration) and the transition process. Figure 6 summarizes the results. It is apparent that they differ drastically in their influence on the smolder rate. In the absence of any adjacent wood, they appear to be equally effective in preventing flaming, i.e., neither permitted the appearance of flaming at air velocities up to about 5 m/s, the maximum value achievable with the present apparatus.

Shafizadeh, et al. [17] have investigated the effect of boric acid and borax on the smoldering behavior of pure cellulose. They report that there are two types of effects of these additives, both on the char oxidation process. The net reaction heat is affected by shifts in the relative quantities of CO and CO_2 generated; boric acid is especially effective at suppressing CO_2 formation in favor of CO, leading to a lesser heat output per unit weight of char oxidized. In addition, both additives affect the rate of char oxidation; boric acid retards char oxidation while borax accelerates it. Borax apparently suppresses flaming of pure cellulose mainly by increasing the amount of char formed; Shafizadeh et al. found that less than one percent of borax tripled the mass of char formed during cellulose pyrolysis.

The material used here, being mainly ground wood pulp, is only about one-third cellulose; the remainder is hemi-celluloses and lignin. Figure 7 shows the thermal analysis behavior of the three compositions studied here. The usual two peaks of weight loss and heat evolution are apparent in all cases; the first is due to oxidative pyrolysis and the second to oxidation of the char left by the first reaction stage. The effectiveness of boric acid at slowing the char oxidation process is obvious; it also has a weaker retarding effect on oxidative pyrolysis which has not been explained.

The impact of borax is much more subtle; the peak in the char oxidation process shifts downward only about 4°C, a much lesser effect than Shafizadeh saw with pure cellulose. This is probably due to the presence of various char oxidation accelerators already in the unretarded insulation before borax addition; McCarter [17] has shown that various alkali and alkaline-earth metals normally present in woody materials are char oxidation promotors. Here the ash content of the unretarded material is 3.6 weight percent, a high value reflecting, in part, the presence in the insulation of newsprint coated with colored inks. The dyes in these inks can contain heavy metals such as lead, iron and chromium which are very effective char oxidation promotors [16]. Thus, the addition of borax cannot add that much to an already accelerated process. Nevertheless, small shifts in the position of the char oxidation peak, as seen in the thermal analysis, are apparently significant since the only thermal analytical differences between batch one and batch two unretarded material (whose smolder behavior differs with regard to the CO flames, see Fig. 3) are comparable shifts in the char oxidation peak to those seen with borax addition to batch two material. In this case batch one material shifts upward 4°C and the apparent result during smoldering is incomplete char oxidation followed by the intermittent glowing and flames in the residue, described previously. In any event, one must be cautious since thermal analysis at one heating rate does not unambiguously reveal the change in kinetic constants that would be felt under smolder conditions.

The striking differences in smolder velocities at equal air velocities in Fig. 6 are once again a demonstration that external oxygen supply rate alone does not dictate smolder velocity. The preceding arguments about the importance of the leading edge of the smolder zone again apply here. If it is kinetically-limited as hypothesized, it is sensitive to catalysts and inhibitors of the char oxidation process. Thus boric acid slows the propagation by inhibiting char oxidation in the leading edge region. By slowing down, the thermal wave becomes thicker and the heat losses to the virgin fuel decrease. The char oxidation process becomes less complete thereby insulating itself beneath the char residue, cutting heat losses still further [4]. By covering itself with such an insulating layer, the char oxidation zone interposes an additional series resistance to oxygen transport that makes it less sensitive to changes in external air flow velocity. Because of these interacting effects, quantitative prediction of the net effect of a given change in char oxidation rate, for example, requires a detailed model of the entire two-dimensional system.

Borax, as noted, causes some acceleration of the char oxidation process. The acceleration is small relative to the unretarded case and the smolder velocities are only slightly greater. There is, however, no transition to flaming here. The leading edge of the smolder front thus moves faster with further air flow increases, becomes thinner and is able to tolerate the increased heat losses. The remaining portion of the smolder wave must adjust its shape to assure a sufficient oxygen supply rate so that it can keep up. It has practically no "cover" between the char reaction zone and the external air flow (only a 1-2 mm quenched skin of char on the top of the fuel bed) and so it is highly responsive to changes in the external air flow velocity.

Figure 8 shows the differing shapes of the overall reaction zone that facilitate the widely differing smolder velocities at the same air velocity. Note that the reaction zone length is stretched out in the borax case by about 40% to about 37 cm from about 27 cm for boric acid. Thus not only does the borax case assure its reaction zone a higher oxygen supply rate by remaining close to the top surface of the fuel bed, it also stretches out the reaction zone at a more shallow angle to facilitate a greater supply rate per unit length of reaction front.

The failure of the transition to flaming to occur with either retardant is presumably due to differing causes. For boric acid, the infrared TV viewing the top surface makes it apparent that the surface is much cooler than the unretarded (or borax) case. Thus it is probable that, for nearly all of the air flow range, the temperature was insufficient to ignite a flammable mixture of pyrolysis products even if it existed above the fuel bed surface. The situation is evidently changing at flow velocities above 4.5 m/s since the smolder velocity begins to accelerate; one brief episode of flaming in the char was noted at the highest flow velocity. The behavior of the upstream end of the bed at high air velocities also indicates a new mode of behavior in insulation containing boric acid. Here the oxygen transport rate is highest due to the direct impingement of the flow and lack of any upstream oxygen depletion. The highest temperatures measured in any of the tests (nearly 900°C, 650-700°C was typical of other compositions) occurred in this region at an air velocity of about 5 m/s. Evidently the retarded char can be made to oxidize completely if the oxygen supply rate and temperature are sufficient. Onset of this more complete char oxidation near the leading edge may be the source of the upturn of the boric acid curve in Fig. 6; note that the slope in the upturn region matches that for borax where char oxidation is normally more nearly complete in the forward part of the smolder wave.

In view of the minor effect that borax has on the thermal analysis behavior (Fig. 7), its success in suppressing flaming is surprising. That is, it does not appear to act by promoting char formation as it does with cellulose since the amount of char indicated in Fig. 7 is about the same as for unretarded material. Its mode of action is not apparent; it could be an indirect effect such as a failure to facilitate formation of the intermittent cavity-like depressions at the leading edge of the smolder front. Recall that these were the source of flaming ignition in the unretarded case.

3.3 Effect of Adjacent Wood

Even though the retarded insulation layers of the preceding section did not yield flames, the increased air flow did accelerate the smolder and raise the peak bed temperatures. At air velocities below any transition to flaming, these peak temperatures tend to occur just below the surface of the char away from the leading edge of the smolder front; thus there is no adjacent source for pyrolysis gases to support flaming. However this glowing char is an excellent source of radiant heat. Furthermore the shape of the char surface toward the middle to rear portion of the smolder wave facilitates radiation toward the adjacent vertical walls supporting the insulation layer. The char surface tends to pull somewhat away from the adjacent wall forming a gap that allows air inflow; the char can thus oxidize readily and radiate its evolved heat toward the adjacent vertical wall with a fairly good view factor. If this wall is an unretarded flammable material, flaming ignition is to be expected. The only question is, at what air flow velocity?

White pine boards (1.27 cm thick) were substituted for the Marinite sideboards to assess the impact of flammable sidewalls such as would be used in a realistic attic installation of cellulosic insulation. For the unretarded insulation (Fig. 3), there was some scatter in the data but the net implication is that the critical air flow velocity for the appearance of flaming (either spreading flames on the insulation or flames on the wooden sidewalls) was basically unchanged. The scatter was probably due to variation in the insulation composition since differing bags of material were used in tests at different times.

Figure 6 shows that, when wooden sidewalls are present, all of the flaming suppression effectiveness of borax is lost. The glowing char ignites the wood at about the same air flow velocity as is found with unretarded insulation. The flames in this case, tend to anchor in the gap between the insulation and the wood. For white pine, which is a low density wood, the flames burn through the 1.27 cm thickness in 5-10 minutes.

Figure 6 shows that the presence of adjacent wood yields a partial loss of effectiveness for flaming suppression with boric acid; the critical air flow velocity moves down from something over 5 m/s to about 3-3/4 m/s. This is still an improvement over the 2 - 2 1/2 m/s critical velocity in the unretarded case. This improvement comes about because, at air flow velocities up to about 3 1/2 m/s, retardation of the char oxidation process cuts the char surface temperature and reduces its radiating power. At higher air velocities the high temperature, complete oxidation of the retarded char begins, especially at the upstream end of the fuel bed, as discussed above; this readily ignites adjacent wood.

3.4 Implications for a Smolder-to-Flaming Test Method

This technique can indeed provide a quantitative measure of smolder-to-flaming transition tendency. Furthermore, the range of results obtained and the fact that they probably could not be expected to show a one-to-one correlation with results for the same materials in the current smolder ignitability (cigarette) test indicate the need for a test along the present lines.

There is some inevitable scatter in the measured critical air flow velocity for the transition. It is minimized by careful packing and by the use of high layer densities but it cannot be eliminated because of the coarse nature of the test material and the participation in the transition process of intermittent cavities in the smolder front. Furthermore, the exact value of the critical flow velocity is undoubtedly not only a function of the insulation composition but also of the test configuration. The transition process is a combined kinetic and oxygen transport phenomenon. The critical balance of each could be shifted if the air encountered the smoldering insulation layer in a different configuration, e.g., if the insulation layer had been recessed into the floor of the flow tunnel used here. The present configuration is fairly realistic but real world configurations undoubtedly vary as well. Thus the critical flow velocity is best viewed as a relative parameter and not an absolute measure of safety.

A substantial problem with the present configuration and mode of operation is that it requires several hours to establish the question of flaming or non-flaming at a given flow velocity. It is highly desirable to shorten this to about one hour. Most of the time would inevitably go into establishing a robust smolder wave; careful attention to igniter design is needed to assure a realistic smolder wave. The actual air flow portion of the test could probably be confined to 10-15 minutes (enough time to allow some random fluctuations in the behavior of the smolder front as it passes over small scale variations in packing density and local composition. The test result would be of a go/no-go nature at a fixed flow velocity. A few replications, run in parallel, would be desirable.

The presence of adjacent wood clearly has a major impact on the test outcome. Since it is present in the actual application, it should be present in the test as well. It would have to be carefully specified to avoid introducing a further source of scatter.

Needless to say, an appropriate test of this nature requires further development and some calibration testing against one or more configurations of realistic attic mock-ups with induced air flow. This calibration would serve to establish a realistic value for the pass/fail level of critical air flow velocity. Some exploration of the effects of insulation layer depth, bulk density, moisture content and insulation composition are needed to assure that no new phenomena enter in which could complicate the test interpretation in routine usage. Any dependence of critical air flow velocity on procedural variables (such as the length of the smoldering period prior to onset of air flow) also needs to be quantified. A flame detector (probably optical) may be desirable to minimize dependence on operator attentiveness or judgment. This tentative procedure for assessing the tendency of an insulation to undergo transition from smoldering to flaming is significantly more complex than the existing cigarette test so it will require more extensive developmental testing.

In carrying out the suggested development, one should run the standard cigarette tests on all compositions used. Although a good correlation between the pass/fail performance of cellulosic insulations in the two types of tests is rather improbable, if it was found it would obviate the need for a smolder-to-flaming test.

4. SUMMARY AND CONCLUSIONS

For a given insulation composition, there is a large difference in response between a smolder wave moving in the same direction as the accompanying air flow (forward smolder) or in the opposite direction (reverse smolder). Reverse smolder of an unretarded insulation showed only a weak increase in velocity as the air flow increased; no transition to flaming was seen at air velocities up to 5 m/s. Forward smolder of the same insulation was accelerated considerably more, and, at air velocities in the range 2 - 2 $1/2$ m/s, flames were developed which spread over the uncharred material ahead of the smolder zone. These differing responses are not due solely to differences in oxygen transfer rate to the smoldering fuel. They are qualitatively consistent with the idea that the leading edge of the smolder front is kinetically-limited and is therefore sensitive to the differences in convective heat transfer implicit in forward and reverse configurations. The overall smolder wave is thus partially kinetically-controlled (leading edge region) and partially oxygen transport-controlled (bulk of wave behind leading edge).

Borax and boric acid assert their influence through the kinetically-controlled leading edge region by accelerating (borax) or slowing (boric acid) the char oxidation kinetics. By slowing the char oxidation kinetics to the point of incomplete char consumption, boric acid also manages to slow the oxygen supply rate to the trailing portion of the smolder wave making it less responsive to changes in air flow velocity. This partial suppression of char oxidation is lost at sufficiently high air velocities and a very hot smolder process is generated. Nevertheless, boric acid suppresses flaming up to at least 5 m/s. Borax does also, even though it somewhat accelerates the smolder propagation process; its mode of flaming suppression in not clear.

Actual installations of cellulosic insulation almost invariably juxtapose layers of the material with wooden structural supports. The wood, of course, contains no retardants. When wooden sidewalls are included in the forced-flow smolder apparatus there is no significant impact on the critical velocity for appearance of flaming with unretarded insulation. However, the benefits of borax are completely lost; the glowing insulation smolder zone that does not itself transition to flaming ignites the adjacent wood at essentially the same air velocity as is seen with unretarded insulation. The benefits of boric acid are reduced but not lost when wooden sidewalls are present; the critical air flow velocity for appearance of flames drops from above 5 m/s to about 3-3/4 m/s. Since borax and boric acid are usually used together, it is probable that the combination offers less margin of improvement than boric acid alone. From this and the rather weak effect that boric acid has on increasing the minimum temperature for initiation of smoldering in cellulosic insulation, one sees a continuing need for more effective smolder retardants.

The test methodology developed here can provide a quantitative basis for measuring the smolder-to-flaming tendency of an insulation composition. The method needs further development, however, to assess its sensitivity to test details and to calibrate it against mock-ups of realistic installations.

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TABLE 1. Compilation of Test Results

Insulation Composition	Layer Depth (cm)	Bulk Density (g/cm^3)	Wood Sidewalls	Smolder Configuration	Air Velocity (m/s)	(Photos) Smolder Velocity (cm/s)	(TC's) Smolder Velocity (cm/s)	Peak Temp. (°C)	Comment
Unretarded, 1*	10.2	0.090	No	Reverse	0.10	-	$3.12 \cdot 10^{-3}$	> 567 **	
Unretarded, 2	10.2	0.090	No	Reverse	0.29	$3.00 \cdot 10^{-3}$	$2.94 \cdot 10^{-3}$	—	
Unretarded, 2	10.8	0.095	No	Reverse	1.92	$3.60 \cdot 10^{-3}$	-	—	Extinguished bed used for mass transfer meas.
Unretarded, 2	10.6	0.097	No	Reverse	1.92	$3.51 \cdot 10^{-3}$	-	—	
Unretarded, 1	10.7	0.086	No	Reverse	2.0	$3.92 \cdot 10^{-3}$	$3.79 \cdot 10^{-3}$	> 596	
Unretarded, 2	10.2	0.090	No	Reverse	2.05	$3.68 \cdot 10^{-3}$	$3.96 \cdot 10^{-3}$	—	
Unretarded, 2	10.8	0.085	No	Reverse	2.1	-	$4.02 \cdot 10^{-3}$	—	Elec. arc in gases gave no flames
Unretarded, 2	11.1	0.082	No	Reverse	3.0	$4.57 \cdot 10^{-3}$	$4.49 \cdot 10^{-3}$	750	CO flames in char
Unretarded, 1	10.9	0.084	No	Reverse	4.05	$5.00 \cdot 10^{-3}$	$4.90 \cdot 10^{-3}$	743	CO flames in char
Unretarded, 2	10.8	0.085	No	Reverse	4.05	-	$4.98 \cdot 10^{-3}$	644	Elec. arc in gases gave no flames
Unretarded, 1	11.3	0.081	No	Reverse	4.50	$5.22 \cdot 10^{-3}$	$4.90 \cdot 10^{-3}$	703	CO flames in char
Unretarded, 1	10.8	0.085	No	Reverse	5.05	$5.15 \cdot 10^{-3}$	$5.34 \cdot 10^{-3}$	731	CO flames in char
Unretarded, 1	10.2	0.090	No	Forward	0.10	-	$3.60 \cdot 10^{-3}$	487	
Unretarded, 1	10.2	0.090	No	Forward	0.20	$4.26 \cdot 10^{-3}$	$4.04 \cdot 10^{-3}$	> 520	
Unretarded, 1	10.2	0.090	No	Forward	0.49	$4.50 \cdot 10^{-3}$	$4.50 \cdot 10^{-3}$	> 525	
Unretarded, 1	10.2	0.090	No	Forward	1.0	$5.05 \cdot 10^{-3}$	$4.72 \cdot 10^{-3}$	> 570	CO flames in char
Unretarded, 1	11.4	0.080	No	Forward	2.0	$7.96 \cdot 10^{-3}$	$8.04 \cdot 10^{-3}$	708	CO flames in char
Unretarded, 1	11.4	0.080	No	Forward	2.25	$8.44 \cdot 10^{-3}$	$8.18 \cdot 10^{-3}$	687	CO flames in char
Unretarded, 1	11.1	0.083	No	Forward	2.45	$8.16 \cdot 10^{-3}$	$8.08 \cdot 10^{-3}$	≳ 688	CO flames in char
Unretarded, 1	11.1	0.083	No	Forward	2.95	-	-	—	Spreading pyrol. flames
Unretarded, 1	11.1	0.083	No	Forward	2.95	-	-	—	Spreading pyrol. flames
Unretarded, 2	10.2	0.103	No	Forward	0.49	$3.68 \cdot 10^{-3}$	$3.90 \cdot 10^{-3}$	—	
Unretarded, 2	10.2	0.103	No	Forward	1.0	$3.86 \cdot 10^{-3}$	$3.62 \cdot 10^{-3}$	609	
Unretarded, 2	10.2	0.103	No	Forward	1.55	$5.18 \cdot 10^{-3}$	$5.00 \cdot 10^{-3}$	633	
Unretarded, 2	10.2	0.103	No	Forward	1.77	$5.93 \cdot 10^{-3}$	$5.53 \cdot 10^{-3}$	678	
Unretarded, 2	10.8	0.095	No	Forward	1.9	$7.02 \cdot 10^{-3}$	-	—	Extinguished bed used for mass transfer meas.
Unretarded, 2	10.5	0.098	No	Forward	1.92	$6.65 \cdot 10^{-3}$	-	—	
Unretarded, 2	10.2	0.103	No	Forward	1.95	$6.05 \cdot 10^{-3}$	$5.78 \cdot 10^{-3}$	659	
Unretarded, 2	10.2	0.103	No	Forward	2.27	-	-	—	Spreading pyrol. flames
Unretarded, 2	10.2	0.094	Yes	Forward	1.77	$5.84 \cdot 10^{-3}$	$5.60 \cdot 10^{-3}$	684	
Unretarded, 2	10.8	0.095	Yes	Forward	2.25	$7.34 \cdot 10^{-3}$	$7.95 \cdot 10^{-3}$	701	
Unretarded, 2	10.8	0.095	Yes	Forward	2.6	-	-	—	Spreading pyrol. flames
15% Borax***	11.1	0.086	No	Forward	2.0	$9.10 \cdot 10^{-3}$	$11.0 \cdot 10^{-3}$	> 512	CO flames in char
15% Borax	10.8	0.088	No	Forward	3.5	$10.9 \cdot 10^{-3}$	$14.3 \cdot 10^{-3}$	> 539	

TABLE 1. (continued)

Insulation Composition	Layer Depth (cm)	Bulk Density (g/cm³)	Wood Sidewalls	Smolder Configuration	Air Velocity (m/s)	(Photos) Smolder Velocity (cm/s)	(TC's) Smolder Velocity (cm/s)	Peak Temp (°C)	Comment
15% Borax	11.1	0.086	No	Forward	4.4	$16.7 \cdot 10^{-3}$	-	616	
15% Borax	11.1	0.086	No	Forward	4.45	$15.6 \cdot 10^{-3}$	-	> 599	
15% Borax	10.5	0.091	Yes	Forward	0.30	$4.42 \cdot 10^{-3}$	$4.36 \cdot 10^{-3}$	> 601	
15% Borax	10.5	0.091	Yes	Forward	1.5	$6.53 \cdot 10^{-3}$	$7.37 \cdot 10^{-3}$	> 552	Spreading pyrol. flames late in test
15% Borax	10.5	0.091	Yes	Forward	1.75	$7.53 \cdot 10^{-3}$	$7.85 \cdot 10^{-3}$	> 597	No flames
15% Borax	10.5	0.091	Yes	Forward	2.1	-	-	—	Spreading pyrol. flames early in test
15% Boric Acid	10.5	0.091	No	Forward	0.28	$2.18 \cdot 10^{-3}$	$1.96 \cdot 10^{-3}$	617	
15% Boric Acid	10.8	0.101	No	Forward	1.95	$2.54 \cdot 10^{-3}$	$2.60 \cdot 10^{-3}$	> 666	
15% Boric Acid	10.5	0.091	No	Forward	3.05	$2.86 \cdot 10^{-3}$	$2.70 \cdot 10^{-3}$	> 763	
15% Boric Acid	10.8	0.088	No	Forward	4.45	$3.34 \cdot 10^{-3}$	$2.58 \cdot 10^{-3}$	823	Possible CO flame in char
15% Boric Acid	10.2	0.094	No	Forward	4.8	$4.04 \cdot 10^{-3}$	-	851	
15% Boric Acid	10.2	0.100	No	Forward	4.9	$4.43 \cdot 10^{-3}$	$3.48 \cdot 10^{-3}$	895	Once, CO flame in char
15% Boric Acid	10.5	0.091	Yes	Forward	0.3	$2.57 \cdot 10^{-3}$	$2.28 \cdot 10^{-3}$	656	
15% Boric Acid	10.5	0.091	Yes	Forward	2.95	$2.82 \cdot 10^{-3}$	$2.70 \cdot 10^{-3}$	> 706	
15% Boric Acid	10.5	0.091	Yes	Forward	3.95	$3.22 \cdot 10^{-3}$	$2.93 \cdot 10^{-3}$	> 701	Spreading pyrol. flames late in test
15% Boric Acid	10.5	0.091	Yes	Forward	4.95	-	-	—	Spreading pyrol. flames
15% Boric Acid	10.5	0.091	Yes	Forward	5.0	-	-	--	Spreading pyrol. flames

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*Numbers 1 and 2 refer to two different batches of unretarded insulation made by the same commercial manufacturer at two different times.

**This is the peak temperature recorded but in cases with > in front of the temperature the temperature was still rising when the experiment was terminated.

***All compositions with borax and boric acid were made from batch 2 material.

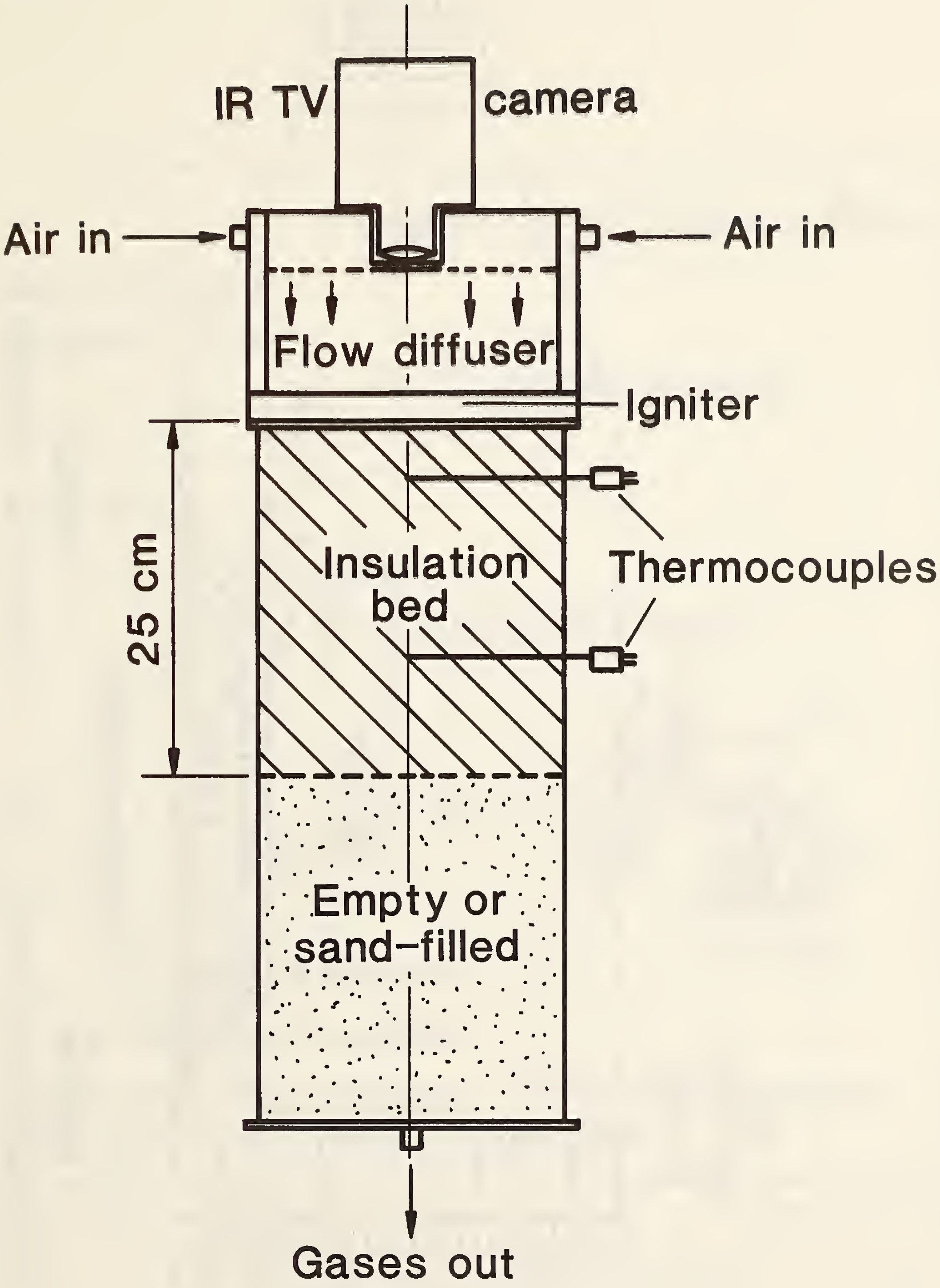

Figure 1. Schematic of apparatus for study of smolder propagation with flow forced through the fuel bed.

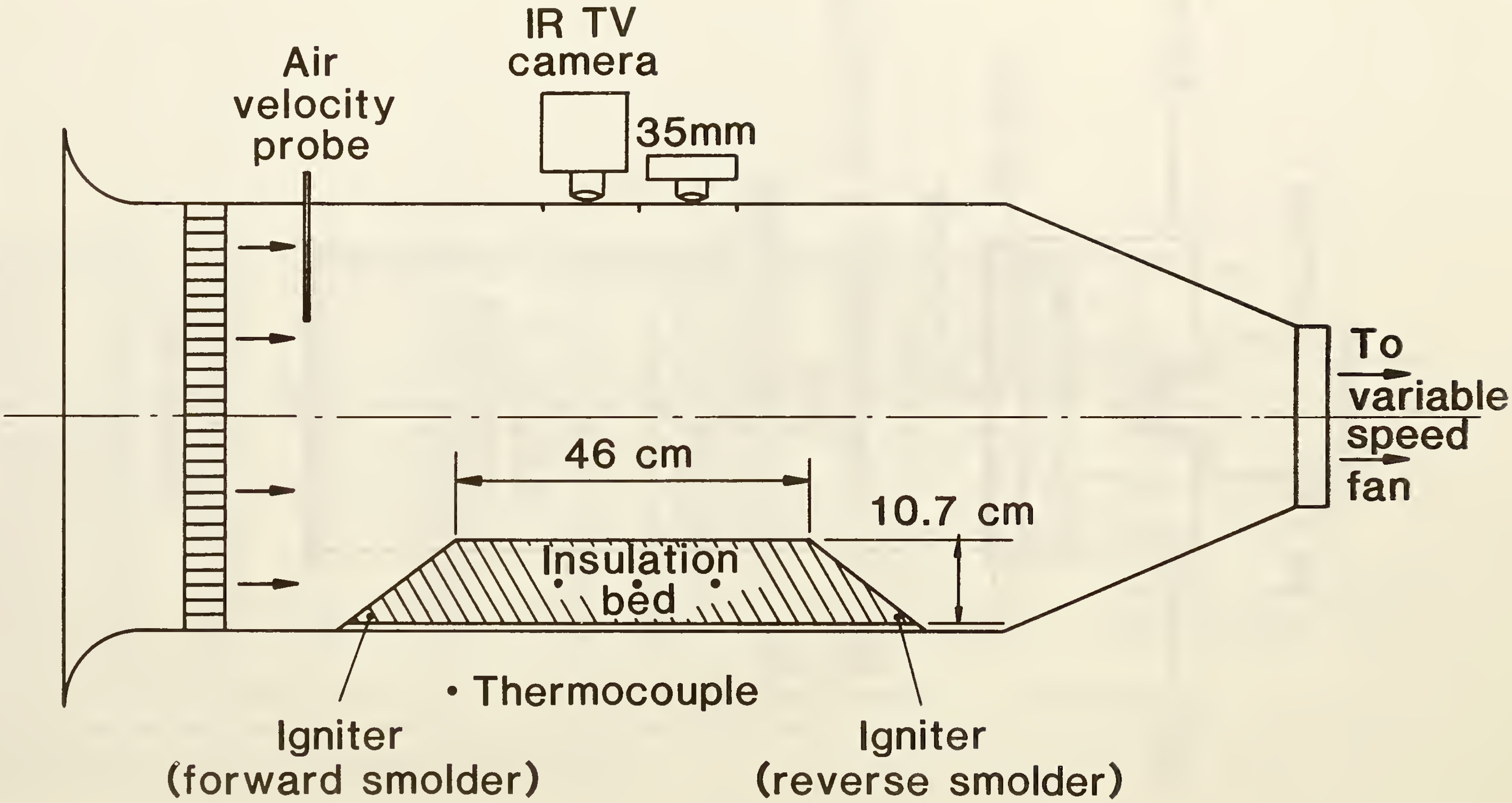

Figure 2. Schematic of flow tunnel apparatus for study of smolder propagation with flow over the fuel bed. Flow tunnel cross-section is 20.3 cm wide by 56 cm high.

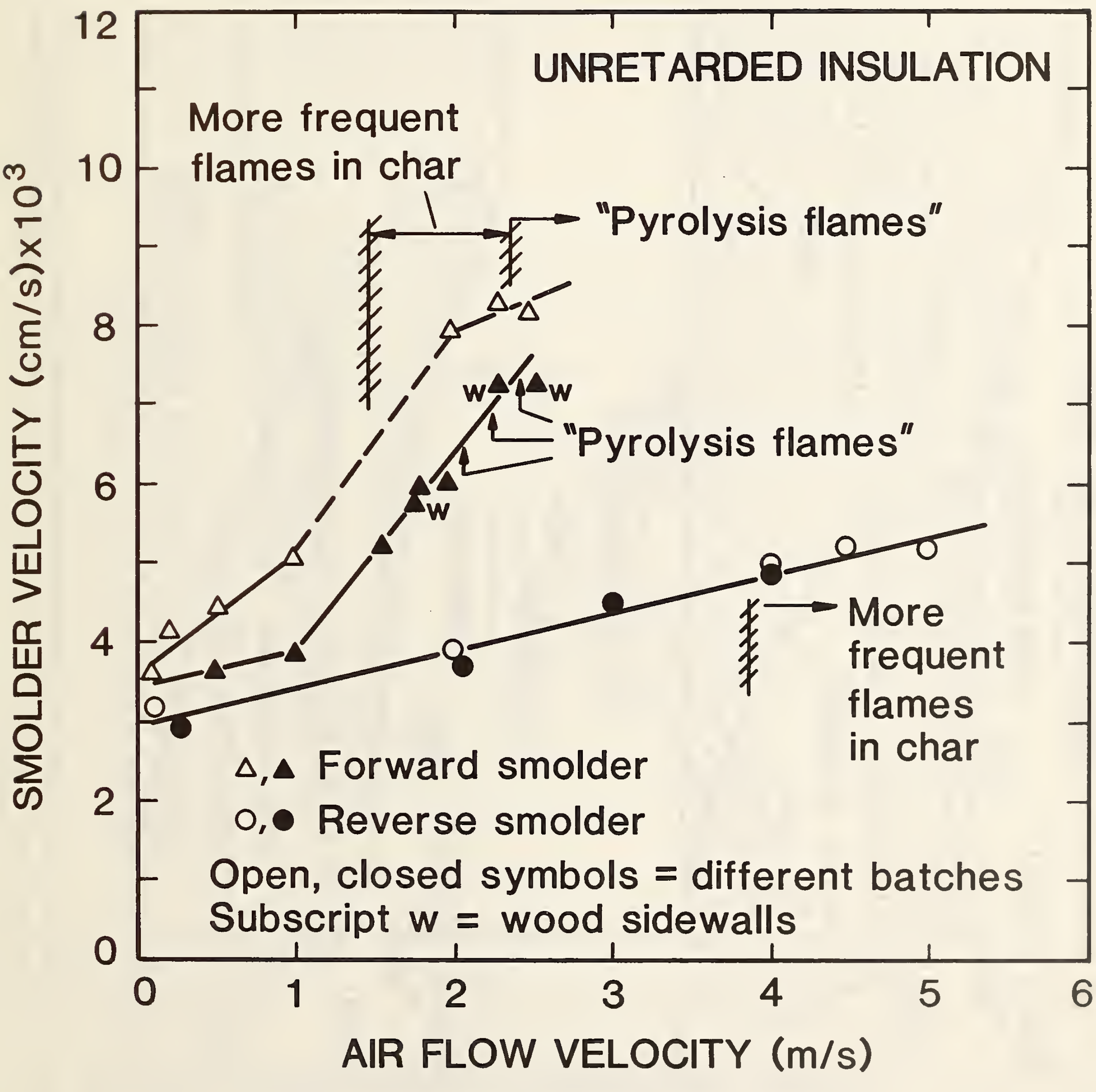

Figure 3. Measured dependence of smolder velocity on velocity of air flowing over the fuel bed in both forward and reverse configurations.

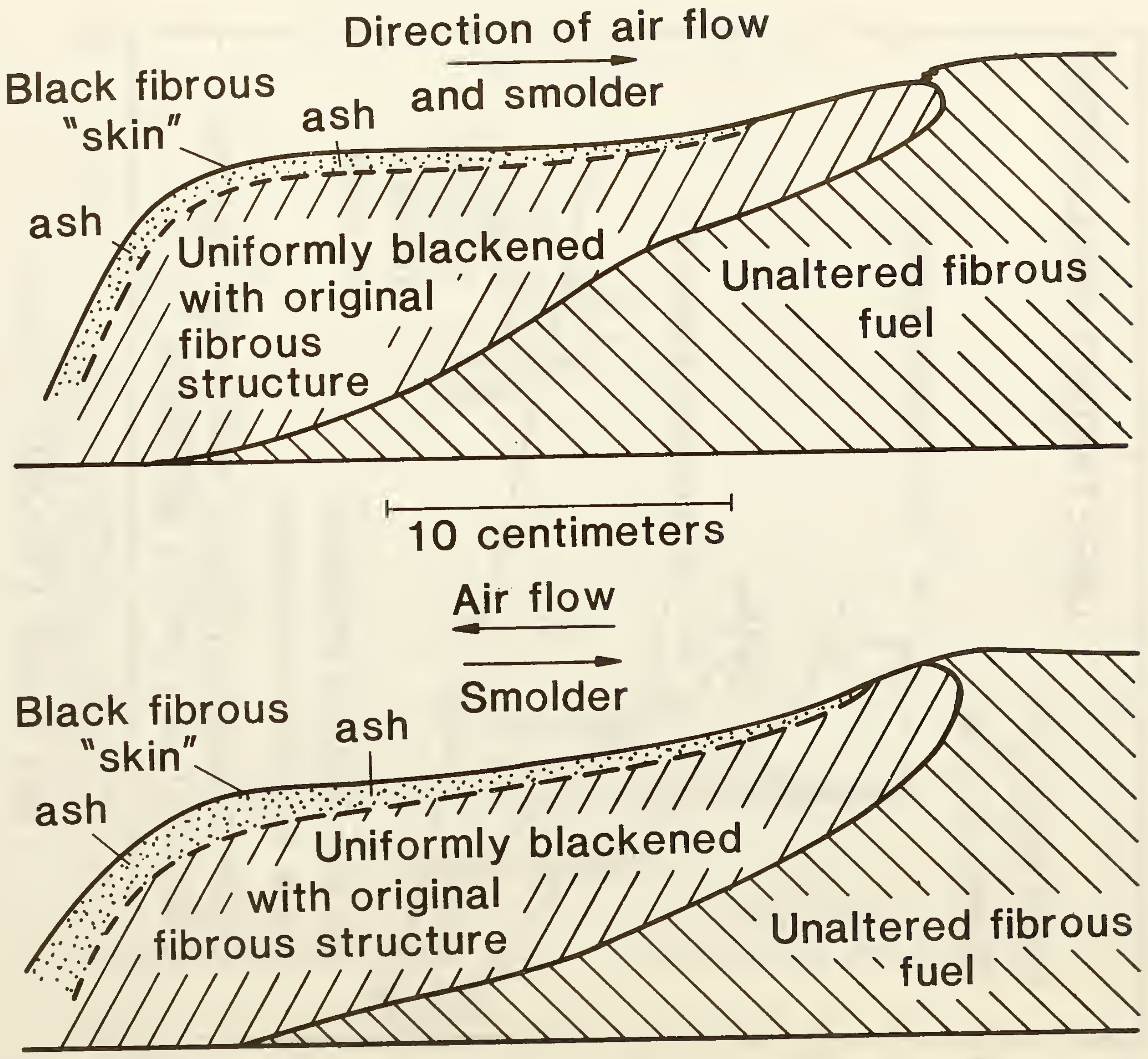

Figure 4. Measured cross-sectional profiles of extinguished forward (top) and reverse (bottom) smolder waves. Note that the bottom profile has been turned around for ease of comparison.

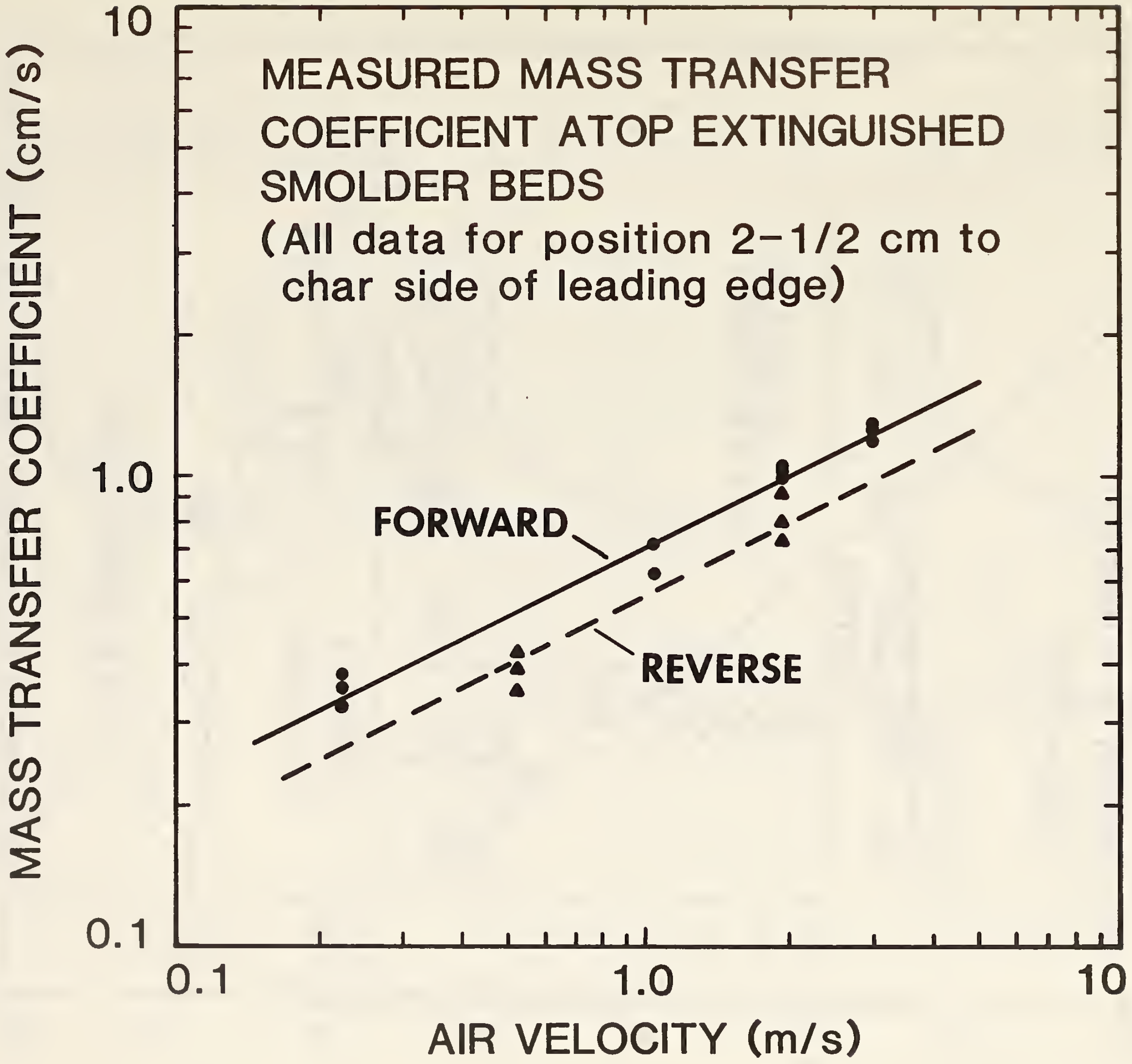

Figure 5. Measured mass transfer coefficient between air stream and top surface of fuel bed for both forward and reverse configurations.

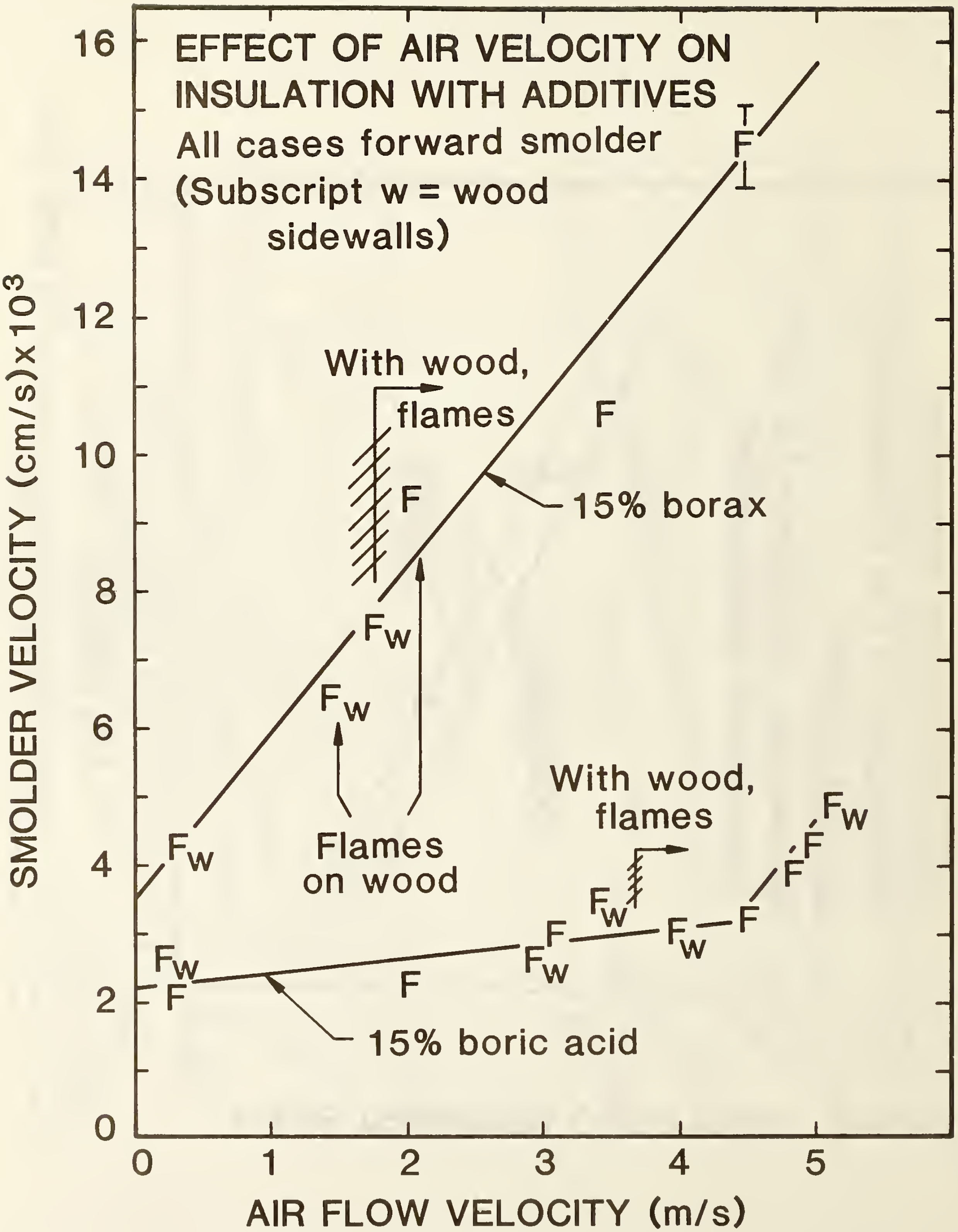

Figure 6. Measured effect of air velocity on smolder velocity of two compositions with additives; all results for forward smolder mode. Flames appeared only when wood sidewalls were present.

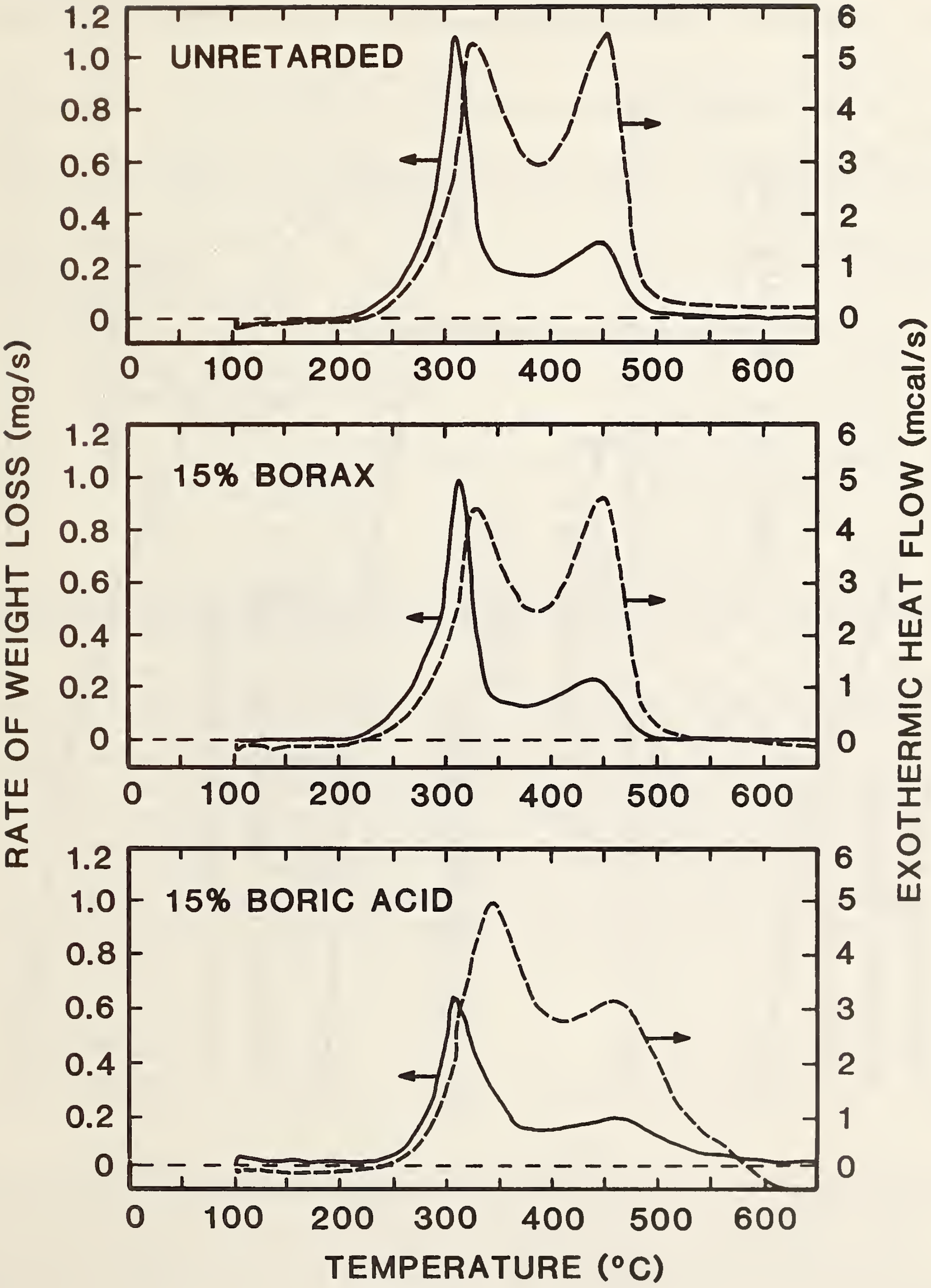

Figure 7. Comparison of thermal analysis behavior (4 mg sample, 5°C/min in air) of three insulation compositions.

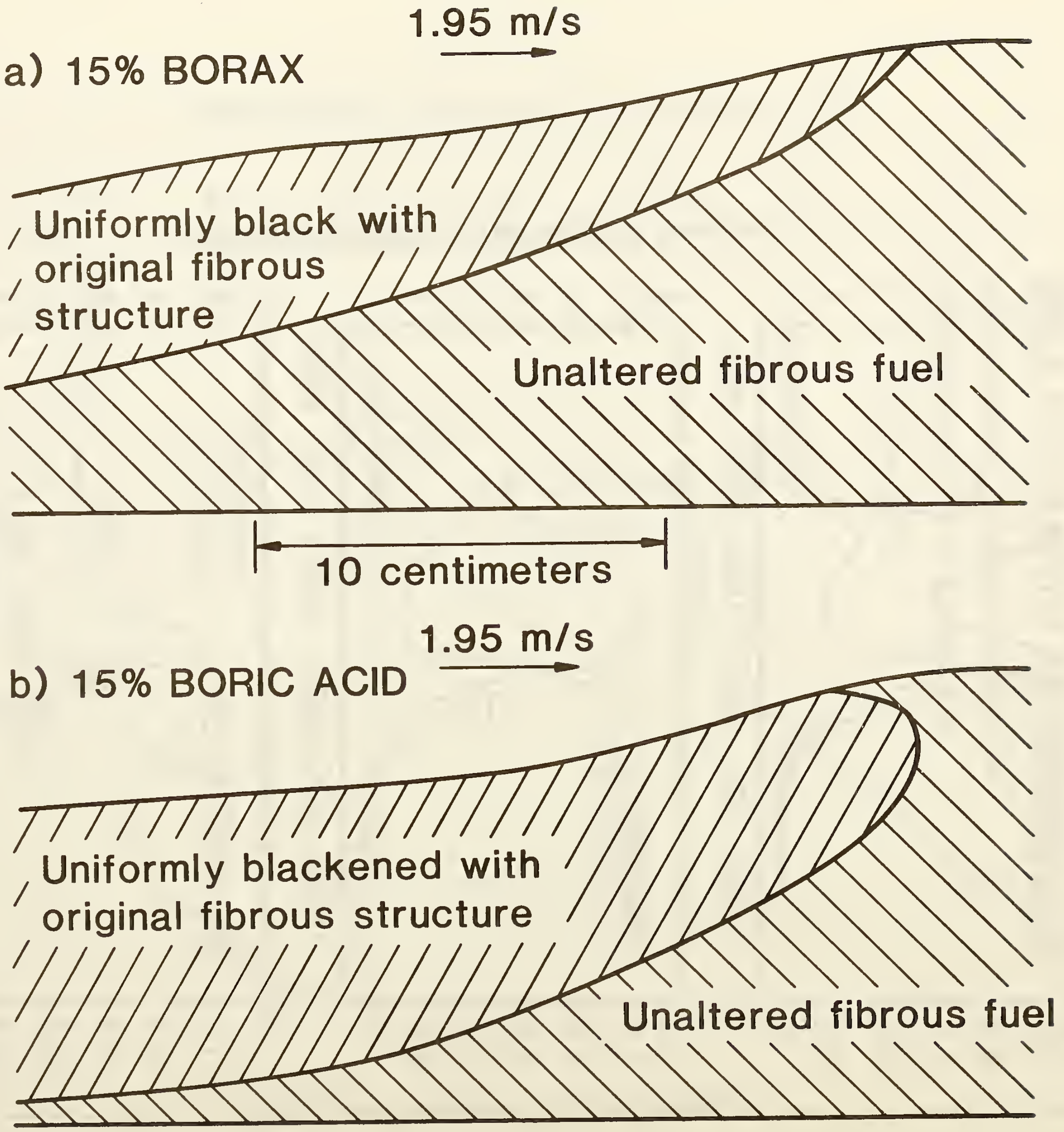

Figure 8. Measured cross-sectional profiles of extinguished smolder waves with differing compositions at same air velocity (1.95 m/s, forward smolder mode).

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5. AUTHOR(S)

Thomas J. Ohlemiller

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

It is well known that a smoldering fuel responds to an increased oxygen supply by becoming faster and hotter until, eventually, flames erupt. This sequence is examined quantitatively for thick horizontal layers of a permeable fuel, i.e., cellulosic insulation. Two configurations are possible, forward and reverse smolder; both are investigated experimentally. The influence of combustion retardants is also investigated; these include boric acid, a smolder retardant; and borax, a flaming retardant. Both prevent the transition to flaming in the absence of adjacent flammable material but are less effective in its presence. The overall response of these various fuel mixtures and configurations suggests that both kinetics and oxygen supply rate (not the latter alone) play substantial roles in dictating smolder response to an air flow.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air flow, cellulosic materials, flame retardant, insulation, smoldering, smolder retardant

13. AVAILABILITY

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