G. Rein, *Smoldering Combustion*, Chapter 19 in: **SFPE Handbook of Fire Protection Engineering**, 5th Edition, pp 581-603, Springer, 2016. http://link.springer.com/chapter/10.1007/978-1-4939-2565-0_19

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Smoldering Combustion

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Introduction

Smoldering combustion is the slow, low temperature, flameless burning of porous fuels and is the most persistent type of combustion phenomena. The heat is released when oxygen directly attacks the surface of a solid fuel [Ohlemiller, 1985]. It is especially common in porous fuels which form a char on heating [Drysdale 2011], like cellulosic insulation, polyurethane foam or peat. Smoldering combustion is among the leading causes of residential fires and fire deaths [Hall 2004, Ahrens 2013], and it is a source of safety concerns in industrial premises as well as in commercial and space flights. Smoldering is also the dominant combustion phenomena in megafires in natural deposits of peat and coal which are the largest and longest burning fires on Earth [Rein 2013]. These fires contribute considerably to global greenhouse gas emissions, and result in widespread destruction of ecosystems and the waste of natural resources.

Smoldering constitutes a hazard in the built environment, as emphasized in this chapter, for two main reasons. First, it typically yields a higher conversion of the fuel to toxic compounds than flaming, though this occurs more slowly. Second, smoldering provides a path to a flaming fire that could not be initiated by heat sources too weak to directly ignite a flame. A burning cigarette or charcoal embers are familiar examples of smoldering combustion. The latter is illustrated in Figure 2-9.1 (left). A less familiar case but more common fire threat is the burning of foam in upholstery as seen in Figure 2-9.1 (right). The burning behavior of foams is also related to fire safety concerns of insulating materials prone to smoldering fires which is gaining further relevance because of the current emphasis of the construction industry on energy efficiency and carbon footprint.



Figure 2-9.1: Left) Smoldering embers and ash residue (photo by J. B. Nielsen, Public domain, via Wikimedia Commons). Right) Cross-section of a polyurethane slab 125 mm in diameter smoldered in microgravity conditions (photo by NASA).

Due to its complexity and coupling of transport and thermochemical processes inside a reactive porous media, and despite its broad implications to safety and the environment, current understand of smoldering combustion is limited, and considerably less advanced than flaming combustion. The most comprehensive reviews of smouldering combustion in the literature include Ohlemiller (1985), T'ien et al (2001), Ohlemiller (2002), Babrauskas (2003), Rein (2009) and Drysdale (2011).

Smoldering and Flaming Combustion

The core of any combustion process is a global exothermic reaction that results in the release of heat, and both gaseous and solid products. Whether smoldering or flaming will be the dominant mode is dictated by which chemical species is oxidized. If the oxidation takes place in the solid phase, smouldering is dominant and if the oxidation is gas phase then flaming dominates.

In general, the combustion of a solid fuel involves countless elementary chemical reactions, but the global reactions, in its simplest form, can be approximated by two lumped chemical pathways: pyrolysis (Eq. 1) followed by oxidation (Eqs. 2a or 2b).

Pyrolysis:

$$\text{Fuel (solid)} + \text{Heat} \rightarrow \text{Pyrolyzate (gas)} + \text{Char (solid)} + \text{Ash (solid)} \quad (1)$$

Heterogeneous oxidation:

$$\text{Char (solid)} + \text{O}_2\ \text{(gas)} \rightarrow \text{Heat} + \text{CO}_2 + \text{H}_2\text{O} + \text{other gases} + \text{Ash (solid)} \quad (2a)$$

Gas-phase oxidation:

$$\text{Pyrolyzate (gas)} + \text{O}_2 \rightarrow \text{Heat} + \text{CO}_2 + \text{H}_2\text{O} + \text{other gases} \quad (2b)$$

Pyrolysis[1] results in gaseous and solid products. Of these, both the pyrolysate and the char are susceptible to subsequent oxidation[2]. Char oxidation (Eq. 2a) is a heterogeneous reaction (involving solid and gaseous species) and takes place on the char produced by the pyrolysis reaction and leads to smoldering combustion. Oxidation of the pyrolysate (Eq. 2b) is airborne and takes place in the gas phase, which is a homogenous reaction (involving only gaseous species) and leads to flaming combustion.

Char is a carbon-rich porous material, also called charcoal or black carbon, with a high surface-to-volume ratio and a rather high heat of reaction. The attack of oxygen is facilitated by metal and mineral impurities which can catalyze the oxidation process. The other important solid species is ash, a mineral-rich residue of negligible reactivity that is left after the fire.

General Characteristics of Smoldering Combustion

The characteristic temperature, spread rate and power of smoldering combustion are low compared to flaming combustion. Typical peak temperatures for smoldering are in the range from 450 to 700°C, although very energetic and dense fuels such as coal can reach peaks at around 1000°C. The effective heat of combustion taking into account the combustion efficiency is in the range from 6 to 12 kJ/g. These are much lower compared to typical values of around 1500°C and 16 to 30 kJ/g respectively for flaming combustion. The heat release rate per unit area of burning front is low and ranges from 10 to 30 kW/m^2 [Ohlemiller and Shaub 1988]. Because of these characteristics and despite the considerable variation in the chemical nature of smoldering fuels, smoldering spreads in a creeping fashion, typically around 1 mm/min, which is two orders of magnitude slower than flame spread.

As we will see in the following sections, smoldering combustion can be initiated with weaker ignition sources and is more difficult to suppress than flaming combustion. This makes smoldering the most persistent combustion mode. In the presence of a large quantity of fuel, a smoldering fire can burn for very long periods (months, years, decades) despite fire-fighting attempts, extensive rain or weather changes. Indeed, the longest-burning urban fire in modern history occurred after the collapse of the Word Trade Center towers on Sept. 11, 2001. The immense piles of debris had smoldered for three to five months in one of the most heavily populated cities of the world, resisting all suppression attempts until the slow removal of debris cleared the pile [Beard 2001]. And the oldest continuously burning fire on Earth is *The Burning*

[1] Pyrolysis in this context is the chemical decomposition of a solid material solely by heating. It does not involve oxidation reactions and it is endothermic. It involves the irreversible and simultaneous change of chemical composition and physical phase.

[2] Oxidation in this context is the reaction of a species with the oxygen in the air. It is an exothermic reaction.

Mountain in New South Wales, Australia, a large coal seam which has been smoldering for more than 6,000 years [Ellyett and Fleming, 1974].

Many materials can sustain a smoldering fire. These include synthetic fuels such as charring polymers, polyurethane foam, cellulosic insulation, particleboard and sawdust, and natural fuels like wood, peat, forest litter, and coal. In chemical terms, most smoldering fuels form a char on heating. In physical terms, smoldering fuels consist of a permeable medium formed by grains, fibers or some other porous matrix. This aggregate nature provides a large surface area per unit volume, which facilitates the heterogeneous reaction with oxygen, and permits transport of oxygen through the fuel bed [Ohlemiller 1985]. For example, synthetic foams prone to charring, like polyurethane foam (see Figure 2-9.1, right), are highly susceptible to smoldering combustion. Liquid fuels soaked in an inert porous matrix can also sustain smoldering fires, examples include lagging fires [Drysdale 2011, Section 2 Chapter 8 "**Ignition of Liquids**"] and soil remediation based on the assisted burning of liquid contaminants (Switzer et al. 2009).

For most smoldering fuels under typical conditions, the two mechanisms controlling the rate of spread are the oxygen supply and the heat transfer [Ohlemiller, 1985]. Both mechanisms are dictated by heat and mass transfer process in porous media. At the micro scale, smoldering takes place on the surface of the pores of a solid fuel, while at the macro scale, it is a bulk phenomenon affecting the fuel bed at large. The fire can penetrate deep into the bed of fuel if oxygen can be transported from a free surface (open atmosphere, crack or channel). Depending on the depth of the fire, the importance of the heat and mass transfer mechanisms vary. The rate of oxygen supply to the reaction zone enhances the spread. This oxygen supply decreases with depth inside a fuel bed. The rate of heat loss from the reaction zone hinders the spread rate and decreases with depth. Thus, depending on the fuel bed characteristics and wind conditions, there are minimum and maximum depths between which smoldering can spread, and an optimal depth at which burning is fastest. The concept of an optimal depth is not sufficiently studied yet and could vary widely for different systems in the scale from cm to m.

Each location of a burning fuel bed sees the successive arrival of four distinct thermal and chemical waves that form the structure of a smoldering front. These are the preheating, drying, pyrolysis and oxidation subfronts [Ohlemiller 1985, Torero and Fernandez-Pello 1995].

The endothermic preheating, drying and pyrolysis subfronts store or consume thermal energy and move ahead of the oxidation subfront where the heat is released. Heat from the fire is transferred to the undisturbed fuel matrix by conduction, convection and radiation, raising the temperature above ambient and preheating the fuel. The preheating subfront does not involve chemical reactions or gas emissions in any significant quantity. The drying subfront follows with evaporation becoming significant above 50°C, emitting water vapour and leaving behind dry fuel. Drying is most significant for fuels with substantial moisture contents (>10% in dry weight), so it is negligible in most residential fire scenarios but important in the natural environment (see section 'Wildland Fires'). The pyrolysis subfront (Eq. 1) follows the preheating and drying when the fuel temperature increases above a certain threshold. This threshold[3] is approximately at 200 °C for polyurethane and to 250 °C for cellulose [Rein et al. 2006]; subsequent heating above this temperature increases the pyrolysis rate and char production. The oxidation subfront consumes char and oxygen, releasing heat. It actually involves the oxidation of the fuel and the char, but char oxidation (Eq. 2a) is much more exothermic. The oxidation and pyrolysis subfronts may overlap in space. The extent of this overlap depends on the propagation conditions [Rein et al., 2007] and is discussed in the section "Smoldering Kinetics".

It is convenient to characterize one-dimensional smoldering by its direction of propagation relative to the direction of the oxygen supply. Two one-dimensional modes exist. Forward propagation occurs when the oxygen supply is moving in the same spread direction of the smolder front. Opposed propagation (also called reverse) occurs when the oxygen supply is moving opposite to the spread direction of the smolder front. These are illustrated in Figure 2-9.2. The most familiar example of forward propagation is a cigarette during a draw Figure 2-9.2 (right). Although one-dimensional spread is an idealized situation, it can occasionally be found in fires, but in general, real smoldering fires are multidimensional and cannot simply be readily classified into either one of the two one-dimensional modes.

In forward propagation, the pyrolysis subfront is located at the leading edge of the front, and the oxidation subfront at the trailing edge, where oxygen is drawn (see Figure 2-9.2, right). The oxygen supply flows first through the char where it is consumed. Then the hot, oxygen-depleted gases of combustion flow through the virgin fuel. This convective transport results in enhanced drying and preheating, but it also results in some water condensation on the virgin fuel as the combustion gases cool down.

In opposed propagation, the oxygen supply flows first through the virgin fuel, and through the preheating and evaporation subfronts before reaching the char where the oxidation front is. Then the hot, oxygen-depleted gases of combustion flow through the unreacted char and ash residues. This means that the heat is lost by convection in the opposite direction to the virgin fuel, reducing the drying and preheating which in turn results in a weaker smoldering process. Consequently, forward smolder is faster than opposed under the same fuel and oxidizer supply, and allows for

[3] The onset of pyrolysis or oxidation does not occur at one fixed temperature but it is known to be a function of the heating rate and start over a range of temperatures; higher onset temperatures are observed for higher heating rates. See [Rein et al. 2006] and the section "Smoldering Kinetics" for evidence of this.

more complete combustion of the fuel [Ohlemiller and Lucca 1983]. In opposed propagation, the pyrolysis and oxidation subfronts largely overlap on top of each other from leading to trailing edges [Rein et al., 2007].

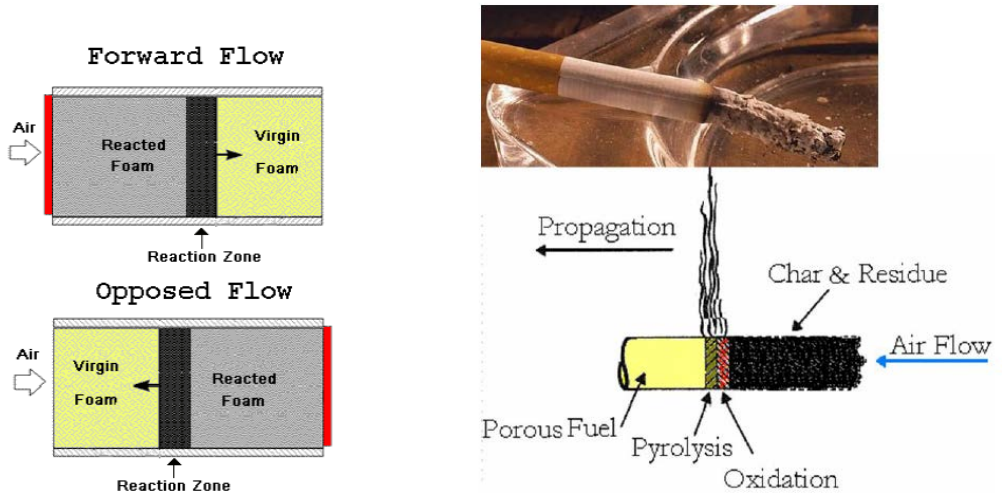


Figure 2-9.2. Left) Forward and opposed configurations of one-dimensional smoldering propagation inside a slab of porous fuel. Right) Structure of a one-dimensional front in forward smoldering and approximate correspondence with a burning cigarette. By G. Rein, CC BY license.

Ignition

The process of smoldering ignition requires the supply of heat, and is governed by heat transfer and fuel kinetics, with the oxygen supply rate playing a secondary role. Above a critical threshold of heat supply, the temperature increase initiates endothermic pyrolysis, which is followed by the onset of oxidation. When the heat released by oxidation is high enough to balance the heat required for the endothermic processes (heat losses, pyrolysis, drying and preheating of fuel), propagation occurs and the reaction might become self-sustaining (only then oxygen supply rate will play an important role). This section discusses four types of ignition sources: radiant, conductive, by embers and self-heating. For all four, it is proven that the critical energy condition needed for smoldering is significantly lesser than that for flaming. The results discussed here are on individual fuel samples. But note that a pertinent smoldering scenario, that of upholstery and bedding fires, is a composite problem with the ignition propensity of both the fabric and the substrate contributing to the overall behavior of the ensemble [Ortiz-Molina et al. 1979].

Radiant Ignition

The effects of exposing polyurethane foam to an external radiant heat flux of increasing magnitude is illustrated in Figure 2-9.3. The heat flux needed to initiate smoldering is significantly lower than that for flaming (see Table 2.9.1). For instance, the critical radiation heat flux for smolder ignition of polyurethane foam is 7 kW/m^2, while for spontaneous flaming is 30 kW/m^2 [Hadden et al. 2012]. For piloted flaming ignition, the critical level is 13 kW/m^2 (see Section 3 Chapter 4, "**Generation of Heat and Chemical Compounds in Fires**").

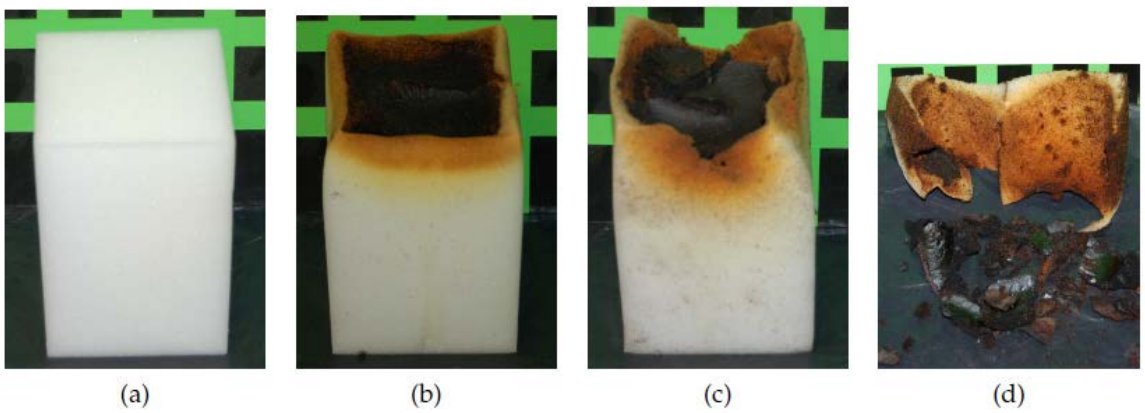


Figure 2-9.3: Images of polyurethane foam samples exposed to radiant heat fluxes levels (from left to right): (a) virgin foam (not exposed to heat flux), (b) charred foam in which a smoldering front did not propagate, (c) sample in which smoldering propagated, and (d) sample which underwent flaming ignition. By R. Hadden, CC BY license.

Table 2-9.1: Critical heat fluxes found experimentally for the ignition of smoldering and spontaneous flaming combustion in samples of different sizes. Data from Hadden et al. [2012].

Sample size [mm]	Critical heat flux for smouldering ignition [$kW \cdot m^{-2}$]	Critical heat flux for flaming ignition [$kW \cdot m^{-2}$]
50	18–19	32–45
100	8–9	32–37
140	7–8	30–31

It has been shown that the onset of smoldering seems to involve a range of threshold temperatures. A threshold temperature is not valid sole criterion for ignition of smoldering but it is part of a multi-criteria signature [Anderson et al. 2000]. Several experimental studies have found that the minimum temperature measured during ignition of polyurethane foam is in range from 300 to 450 ˚C [Hadden et al. 2012, Anderson et al. 2000, Anthenien and Fernandez-Pello 1998]. This is much lower than the surface temperature of 600 °C required for spontaneous flaming ignition of the same material [Hadden et al. 2012]. Figure 2-9.4 (left) shows the experimental data on the peak temperature reached inside a slab of polyurethane foam for the cases of no ignition, smoldering or flaming ignitions. The same experiments (see Figure 2-9.4 (right)) also show that the time to smoldering ignition by radiation depends on the heat flux level and ranges from 1 to 20 min for a heat flux of 45 to 7 kW/m^2 respectively. Spontaneous flaming ignition at high heat fluxes was fast, less than 1 min. The dependence of the time to ignition with radiant heat flux shown in Figure 2-9.4 (right) resembles a $q^{-1/2}$ law, where q is the incident heat flux. This suggests that smoldering ignition can be explained in terms of heat transfer, in the same way that a $q^{-1/2}$ law explains the flaming ignition of a thermally thick fuel (see section 2, Chapter 11, "**Flaming Ignition of Solid Fuels**"). This law originates from the time it takes for heat conduction to result in a critical temperature at a key location. For flaming, the key location is the free surface of the fuel, but for smoldering the key location is inside the fuel bed, at a sufficient depth such that an insulating layer of char is formed over the oxidation front [Anthenien and Fernandez-Pello 1998]. The concept of a critical depth for ignition is not sufficiently studied yet but could be expected to vary for different materials and external conditions in the scale from 1 cm to 10 cm roughly.

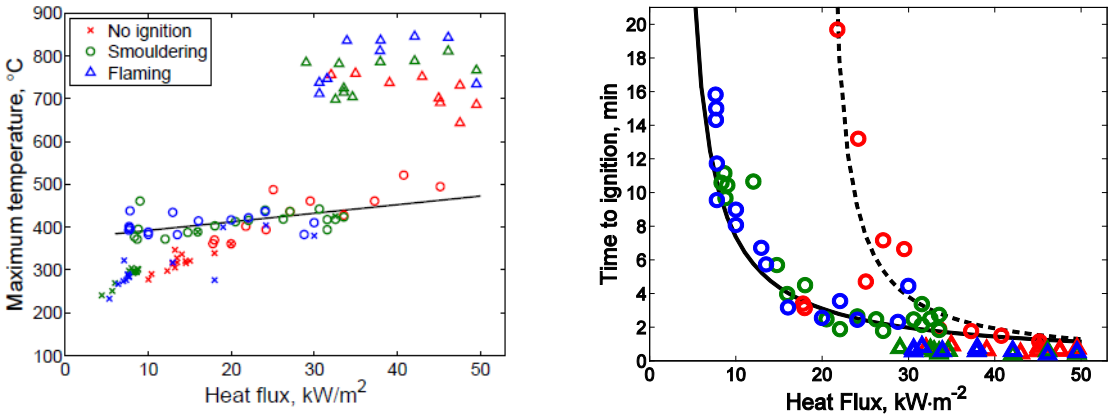


Figure 2-9.4: Radiant ignition of smoldering and flaming in polyurethane samples of different sizes in still air. Left) Maximum temperatures observed. Right) Time to ignition. Red, green and blue represent 50, 100 and 140 mm side square samples respectively. Data from Hadden et al. [2012].

Conductive Ignition

The heat source that can start a smoldering fire with the lowest heat flux is the conductive type. This scenario occurs when a large and hot object is in direct contact with the fuel bed. Heat is transferred by conduction, but in porous fuels, natural and forced convection also play a role. Anthenien and Fernandez-Pello [1998] studied the initiation of smoldering using an electric heater in contact with a sample of polyurethane foam under forced airflow. Ignition was reported at heat fluxes as low as 3 kW/m^2 and the relationship between time to ignition and heat flux was also shown to follow a $q^{-1/2}$ law. Ignition was found to be weakly dependent on the airflow.

Conductive ignition has also been studied on a bed of anthracitic coal particles [Hadden and Rein 2011]. A series of particle beds of uniform diameter ranging from 7 to 45 mm was investigated inside a cubic box (side of 100 mm) with one side open to the atmosphere and multiple perforations on the other sides. The heat source was an electric wire that delivered 80 W. Figure 2-9.5 shows that the relationship of the time to ignition with particle diameter has a 'U' shape. It was not possible to ignite particles smaller than 7 mm. For very small particle sizes, the bed exhibits poor internal convection which limits the airflow and a long ignition time is required. But as the particle sizes increase, the porosity and the flow permeability of the fuel bed increase and a minimum time to ignition of 130 min (average) is required for a particle diameter of 25 mm. As particles become larger, the inter-particle conduction rate decreases resulting in a longer time to ignition.

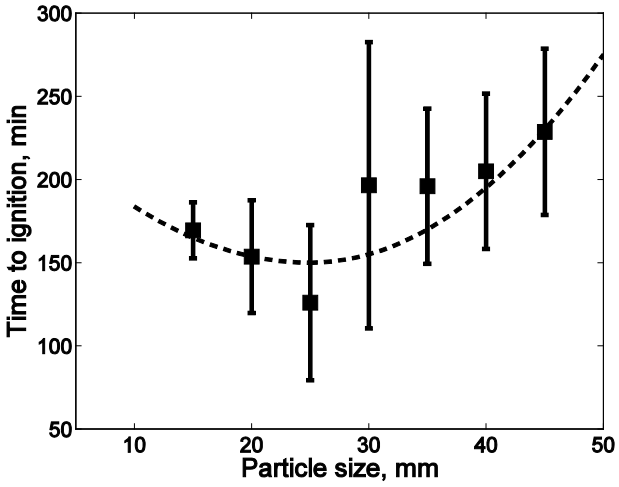


Figure 2-9.5: Experimentally observed relationship between time to ignition and particle size in a bed of anthracite coal. Data from Hadden and Rein [2011].

Ignition by embers

In close connection with conductive sources, a fuel bed can also be ignited by hot embers. This is related to the phenomenon of spotting in wildland fires, when lofted embers land downwind, leading to secondary fires in the wildland or in urban areas remote from the originating flame front [Manzello et al. 2008]. Ignition by embers is a transient phenomenon involving the loss of heat from the ember to the fuel by conduction and convection. Embers can be classified by material (metal or biomass) and thermal state (hot, smoldering or flaming).

[Manzello et al. 2008] compared the ember ignition of three fuel types and found that a bed of shredded paper was much more prone to smoldering than pine needles or mulch. The experimental study of [Hadden et al. 2011] found a relationship between ember size and the critical initial temperature required for ignition of a bed of cellulose powder. They used steel spheres with diameters in the range 0.8 to 19 mm at initial temperatures between 500 and 1300 °C. Smaller embers require higher temperatures to initiate combustion. Their data shows two distinct boundaries as the ember temperature increases, one separating no-ignition from smoldering ignition, and the other from smoldering to flaming ignitions. The minimum ember temperature at which smoldering could be initiated was 550 °C, and the minimum temperature for flaming ignition occurred at 650 °C. Krause and Schmidt 2000 also observed a decrease of the critical temperature with ember size for a series of organic powder samples (cork, beech and cocoa), and reported a minimum temperatures of 400°C for smoldering ignition.

Self-heating ignition

Self-heating of a solid fuel can initiate a spontaneous smoldering reaction deep within a pile of material without any external source, even at ambient temperatures. Self-heating refers to the tendency of certain porous solid fuels to undergo spontaneous exothermic reactions in oxidative atmospheres at low temperatures (Bowes 1984, Drysdale 2011, Section 2 Chapter 10, "**Spontaneous Combustion and Self-Heating**"). It is a well-known problem in the store of large amounts of carbon-rich materials (e.g. waste, coal heaps, organic powders) and the process industries. The process is as follows: initially, the pile of the material releases small amounts of heat by very slow oxidation at ambient temperature. The center of the pile is more insulated, so the heat accumulates there in the long term and results in a sustained increase of the local temperature, which in turn accelerates the oxidation rate. Large pile sizes and poor ventilation conditions facilitate the buildup of heat. The process self-accelerates for some time (hours, days or weeks) and above a certain threshold temperature it leads to a thermal runaway. This results in a smoldering fire that can spread from the inside to the outside, and may undergo transition to flaming at a later stage when it reaches the free surface (discussed in section "Transition to Flaming").

Size effects

There is a minimum size below which a fuel sample will not undergo ignition. This is determined by the balance between the rates of heat generation and heat loss from the system. The rate of heat loss scales with the surface area, and the rate of heat generation scales with the sample volume. Consequently, as the size of a sample decreases, the surface -to-volume ratio[4] of the smoldering front increases. Below a certain size, heat losses overwhelm heat generation and ignition will not occur.

Palmer [1957] found experimentally that the minimum thickness for smoldering of horizontal layers of sawdust was around 10 mm. Ohlemiller and Rogers [1980] found the minimum thickness for cellulosic insulation to be 35 mm. A more recent experimental investigation of the effect of sample size [Hadden et al 2012] is reported in Table 2-9.1 and Figure2-9.4. Both the critical heat fluxes for smoldering and flaming ignition increase with decreasing sample size, with smoldering ignition being significantly more sensitive to the sample size than flaming. Krause and Schmidt [2000] studied the ignition of organic dust samples by embers, and found that the larger the samples, the lower the critical ember temperature. The fact that large samples are easier to ignite than small samples has implications for testing standards and the translation of results from small-scale testing to real scale.

The process of ignition is related to self-sustained propagation (as discussed in the section "Smoldering Spread") which allows an approximate analytical treatment. The critical size L_c for self-sustained propagation in a prismatic sample of square cross-section can be estimated by Eq. (3) provided by Rein [2009] based on the energy balance by Torero and Fernandez-Pello [1995 and 1996] and Bar-Ilan et al. [2004a, 2004b].

$$L_c = \frac{4\delta U(T_s - T_0)}{Q_s \dot{m}''_{O_2}} \qquad (3)$$

where δ is the smolder-front thickness perpendicular to the propagation direction, T_s is the peak temperature, and Q_s is the heat of smoldering, which all depend on the fuel. The overall heat loss coefficient U, the ambient temperature T_0 and the supply of oxidizer $\dot{m}''_{O_2}$ depend on the geometry and external conditions. For polyurethane foam, Eq. (3) says the critical

[4] The surface-to-volume ratio of a sample is inversely proportional to its characteristic length (e.g., thickness for a very wide layer, diameter for a cylinder, side length for a prism or diameter for a sphere).

size is around 160 mm [Hadden et al. 2012]. If a sample is below the critical size L_c, sustained smoldering will not be achieved. Smoldering will only spread if the heat losses are reduced or the rate of heat generation is increased, or both. The former would involve insulating the sides of the reaction front or supplying additional heat from an external source, and the latter would involve increasing the supply of oxidizer.

Smoldering Spread

The spread of smoldering is controlled by the oxygen supply and heat transfer [Ohlemiller 1985]. Conditions sufficient to yield smolder initiation, especially near an external heat source, might not be sufficient for self-sustained spread away from the ignition region. If the external heat supply continues, assisted propagation is possible. Otherwise, once the external heat supply ceases, smoldering reaction will be self-sustained or lead to extinction.

Experimental and modeling work has demonstrated that the smolder spread rate is linearly dependent on the total air supply rate to the smoldering front [Ohlemiller 1985, Bar-Ilan et al. 2004a and 2004b]. Some of these results are presented in Figure 2-9.6. Torero and Fernandez-Pello [1995] reported than this linear increase breaks down for opposed propagation at high airflows and stars decreasing (at ~3 mm/s for polyurethane foam slabs of 150 mm square cross section). Air is transported to the reaction front by convection and diffusion. Convection can be natural (buoyant) or forced. In the absence of forced flow, buoyancy tends to dominate over diffusion in regions of lesser flow resistance, for example near the free surface or in a bed of large particles. The diffusion flux is dominant when deep layers of fine dust are ignited from below [Palmer 1957]. Forced convection in smoldering fires usually takes the form of an air current flowing towards or over the free surface of the fuel bed. Forced convection directly flowing through the bed of the fuel is often used in laboratory studies (eg, see Figure 2-9.6). It provides controllable conditions to investigate the phenomena in-depth. These studies have found a critical air supply rate required for self-sustaining propagation (around 0.6 g/m^{2}s of oxygen flow for opposed mode in a 120 mm diameter slab of polyurethane foam [Bar-Ilan et al. 2004b]). This critical supply rate is known to be a function of the heat losses. For example, microgravity experiments on the same polyurethane samples [Bar-Ilan et al. 2004b] have shown that the removal of lateral heat losses by natural convection allows self-sustained propagation at significantly lower oxygen supplies (0.3 g/m^{2}s).

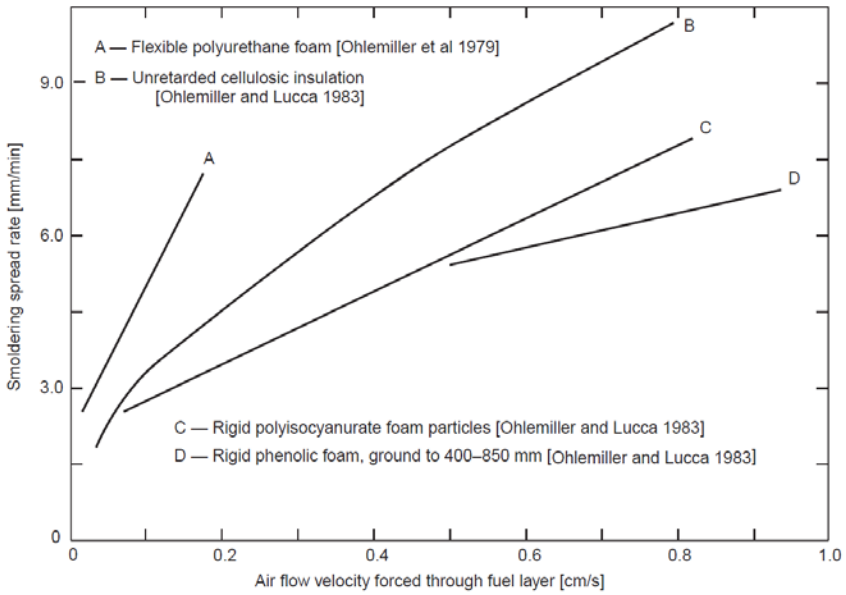


Figure 2-9.6. ***Spread rate of smoldering assisted by airflow forced through the bed in opposed mode for a variety of materials. After*** **Ohlemiller (2002).**

When a bed of fuel is ignited locally at a small region, the spread will be multidimensional and include both horizontal and vertical fronts. Each front will be dominated by forward or opposed propagation (or a combination) depending on the roles of buoyancy, wind and diffusion. Two important configurations are presented in Figure 2-9.7 where the main spread is either downwards or upwards though the fuel bed.

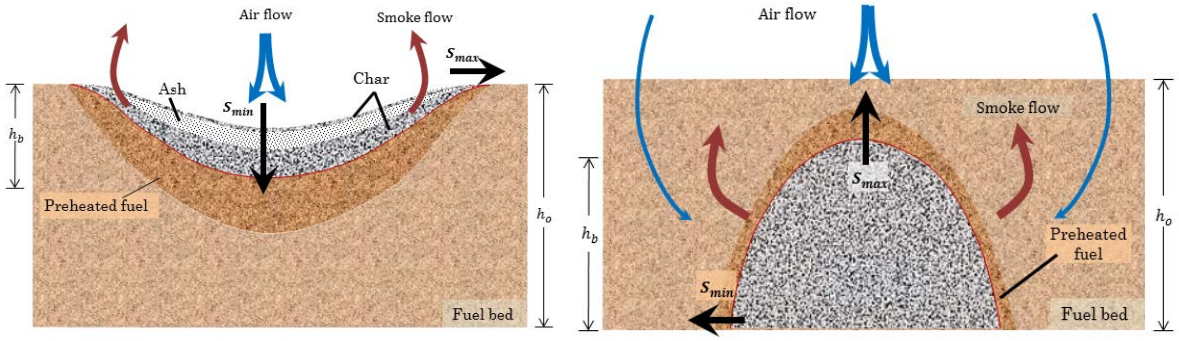


Figure 2-9.7. Diagrams of downward (left) and upward (right) propagation in a porous fuel bed. By X Huang, CC BY license.

If initiation occurs on the top surface of the fuel bed, the fire will spread laterally and downward. It leads to a surface void or hole in the general shape of an ellipsoid or pan. Downward spread is dominated by forward smoldering (Figure 2-9.7, left), and creates a growing layer of ash that only decreases if wind carries the particles away. The horizontal lateral spread is enhanced by a direct supply of atmospheric oxygen, which is readily available, and the rate is significantly greater than downward spread where oxygen transfer is limited by the a thicker porous layer of ash and char. Combustion of the uppermost layer is typically quenched due to large convective and radiant heat losses; this leaves a very thin layer of charred material on top while smoldering continues below. Horizontal spread accelerates in response to an increased wind. [Palmer 1957] examined this in thin horizontal layers (3 to 57 mm) of various cellulosic particles (cork, pine, beech, grass). The results in Figure 2-9.8 show that the horizontal airflow has a greater effect in forward propagation, but that airflow in opposed propagation and the particle size have a weaker effect. In the absence of any forced flow over the fuel layer, the flow induced by the buoyant plume rising assures a supply of oxygen to the horizontal spread at the topmost fuel layer. Oxygen then penetrates into the layer mostly by diffusion [Ohlemiller 1990].

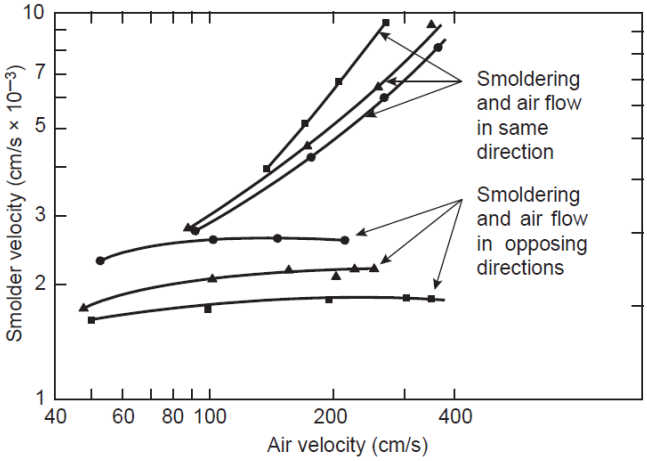


Figure 2-9.8. ***Smoldering spread rate through horizontal layers of sawdust as a function of the horizontal airflow over the topmost layer. Circles: 120 mm particle size; triangles: 190 μm particle size; squares: 480 mm particle size. Data from Palmer [1957], after*** **Ohlemiller (2002).**

If initiation occurs deep within a layer of fuel and the nearest free surface is on the top, the fire will slowly spread upwards dominated by opposed smoldering (Figure 2-9.7, right). The thick layer of virgin fuel above the reaction front hinders the oxygen supply, but also reduces the rate of heat losses. Ultimately, the spread is faster towards the closest free surface, and it is aided in the upward direction by buoyancy, thus leading to fronts in the shape of an elongated bell. The reaction front usually moves through without fully consuming the char left behind. The upward case was studied in Palmer's work [Palmer 1957], which consists of a collection of observations from simple experiments involving the initiation of a smoldering front at the base of sawdust heaps (cork, elm and mixed wood). Some of the results are shown in Figure 2-9.9. Note the scales reported in this data; the time to smolder up through a layer 1 m deep is about 2 weeks, and

the process gave little hint of its presence until it was close to the surface of the fuel heap (smoke gets partially trapped inside the porous bed). The slope of the curve indicates that the time for smolder to penetrate a fuel layer in this mode is proportional to the square of the layer depth. Palmer showed that such dependence suggests the smolder front spread is proportional to the diffusion rate of oxygen from the free surface, through the unburned fuel, to the reaction front.

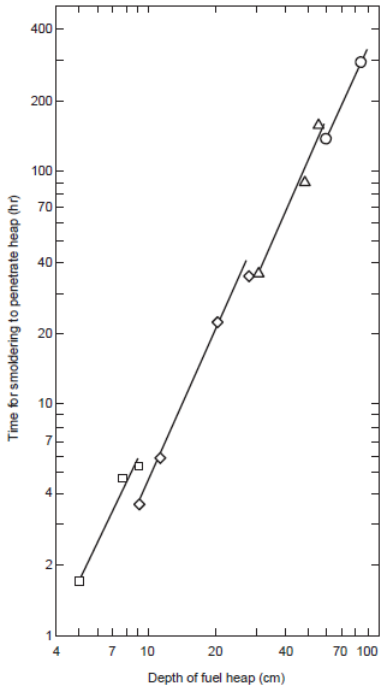


***Figure 2-9.9. Smoldering spread by air diffusion. Ignition at base and spread upwards in heaps of wood sawdust. Squares: layer 0.025 m deep in 0.3 m square box; diamonds: layer 0.052 m deep in 0.3 m square box; triangles: layer 0.052 m deep in 0.6 m square box; circles: layer 0.052 m deep in 0.9 m square box. Data from [Palmer 1957], after* Ohlemiller (2002).**

Data from other experiments on a variety of fuels and air supply conditions are summarized in Table 2-9.2.

Table 2-9.2. *Experimental data on smoldering in various fuels and configurations. After Ohlemiller (2002).*

Fuel	Configuration	Air Supply	Spread Rate	Peak Temperature	Reference	Comments
Pressed fiber insulation board, 230 to 290 kg/m^3	13 mm thick horizontal strip, width large compared to thickness	Natural convection	0.8 to 1.3 mm/min	NA	Palmer 1957	Smolder velocity increased ≈50% for strips with width ≈ thickness
Pressed fiber insulation board, 230 to 290 kg/m^3	13 × 13 mm strip at varied vertical inclinations	Natural convection	1.6 to 2.8· mm/min	NA	Palmer 1957	Smolder velocity highest for upward spread; lowest for horizontal spread
Fiber insulation board	13 × 50 mm strip forward smolder	Airflow over 20–1500 cm/s	2.1 mm/min (20 cm/s arflow) 7.8 mm/min (1400 cm/s airflow)	790°C (900 cm/s airlfow)	Palmer 1957	Some samples extinguished due to cooling at airflows >1450 cm/s
Fiber insulation board	13 × 50 mm strip opposed smolder	Airflow over strip, 80–900 cm/s	1.7 to 2.1 mm/min	NA	Palmer 1957	Extinguishment >900 cm/s

Fiber insulation board (pine or aspen)	13 mm thick sheet, horizontal, forward smolder	Airflow over sheet, 10–18 cm/s	1 mm/min	NA	Brenden and Schaffer, 1980	
Cardboard	Vertical rolled cardboard cylinder, downward propagation, diameter 1.9–3.8 mm	Natural convection	3 to 5 mm/min	NA	Kinbara and Endo, 1967	Small dia. ≈2× faster than large dia.; ambient temp. effect measured
Shredded tobacco	8 mm diameter cigarette, horizontal, in open air	Natural convection	1.8 to 3 mm/min	820°C	Egerton et al. 1963	
Cotton upholstery fabric	Double fabric layer, 2 mm thick, horizontal, forward smolder	Airflow over fabric, 10 cm/s	~6 mm/min	770°C	Donaldson and Yeadon 1963	Smolder behavior dependent on alkali metal content
Cellulosic upholstery fabric on substrates	Various weight fabrics horizontal on fiberglass, PU foam, cotton.	Natural convection	1.8 to 45· mm/min (depends on substrate)	Reported values suspicious -ly low	Donaldson and Yeadon 1963, Stiefel et al 1990	Smolder fastest on inert fiberglass substrate
Cotton batting, densities 5 to 100 kg/m^3	15 cm cube, hold together by metal mesh and open to the air on all sides.	Natural convection	2 to 4 mm/min (decrease as density increases)	690°C	Hagen et al. 2011	Lower densities or repeated heating of sample result in higher ignition temperature.
Wood char, densities 290 to 435 kg/m^3	22 cm tall packed bed of particles, diameter 1 to 3 mm.	Natural convection	Upward ~0.4 mm/min. Downward ~0.05 mm/min	Upward 530°C. Downward 800°C.	He and Behrendt ,2011	Downward peak temperature decreases as the height of ash layer increases.
Cork, beech and cocoa powders	Mesh wire baskets with volumes of 0.8 to 200 litre	Natural convection	0.1 to 1.5 mm/min and decreasing relationship with basket volume	260 to 375 °C and decreasin g relationshi p with basket volume	Krause and Schmidt, 2000	Ignition sources tested include hot body, glowing nest and electric coil.

Smoldering Kinetics

The spread rate of self-sustained smoldering is typically controlled by oxygen transport and heat transfer. Yet, heterogeneous chemical kinetics governs the front structure and is ultimately responsible for determining the conditions under which a material ignites.

Smoldering combustion of a solid fuel involves multiple pathways to chemical reactions, and these pathways are not yet fully understood. In spite of the complex kinetic behavior, experimental evidence suggests that mechanisms consisting of only a few global reactions capture the most important characteristics of the decomposition process and allow an approximate analysis. Smoldering chemistry in its simplest form can be understood as a two-step process: pyrolysis of fuel (Eq. 1) produces the char that is then oxidized in situ (Eq. 2a). In this section we explore more comprehensive kinetics.

To begin with, the simple two-step scheme proposed in Eqs (1) and (2a) can be revised to include the direct oxidation of the fuel. Char oxidation (Eq. 2a) is the principal heat source in most self-sustained smolder propagation processes; the potential for smoldering combustion thus exists with any material that forms a significant amount of char during thermal decomposition. The fuel is oxidized as well (Eq. 4) but the most exothermic reaction is that of char, and therefore the simplest overall mechanisms does not include fuel oxidation. Fuel oxidation is also related to self-heating when it takes place at low temperature close to ambient (see Section 2, Chapter 10, "**Spontaneous Combustion and Self-Heating**").

Direct heterogeneous oxidation of the fuel:

$$\text{Fuel (solid)} + O_2 \rightarrow \text{Heat} + CO_2 + H_2O + \text{other gases} + \text{Char (solid)} + \text{Ash (solid)} \quad (4)$$

The materials for which smoldering kinetics are best known are polyurethane foam and cellulose. [Kashiwagi and Nambu 1992] provided a quantified 3-step mechanism for cellulose, including cellulose pyrolysis, cellulose oxidation and char oxidation and accounting for three solid species; cellulose, char and ash. In flexible polyurethane foam, the presence of oxygen during degradation plays another key role, because without oxygen, many foams do not form char [Rogers and Ohlemiller, 1980]. Rein et al. [2006] provided a 5-step mechanism for polyurethane consisting of two foam pyrolysis, two foam oxidations and one char oxidation reaction, and accounting for four solid species (foam, β-foam, char and residue). This mechanism was developed and the kinetic constants found from thermogravimetric experiments, as shown in Figure 2.9.10. This multi-step mechanism allows explaining the different contributions of the pyrolysis and oxidation reaction to the degradation of the foam in the presence of air, as seen in Figure 2.9.11. The separation of pyrolysis from oxidation is essential in any smouldering kinetics scheme.

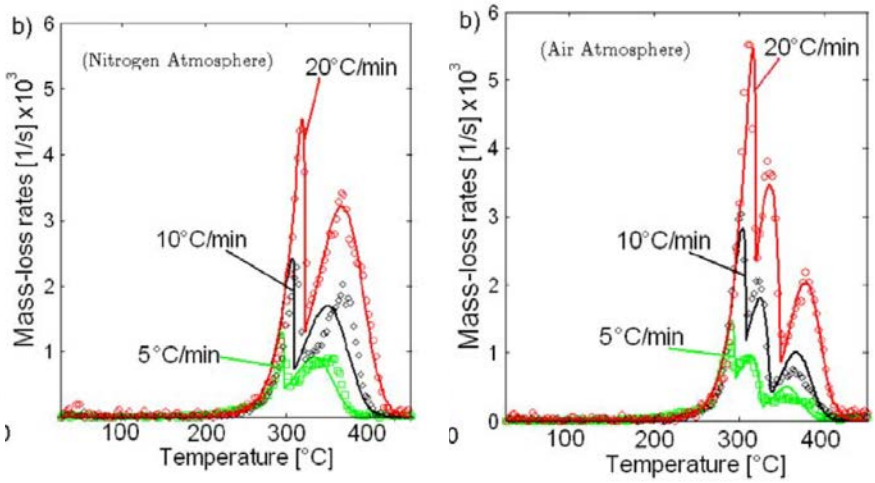


Figure 2-9.10. **Thermogravimetric *m*ass loss rate of Polyurethane foam in; a) nitrogen atmosphere, and b) air atmosphere, as a function of temperature for three heating rates. Symbols are data from experiments [Chao and Wang 2001], and lines are data from numerical simulations [Rein et al. 2006].**

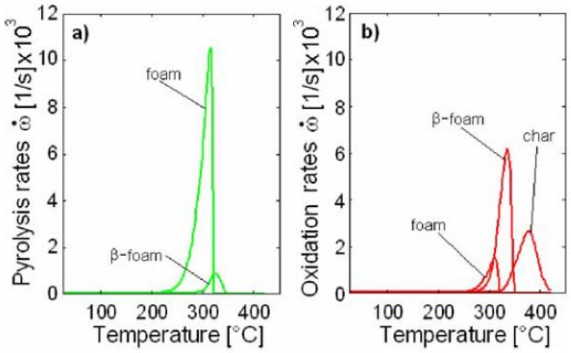


Figure 2-9.11. Numerical results for the different reactions rates (pyrolysis on the left, oxidation on the right) in polyurethane foam decomposition in air atmosphere. This simulates the experimental* thermogravimetric *data of Figure 2-9.10 (right) and allows explaining the origin of the three mass-loss peaks. Data from Rein et al.[2006].

It was the work of Rein et al. 2007 that proved that the same kinetic mechanism was able to explain both forward and opposed smoldering. In forward smoldering propagation (Figure 2.9.12, right), the oxidation and the pyrolysis reactions form two distinct propagating fronts. The pyrolysis front arrives first to the virgin foam and then followed by the oxidation

front. In opposed smoldering (Figure 2.9.12, right), the oxidation and the pyrolysis reactions overlap to form a single propagating front. Previously to the work of Rein et al. [2007], smoldering chemistry had been described as a function of the propagation mode: forward smoldering with a 2-step chemistry, whereas opposed smoldering with a 1-step.

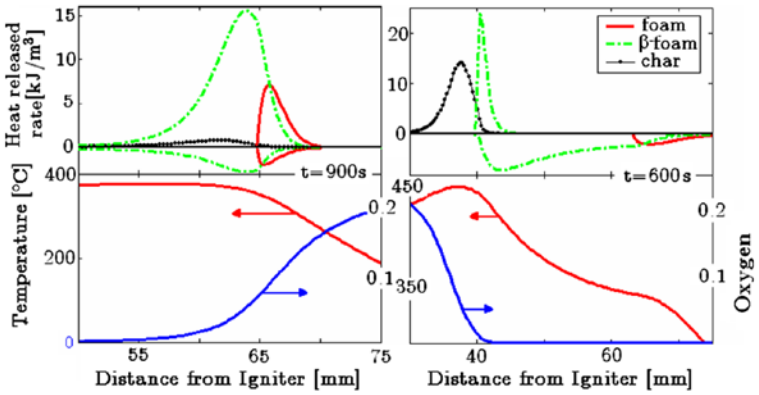


Figure 2-9.12. Numerical results for the front structure during self-propagation; (left) opposed smoldering; and (right) forward smoldering. Top figures show the heat-released rate of each reaction (positive for oxidation, negative for pyrolysis). Bottom figures show the temperature and oxygen profiles. Data from [Rein et al 2007].

Smoldering kinetics is a very immature field of solid phase chemistry due to is complexity and secondary role in fire spread. It has been the objective of very few studies to date. Despite the recent advances reviewed in this section, the topic remains mostly undeveloped.

Suppression

A smoldering fire can be extraordinarily difficult to suppress. Experiments on heaps of coal show that smoldering requires large amounts of water. For example, the amount of water required to suppress smoldering coal was measured to be in the range from 1 to 2 liters of water per kg of burning fuel. And smoldering requires low oxygen concentration to be smothered, around 10% O_2, compared to 16% O_2 for flaming [Hadden et al. 2013, Belcher et al. 2010]. Oxygen removal is insufficient unless it is continued until the whole fuel bed is cooled to a point where oxygen readmission will not cause re-ignition. Because cooling of a fuel bed is a very slow process in general (long thermal response time), this means that the holding time for smothering are much longer for smoldering than for flaming[5] (months vs. h) [Hadden and Rein 2011].

One practical problem in suppressing a large fuel bed is the tendency of the extinguishing fluid agents to follow higher permeability channels and thereby miss significant in-depth burning zones. Channeling arises when a substantial fraction of the water takes the same flow path through the bed, resulting in limited contact surface area between the agent and the burning fuel. This, coupled with the lower residence times in regions of high permeability because of the higher flow velocities, requires large quantities of water for suppression. [Hadden and Rein 2011] investigated three water suppression methods (pipe, shower and spray) on a small-scale coal bed. They showed that the most efficient method with respect to total water required is the shower. However, using a spray results in less water runoff and thus offers a higher efficiency. The injection pipe is significantly less efficient, requiring three times more water than a spray of which more than 80% is lost as run-off. Tuomisaari et al. [1998] tested a number of extinguishing agents (liquids: water, water with additives; gases: N_2, CO_2, Ar and Halon) in series of tests on a small bed of smoldering wood chips and gaseous CO_2, fed from the bottom, was found to be the most effective.

Gas Emissions

Gas emissions from smoldering fires differ significantly to those from flaming fires. First, the emissions rate per unit area is much lower but also the chemistry is different. Smoldering is characteristically an incomplete combustion, releasing species and quantities that substantially depart from that in stoichiometric and complete combustion. For

[5] Avoidance of flaming re-ignition of a non-porous fuel requires cooling of the surface layer only.

example, the CO/CO_2 ratio which can be thought of an index of the incompleteness of the combustion is ~0.4 in smoldering but ~0.1 in flaming combustion [Rein et al., 2009]. The presence of pyrolysate, which does not burn in the absence of a flame, significantly contributes to the presence of a complex gaseous mixture including volatile organic compounds (VOC), polyaromatic hydrocarbons (PAH), other hydrocarbons and particulate matter (PM). While the yield of toxic species is larger in smoldering fires than in flaming fires [Stec and Hull 2011], the production rate, which is proportional to the spread rate, is much lower. This means that inside an enclosure, a smoldering fire of long duration (in the range from 1 or 3 h for a single bedroom size compartment [Quintiere et al. 1982]) can lead to a lethal dose of toxicity, especially CO. But there are not as yet sufficient data on the toxicity of smoldering materials to definitively resolve the issue of life hazards.

Limited information is available on the aerosol emitted by a smolder source. The residual matrix left behind the smolder front and the original porous bed both are effective filters for aerosol. This finding helps explain the observation by Palmer [1957] that upward smoldering in a thick layer of fuel was not detectable until it neared the surface (like in Figure 2.9-7 right). The mean particle size of the aerosol in smoldering cellulose was measured [Mulholland and T. Ohlemiller 1982] to be in the range from 2 to 3 μm; this is about 50 to 200 times larger than the sooty particulates produced by flaming combustion. Only limited information is available on gas emissions from smoldering. Some more information is presented in Section 2, chapter 6 "**Toxicity Assessment of Combustion Products**" and in [Stec and Hull 2011].

The low heat release rate of smoldering fires means that the buoyant plume is weak. This means smoke is slow to reach the ceiling, or it may never reach it, and often, it is the building mechanical ventilation that controls the smoke movement [Hotta et al. 1997] (see also Section 2, Chapter 1, "**Fire Plumes, Flame Height, and Air Entrainment"**). In the natural environment, the low buoyant strength of large smoldering fires leads to haze episodes because the plume accumulates near the ground and can slowly move into populated areas, choking towns and cities for weeks [Rein 2013]. The composition of haze measured by Bertschi et al. [2003] in the tropical savanna shows it contains 130% more CO and 670% more hydrocarbons in mass basis, but 15% less CO_2 and no NO_x when compared to the flaming fires.

Smoldering Wildland fires

In the natural environment, smoldering fires burn two types of biomass: thick fuels, like tree branches or logs, and organic soil, like the duff layer or peat. These are characterized by having a significantly greater thermal time compared to fine fuels like foliage. Thick fuels favor the slow burning of smoldering combustion. The persistent smoldering of thick fuels is typically observed for a few days after a flaming wildfire has passed, and it is often referred to as *residual smoldering combustion*. This can make smoldering be responsible for up to 50% or more of the total burned biomass during wildfires [Bertschi et al., 2003, Rabelo et al. 2004, Davies et al. 2013].

But it is the soil rich in organic matter, in particularly that in peatlands, which is most affected ecosystem by smoldering fires, both in frequency and size. Peat soils are made by the natural accumulation of partially decayed biomass and are the largest reserves of terrestrial organic carbon. Because of this vast accumulation of fuel, once ignited, smoldering peat fires burn for very long periods of time (e.g. months, years) despite extensive rains, weather changes or fire-fighting attempts. These are the largest fires on Earth and large contributors of greenhouse gases. Peat fires occur with some frequency worldwide in tropical, temperate and boreal regions (e.g., in Indonesia, Australia, Alaska, Canada, Florida, British Isles, Siberia). Droughts, drainage and changes in land use are thought to be main causes leading to the high flammability conditions of dry peatlands. Possible ignition events can be natural (e.g. lightning, self-heating, volcanic eruption) or anthropogenic (land management, accidental ignition, arson).

The most studied peat megafire took place in Indonesia in 1997 and led to an extreme haze event. The smoke covered large parts of South-East Asia, even reaching Australia and China, and induced a surge of respiratory emergencies in the population and disruption of shipping and aviation routes for weeks. It was estimated that these fires released between 0.81 and 2.57 Gton of carbon gases [Page et al 2002]. This is equivalent to 13-40% of global man-made emissions of the year 1997. The 1997 megafire was not an isolated case in the region. Analysis of 1960-2006 data shows that smoldering haze episodes have drifted to South East Asian countries once every three years on average [Field et al. 2009]. Rough figures at the global scale estimate that the average greenhouse gas emissions from peat fire is equivalent to >15% of man-made emissions. Moreover, because peat is ancient carbon, and smoldering is enhanced under warmer and drier climates, it creates a positive feedback mechanism in the climate system, a self-accelerating global process [Rein, 2013].

Because the water content of wildland fuels like peat can vary naturally over a wide range of values (from dry to flooded in water), and because water represents a significant energy sink, moisture content is the single most important property governing the ignition and spread of smoldering wildfires. The critical moisture content for ignition (related to the moisture of extinction) of boreal peat has been measured in the range 110% to 120% in dry basis[6] [Frandsen 1997,

[6] The water content in dry basis is the mass of water divided by the mass of a dried sample expressed as a %.

Rein et al 2007]. Any peat drier than this is susceptible to smoldering. The prominent role of moisture is such that natural or anthropogenic-induced droughts are the leading cause of smoldering megafires.

The second most important property is the mineral content[7]. As experimentally found by Frandsen [1997], there is a decreasing linear relationship between the mineral content and the critical moisture content: higher mineral loads mean soil can only ignite at lower moistures. This is because the inert content is a heat sink to the fire. The results are shown in Figure 2-9.13. This rule can be applied to most organic soils or fuel beds to determine if they are susceptible to smoldering. Any soil which composition is more than 80% mineral, cannot sustain a smoldering fire [Frandsen 1997]. After moisture and mineral contents, other important properties are bulk density, porosity, flow permeability and organic composition.

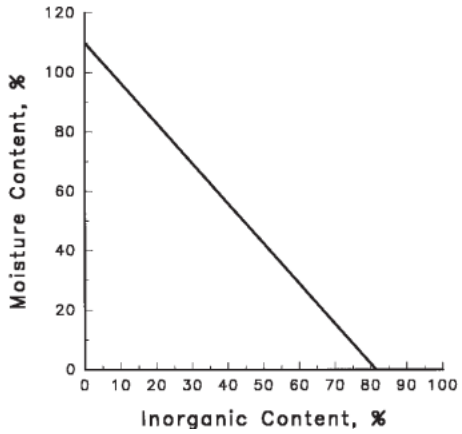


Figure 2-9.13. The line separates the ignition (bottom) from the no-ignition (top) limits for a mixture of peat, moisture and mineral content to given a fixed bulk density of 110 kg/m3. Data from Frandsen (1997).

Because the fuel layers found in the natural environment (soil depths from 0.5 to 30 m) can be much thicker than those in the built environment (~0.1 m), smoldering wildfires can be classified in shallow or deep fronts. Each has significantly different dynamics because of the different role played by the controlling mechanisms of oxygen supply and heat losses.

Organic material located close to the surface of the soil burns in shallow fires (roughly <1 m under the surface). These have a good supply of atmospheric oxygen, but are exposed to large convective heat losses. They propagate laterally and downwards along the organic layers of the ground, leave voids or holes in the soil (see Figure 2-9.7 left). This has prompted that fuel consumption can be estimated using the depth of burn to calculate the volume of the void. Depth of burn is the vertical distance between the original soil location and the post-fire soil location. A typical value for the depth of burn reported in several field studies is around 0.5 m, which means that the average fuel consumptions per unit area is around 75 kg/m^2. This value is more than two orders of magnitude larger than that in flaming fires [Rein, 2013]. For this reason and in terms of fuel consumption, these are classed as megafires.

Deep fires take place in organic subsurface layers fed by oxygen infiltrating the ground via large cracks, piping systems or channels. For example, it is known that peatlands have an in-built natural piping system for water movement; when drained this system becomes the delivery network for oxygen transport to deeper locations and smoke exhaust to the atmosphere. Deep fires have a poorer supply of atmospheric oxygen but are better insulated from heat losses than shallow fires.

Smoldering fires have detrimental effects on the forest soil, its microflora and microfauna. This is because it consumes the soil (>90% mass loss) and also because the long residence time of smoldering means that heat penetrates deep into the soil layers (Rein 2013). On the contrary, flames produce high temperatures above the ground for short periods of time (in the order of 15 min). This results in minimal heating of the soil below depths of a few cm, reaching peak temperatures of 300°C at superficial layers (<10 mm) and below 80°C at layers more than 40 mm deep [Hartford and Frandsen, 1992]. This superficial heating can leave the soil system relatively unharmed. However, smoldering fires lead to enhanced heat transfer into the soil (see the discussion on the depth of burn above) for much longer durations (i.e. in the order of 1 h) and peak temperatures of 500°C (Rein et al., 2008). As a comparison, these thermal conditions are more severe than medical sterilization treatments, and mean that the soil is exposed to conditions that are lethal to biological agents.

Coal seam fires

[7] The mineral content is the % of the fuel mass (on dry basis) that will not burn or react at high temperatures. It results in ash.

Coal fires are a smoldering phenomenon that has attracted a larger amount of research, especially from geologists and petrologists [Stracher et al., 2010], and share many similarities with poorly studied deep smoldering wildfires. Due to the higher density and higher fraction of carbon of coal, the fire spreads slower (~0.1 mm/min) but burns hotter (~1000 ˚C peak temperature) compared to other smoldering fuels. Because of these characteristics, coal particles smoldering near the free surface are more frequently accompanied by internment flames than any other fuel.

There is evidence to suggest that burning coal seams are the oldest continuously burning fires on Earth. The best examples is *The Burning Mountain* in New South Wales, Australia is a large coal seam which has been smoldering for more than 6,000 years [Ellyett and Fleming, 1974]. Thousands of underground coalmine fires have been identified around the world, especially in China, the United States, and India. Elusive, unpredictable and costly, coal fires burn indefinitely while there is fuel, choking the life out of a community and the environment while consuming a valuable energy resource. The associated financial costs run into millions of dollars including the loss of coal, closure of mines, damage to the environment and fire-fighting efforts. There are some well-documented cases. In 1962, an abandoned mine pit in Centralia, Pennsylvania, USA was accidentally lit. Several unsuccessful attempts were made to extinguish it, letting the fire continue to burn after more than forty years. It is currently being monitored with the front advancing at ~20 m/year [Nolter and Vice, 2004].

Transition to flaming

Smoldering and flaming combustion are closely related, and one can lead to the other. Figure 2-9.14 shows snapshots of an experiment on the transition to flaming in a foam slab. The transition from smoldering to flaming is a severe threat in residential fires, and together with the slow buildup of CO and other incapacitating gases, they pose the largest life hazards of bedding or upholstery fires. The transition to flaming is also a concern in wildfires, since it offers the means for flaming fronts to re-establish in unexpected locations (e.g. across a fire break) and at unexpected times (e.g. long after burn out of the initial flaming front).

However, it has received little attention so the current understanding of this transition is limited. In particular, whether the transition is possible or not or when it will occur cannot be predicted because of a lack of valid models. [Babrauskas and Krasny, 1997] did a literature survey of fire tests on a variety of upholstered furniture items (chairs, sofas and mattresses) where a smoldering fire was ignited and allowed to progress. Out of the 102 fire tests examined, 64% did transition to flaming. The time to transition observed ranged from 22 to 306 min, with an average of 88 min. Revisiting the data from previous experiments on smoldering of furniture, Quintiere et al. [1982] showed that the likelihood of having transition to flaming occur peaks with a 36% probability at 50 to 100 min after ignition. They also showed that within the time period from 50 to 200 min, the likelihood of a transition event is comparable with the likelihood of reaching a lethal CO dose inside a single bedroom compartment.



Figure 2-9.14. **Series of photographs of a combustion experiment illustrating the transition to flaming in a smoldering polyurethane slab 40 cm high under external forced flow (photo by team of Prof. Carlos Fernandez-Pello, University of California at Berkeley). After 1 h of smoldering only half the sample has burned (photo 1, far left). When the rapid transition to flaming takes place (photos 2 and 3), the whole sample is engulfed in flames in just a few seconds (photos 4 and 5, far right).**

The transition is a spontaneous gas-phase ignition supported by the smoldering reaction, which acts both as the source of gaseous fuel, the pyrolysate produced in Eq. (1), and the source of the heat required to initiate the flame (Eq. 2b) [Ohlemiller 1990, Drysdale 2011]. The transition occurs not at the foam/air interface, but rather within the depth of the char left by the smolder front [Tse et al. 1996, Putzeys et al. 2007]. This is the location where both critical conditions of flammability of the pyrolysate mixture and the net excess of heat released by char oxidation are met. The heat driving the transition is released mostly by the secondary char oxidation [Torero and Fernandez-Pello 1995, Putzeys et al. 2007], which is more exothermic and takes places at higher temperatures (~700 C for polyurethane [Ohlemiller 1991]) than char oxidation in Eq. (2a). This temperature range is towards the highest temperatures typical of smoldering combustion and hence secondary char oxidation is only of importance during the transition to flaming [Putzeys et al. 2007].

A smoldering fuel responds to an increased oxygen supply (e.g. wind) by becoming faster and hotter until, eventually, flames might erupt. This effect was first studied quantitatively by Palmer [1957] for airflows over horizontal layers of wood sawdust. Depending on the material, the transition occurred at airflow velocities from about 0.9 to 1.7 m/s. Ohlemiller [1990b] did obtain transition to flaming in layers of fibrous insulation materials in forward smolder at air velocities of about 2 m/s. Bar-Ilan et al. [2005] conducted experiments on small samples of polyurethane foam and showed that the transition can be triggered by a combination of increasing the airflow velocity, the oxygen concentration or the external radiant heat. A map of airflow vs. oxygen fraction is shown in Figure 2-9.15. A similar map is presented in Bar-Ilan et. [2005] for airflow vs. external heat. They also provide an analytical expression for the transition boundary.

The transition to flaming has only been observed in forward propagation. Ohlemiller [1990b] argued that this is because in forward mode, the hot gases of combustion preheat the fuel ahead and thereby enhancing the combustion; while in opposed mode, the cool air reduces preheating. However, upward propagation inside a pile of fuel (Figure 2-9.7 right), which is mostly in opposed mode, can lead to the transition to flaming once the reaction breaks through to the free surface and finds a good supply of oxygen.

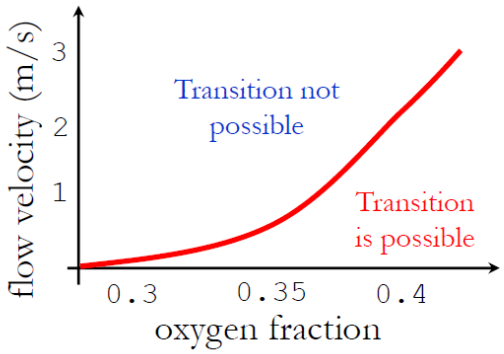


Figure 2-9.15. Transition map from smoldering to flaming on polyurethane samples. Data from [Bar-Ilan et al. 2005].

Concluding Remarks

We have seen that smoldering fires are a source of safety and environmental concerns. It is a type of combustion quite distinct from that in flaming fires, but as diverse and complex. The most studied fuels to date are cellulose and polyurethane foam.

The most important concepts to bear in mind are the following. Smoldering combustion can be initiated with weaker ignition sources (radiant, conductive, embers and self-heating) and is more difficult to suppress than flaming combustion. This makes smoldering the most persistent combustion mode. Large samples are easier to ignite than small samples, which affects the translation of laboratory testing results to the real scale. Smoldering fuels include synthetic materials such as charring polymers or cellulosic insulation, and natural fuels like peat or coal. In chemical terms, most smoldering fuels form a char on heating. In physical terms, smoldering fuels consist of a permeable medium formed by grains, fibers or some other porous matrix. The chemistry involves multiple pathways to chemical reactions, but in its simplest form can be understood as a two-step process: the pyrolysis of fuel and char oxidation. It is characteristically an incomplete combustion reaction, releasing pollutants in greater yields than flaming but at a lower rate. The transition from smoldering to flaming is a severe threat and can be triggered by a combination of increasing airflow, oxygen concentration and external heat. An emerging topic is smoldering wildland fires of organic soils, like peat, which are megafires in terms of the fuel consumption, and together with coal seam fires are the largest and oldest continuously burning fires on Earth.

Regrettably, the state of the art is incomplete, and accurate calculations on smoldering phenomena are not possible. Current understanding is fragmented in different areas, as suggested by the many different names applied to it: non-

flaming combustion, oxidative pyrolysis, glowing combustion, filtering combustion, low oxygen combustion, deep seated fire, hidden fire, lagging fire, smoking material, in-situ combustion, fireflood or underground gasification [Rein 2009]. More experimental and theoretical studies, and a multidisciplinary research approach to smoldering combustion are needed.

Acknowledgements

I am most grateful to Thomas J. Ohlemiller whose pioneering research and reviews on smoldering combustion provided not only the best sources of knowledge and inspiration for my own research and understanding but also contributed to this chapter in the form of material that I reused from his previous version (Ohlemiller 2002). This chapter is the culmination of 15 years of work on smoldering combustion that I have conducted at four universities. These are, in chronological order University of Texas at Austin, University of California at Berkeley, University of Edinburgh and Imperial College London. This work would not have been possible without the contributions and encouragements of my mentors, collaborators and PhD students. Of these, I am especially thankful to Carlos Fernandez-Pello, Jose Torero, Rory Hadden, Claire Belcher, Chris Lautenberger, Matt Davies and Xinyan Huang. A series of institutions have funded this work along the way: Royal Academy of Engineering, Leverhulme Trust, UK Engineering and Physical Science Research Council, IFIC Forensics, Met Office and NASA Space flight Program.

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