

INVITED PAPER

Smouldering Combustion Phenomena in Science and Technology

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Abstract – Smouldering is the slow, low-temperature, flameless form of combustion of a condensed fuel. It poses safety and environmental hazards and allows novel technological application but its fundamentals remain mostly unknown to the scientific community. The terms filtering combustion, smoking problem, deep seated fires, hidden fires, peat or peatlands fires, lagging fires, low oxygen combustion, in-situ combustion, fireflood and underground gasification, all refer to smouldering combustion phenomena. This paper attempts to synthesize a comprehensive view of smouldering combustion bringing together contributions from diverse scientific disciplines. Smouldering is the leading cause of deaths in residential fires and a source of safety concerns in space and commercial flights. Smouldering wildfires destroy large amounts of biomass and cause great damage to the soil, contributing significantly to atmospheric pollutant and green house gas emissions. Subsurface fires in coal mines and seams burn for very long periods of time, making them the oldest continuously burning fires on Earth. Worthy of consideration are the novel environmental and energy technologies being developed based on the direct application of smouldering combustion. These include the remediation of contaminated soils, production of biochar for long term storage of carbon, enchanted oil extraction from reservoirs and gasification of coal seams. The prospect of new opportunities for science and engineering in smouldering combustion are noticeable, but a much larger international research effort is required to increase the number of multidisciplinary experimental, theoretical and field studies. **Copyright © 2009 Praise Worthy Prize S.r.l. - All rights reserved.**

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I. Introduction

Smouldering is a slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel [1] [2]. It is a hazard of importance to several scientific disciplines but also a novel technological concept under development. Smouldering is the leading cause of deaths in residential fires [3] and causes economics losses of the order of \$350 million per year in property damage in the USA alone.

The aerospace industry has growing safety concerns regarding in-flight (including space flights) smouldering fires in hidden areas that cannot be detected or properly extinguished using conventional protection systems [4]. Ecologists and forest scientists study smouldering wildfires because they destroy large amounts of biomass and cause greater damage to the soil ecosystem than flaming fires [5].

Atmospheric scientists have studied acute pollution episodes caused by the Indonesian peat fires in 1997 and the destruction of vast amounts of stored carbon in the soil [6].

Earth scientists study smouldering subsurface fires in coal mines and seams that burn for very long periods of time (even centuries) [7]. There are noteworthy new environmental and energy technologies based on the direct application of smouldering combustion. These include remediation of contaminated soils, production of biochar for long term carbon storage, enhanced oil extraction from reservoirs and gasification of coal seams.

Whereas flaming combustion has been widely studied and is the aim of hundreds of papers per year, smouldering combustion has received very little attention as shown in the scientific publishing records in FIREDOC¹ [8]. This lists less than 600 papers on smouldering out of 80,000 on fire sciences published after 1900. Combustion and fire scientists were the first to research the topic in the 50's. It is only in the last decade that smouldering phenomena is been studied significantly by other scientific fields such as ecology or atmospheric and earth sciences.

¹FIREDOC is the online bibliographic database for the Building and Fire Research Laboratory Research Information Services, National Institute of Standards and Technology, which contains 80,000 journal articles, conference papers, books and reports on fire sciences.

The first widely available scientific work of merit on the topic was published in 1957 [9]. Palmer's seminal work consisted of a collection of observations from simple experiments involving burning piles of dust. This pioneering work was followed by a dozen of papers on smouldering of dust and fibrous materials in the 60's. The same low rate of studies per year continued during the first half of the 70's but with the focus switched to polymeric foams and cigarettes. A sudden increase occurred in the second half and about twenty papers per year on average were published with a focus on smoke detection, toxicity, polyurethane foam and cellulose. The publication rate peaked in the 80's and gradually dropped to an approximate average of 10 papers per year from 2001 to date.

This long-term neglect has led to the split of the topic into rather isolated bodies of research in diverse disciplines. Bridging these gaps would stem from a multidisciplinary understanding of the phenomenon and has the potential to lead into important benefits to our safety, economy and environment.

This paper attempts to synthesize a comprehensive view of smouldering combustion bringing together contributions from diverse scientific disciplines. For an in-depth review, the reader is referred to the work of Ohlemiller [1], which on the date that this paper goes to press still stands as the only review of the fundamental scientific concepts behinds smouldering combustion to date. A more recent review on the issues of smouldering in fire safety engineering is [2].

II. Overall Characteristics of Smouldering

Smouldering is a fundamental combustion problem involving heterogeneous chemical reactions and the transport of heat, mass and momentum in the gas and solid phases.

The fundamental difference between smouldering and flaming combustion is that, in the former, the oxidation reaction and the heat release occur on the solid surface of the fuel or porous matrix and, in the latter, these occur in the gas phase surrounding the fuel. Fig. 1 shows the two burning regimes for forest fuels (top) and the most familiar example of smouldering, coal embers (bottom). The characteristic temperature, spread rate and heat released during smouldering are low compared to those in the flaming combustion of a solid. Typical values in smouldering at ambient conditions are around 500-700 °C for the peak temperature and 6-12 kJ/g for the average heat of combustion; typical values during flaming are around 1500-1800 °C and 16-30 kJ/g respectively. Because of these characteristics, smouldering propagates at low velocities, typically around 10-30 mm/h [2], approximately two orders of magnitude lower than the velocity of typical flame-spread. Significantly higher temperatures and higher heats of combustion can be

expected in technological application of smouldering combustion in porous media with forced flows at high pressure (like in-situ combustion for oil extraction or coal gasification) since these reproduce nearly adiabatic conditions and provide large oxygen supplies.



Fig. 1. Top) Snapshot showing the two regimes of combustion for solid fuels; flaming of the grass and smouldering of the organic soil (for scale reference, the flame is about 10 mm in height). Bottom) Glowing charcoal briquettes (photo by J.B. Nielsen, Public Domain, Wikimedia Commons)

Because of its low temperature, smouldering is characteristically an incomplete oxidation reaction and thus emits a mixture of toxic, asphyxiant and irritant gases and particulates at a higher yield than flaming fires. It favours CO₂ to CO ratios around unity (as opposed to ratios around 10 in flaming combustion), so CO is an important toxic factor in smouldering fires [10], [11].

Many solid materials can sustain a smouldering reaction, including coal (see Fig. 1 bottom), cotton, tobacco, dust, paper, peat (see Fig. 1 top), duff and hummus (see Fig. 1 top), wood, board of organic fibres (see Fig. 2 right), synthetic foams and charring polymers including polyurethane foam (see Fig. 2 left). Smouldering fuels are characterized by having a significantly greater characteristic thermal time than fine fuels but allow oxygen transport to the surface. These characteristics lead to the slow but persistent burning typical of smouldering combustion. In general terms, the fuel consists of an aggregate and permeable medium formed by particulates, grains, fibres or a porous matrix. These aggregate fuel elements facilitate

the surface reaction with oxygen by providing a large surface area per unit volume. They also act as thermal insulation that reduce heat loss but, at the same time, permit oxygen transport to the reaction sites by convection and diffusion [1].

Synthetic foams, like polyurethane foam (see Fig. 2 left), are highly susceptible to smouldering combustion. The porous nature of the foam allows air to feed the exothermic reaction while protecting the reaction zone from heat losses to the surroundings. Polyurethane foam is the material of choice for most laboratory controlled tests of smouldering combustion because it is easy to ignite, has a high propensity to smoulder, and also because its composition and physical properties are very homogeneous an advantage not present in most natural fuels.



Fig. 2. Left) Cross-section of a partly smouldered polyurethane slab 200 mm high burned in microgravity conditions (photo by NASA, [12]). Right) Smouldering of a 80 by 50 mm sample of woody fiberboard (31 min after hot-coil ignition at the bottom)

The smouldering of liquid fuels soaked in a porous matrix is also possible. There are three examples of this in the literature. Lagging fires, well known in fire and process safety, involve the soaking of a porous insulating material by oil or another self-igniting liquid [13]. In the petroleum industry, smouldering fronts are purposely initiated in underground porous reservoirs to extract oil [14]. More recently, a wide range of liquid contaminants saturated in porous mineral soils has been smouldered at laboratory conditions [15]. The presence of the porous matrix is indispensable for smouldering of these liquids to occur, suggesting that the oxidation takes place at the pore surface in contact with the liquid fuel.

Smouldering ignition requires the supply of heat flux to the solid fuel. The subsequent temperature increase of the solid first sets off the thermal-degradation reactions (mainly endothermic pyrolysis) and then oxidation, until the net heat released by oxidation is high enough to balance the heat required for propagation. This net heat released by the reactions is partially transferred by conduction, convection and radiation ahead of the reaction and partially lost to the environment. The oxidizer is transported to the reaction zone by diffusion and convection, in turn feeding the oxidation reactions. Once ignition occurs, the smoulder reaction advances gradually through the material. It is well established that for most materials and typical conditions, the two limiting factors in smouldering

propagation are the oxidizer flux to, and the heat losses from, the reaction zone [1].

The transition from smoulder to flaming is a spontaneous gas-phase ignition supported by the smoulder reaction which acts both as the source of gaseous fuel (pyrolyzate, CO, etc.) and of heat to carry the reaction. Fig. 3 shows snapshots of an experiment of smouldering propagation over a period of several seconds and the transition from smouldering to flaming in a polyurethane foam sample. The transition occurs when critical conditions inside the pores of the solid are met, triggering the onset of gas-phase reactions [16], [17] [18]. These conditions include the flammability of the gas mixture inside the pores and a net excess of heat released by strong solid-phase oxidation reactions. Increased levels of oxygen and airflow (e.g. caused by wind) can strongly influence transition. Transition to flaming has only being observed to date to occur in forward propagation mode because the hot gases preheat the fuel ahead. But currently understanding of the process is rather limited and more research is required on the topic. In particular, the timing of the transition from smouldering to flaming cannot be predicted in practical terms since it is not well described by any model to date.

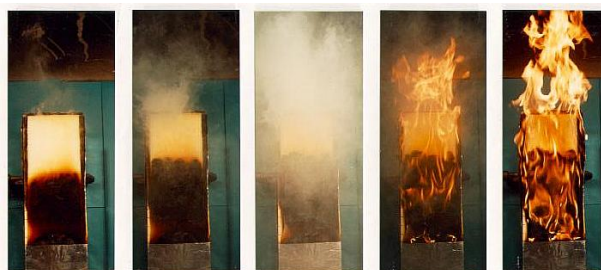


Fig. 3. Series of photographs of a combustion experiment illustrating the transition to flaming in a smouldering polyurethane slab 40 cm high (photo by NASA, [18]). After 1 hour of burning only half the sample has smouldered (photo 1). When transition takes place (photos 2 and 3), the whole sample is engulfed in flames in a few seconds (photos 4 and 5)

The heat flux needed to attain smouldering ignition is significantly lower than that for flaming ignition. For instance, smouldering ignition of polyurethane foam has been reported to occur with a heat flux of 2 kW/m² using a contact heater [12], while direct flaming ignition with a radiant heater occurs only above 10 kW/m² [19]. Thus, the transition from smouldering to flaming combustion provides a hazardous shortcut to flaming fires, which could be initiated with heat sources that are too weak to directly ignite a flame on the solid fuel.

When studying smouldering propagation through the interior of combustible materials, it is common to consider the simpler one-dimensional process and to classify it in two main configurations: opposed and forward propagation. These are defined according to the direction in which the smoulder reaction propagates relative to the oxidizer flow. Fig. 4 shows the two 1D

configurations. In opposed smoulder, the reaction front propagates in the direction opposite to the oxidizer flow, and in forward smoulder, the front propagates in the same direction.

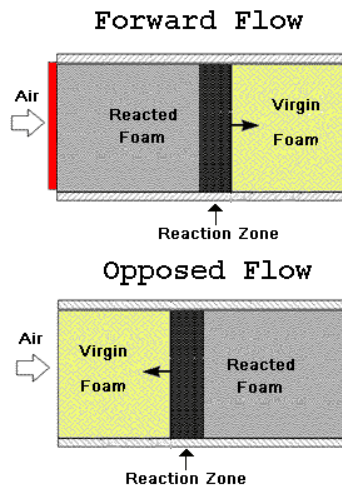


Fig. 4. Configurations in one-dimensional smouldering; forward and opposed

These two configurations are distinguished by the roles played by heat and mass transport mechanisms and chemical reactions. In forward propagation, the oxygen flows through the char, reacts at the smoulder zone and then the oxygen-depleted gas flow continues through the virgin fuel. Convective heat transport is towards the virgin fuel ahead and results in preheating. In opposed propagation, the oxygen flows through the virgin fuel and reacts at the smoulder zone. Then the oxygen-depleted gas flow travels through the char. Convective transport is towards the char left behind the front, reducing the preheating of the fuel.

III. Structure of a Smouldering Front

Fig. 5 shows a photograph of a sample of peat (porous biomass fuel) where a smouldering front has been initiated and is propagating laterally. Superimposed on the photograph is a schematic of the smouldering front structure that can be observed with the naked eye.

Generally speaking, there are four visually discernable regions propagating in a smouldering front.

These are:

1. Preheating of the undisturbed fuel: heat from the reacting front is transported ahead preheating the fuel up to temperatures where water evaporation takes place. This front does not emit gases in any significant quantity.
2. Evaporation: this endothermic reaction occurs within a range of temperatures from approximately 80 to 100 °C, emitting water vapour. In this front the mass loss depends on the moisture content.

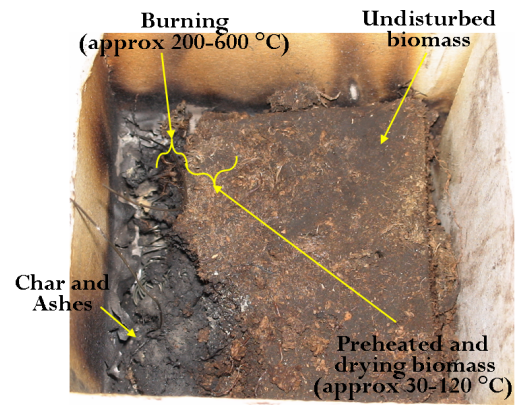


Fig. 5. Front and temperature ranges in a smouldering peat sample 100mm long [5]

3. Burning region: this front is where the pyrolysis and oxidation reactions take place and net heat is released. Pyrolysis reaction absorbs heat and converts the fuel into volatile gases, polyaromatic hydrocarbons, trace levels of CO and CO₂, and water vapour. It leaves behind a solid carbonaceous char. Pyrolysis starts approximately at temperatures above 200-250 °C. Subsequent heating above this temperature increases the pyrolysis rate if fuel is available. Pyrolysis is stronger at deeper layers of the fuel where oxygen transport is reduced and oxidation rate is lower. The oxidation involves the exothermic reaction of the fuel and char left by the pyrolysis front. The peak temperature is found in this region and is where most of the fuel mass is lost. This reaction overlaps with the pyrolysis depending on the propagation mode and oxygen availability [20]. The oxidation reaction occurs at temperatures over 300 °C and is the main source of CO and CO₂. More CO₂ is formed where the oxygen supply is large (e.g. closer to the oxygen supply or free surface) and more CO where it is limited (e.g. further from the oxygen supply or deeper into the fuel layers).
4. Char and ash region: this is where the smouldering has ceased and the remaining matter cools down to ambient temperature. The ash left is the mineral content present in the original fuel and the char is the result of incomplete burning.

The propagation rate of self-sustained smouldering is typically controlled by oxygen transport and net heat losses (see Section VI). Yet, heterogeneous chemical kinetics governs the front structure and dictate the effective value of the global heat released. The degradation of a solid fuel involves multiple pathways to chemical changes (pyrolysis and oxidation), and these pathways are not yet fully understood. In spite of the complex kinetic behaviour, experimental evidence suggests that mechanisms consisting of only a few global reactions capture the most important characteristics of the decomposition process [20], [21], [22], [25], [27].

The polymers for which smouldering kinetics are best known are cellulose and polyurethane foam. Reference [21] provides a quantified mechanism for cellulose pyrolysis, and [22] provides the mechanism and parameters for its thermal degradation in air (includes pyrolysis and oxidation). The mechanism includes cellulose pyrolysis, cellulose oxidation and char oxidation, accounting for three solid species; cellulose, char and ash. However, this mechanism has never been used to predict experimental results of cellulose smouldering. Rein *et al.* [20] 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 has been validated against experiments of polyurethane smouldering [23].

Well established kinetic mechanisms are lacking and thus smouldering combustion is frequently described as a function of the propagation mode. Forward is described using a 2-step mechanism having pyrolysis and oxidation reactions [24], [25], whereas in opposed smouldering these two paths are lumped together in a global single reaction [26], [27]. Only recently, the same kinetic mechanism and parameters was shown to be able to predict both forward and opposed smouldering [23].

In forward smouldering propagation (Fig. 6, 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. This is in agreement with experimental measurements of forward propagation [25] and [28] where two distinct fronts are observed in the temperature profiles.

In opposed smouldering (Fig. 6, left), the oxidation and the pyrolysis reactions overlap to form a single propagating front. This is also in agreement with experimental observations in opposed propagation [27], [29], where a single front is observed in the temperature profiles.

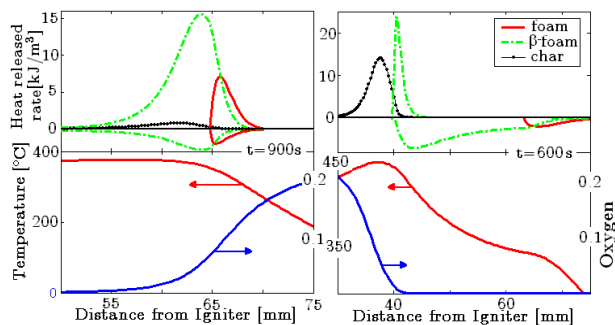


Fig. 6. Numerical results for the front structure during self-propagation [23]. Left) Opposed smouldering; and Right) Forward smouldering. Top) The heat-released rate of each reaction (positive for oxidation, negative for pyrolysis). Bottom) The temperature and oxygen profiles

Fig. 7 shows the one dimensional representation of a smouldering front in a fuel rod and the approximate correspondence with a burning cigarette (one of the most common examples of smouldering). As shown by the results in Fig. 6 for forward smouldering, the pyrolysis front is located at the leading edge of the cigarette burning front since it does not need oxygen to permeate into the solid. The oxidation reaction takes place at the trailing edge of the burning cigarette, where the oxygen supply is available from the surrounding environment, and the heat released is transferred ahead of the front into the virgin fuel and pyrolysis front to drive the propagation.

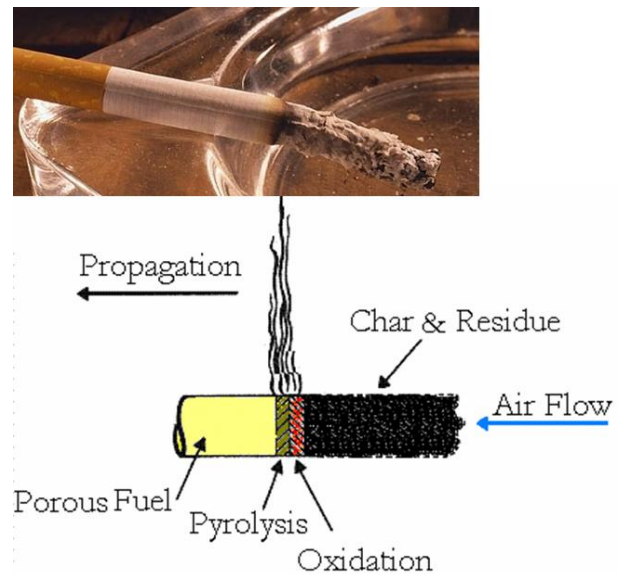


Fig. 7. Structure of a one-dimensional reaction front in forward smouldering and the correspondence in a burning cigarette

IV. Smouldering Combustion in the Absence of Gravity

Combustion intrinsically involves the production of high-temperature gases whose low densities trigger buoyant motion under a gravity field. Buoyancy-induced flows increase the convective transport of heat and mass in the direction opposite to the gravity field. Thus, gravity affects the convective component in both of the primary controlling mechanisms of self-sustained smouldering, the oxidizer supply and the heat losses. In a gravity field, convective heat losses are increased by buoyancy thus hindering smouldering. The buoyant mass-flux could hinder smouldering in the downward propagation, but it promotes smouldering in upward propagation. In absence of gravity, natural buoyant flows are not established and only diffusion or forced convection exists.

The importance of studying smouldering in the absence of gravity (or microgravity) is three-fold: fire safety in space facilities (see Section VIII.2 ahead), fundamental research under simplified flow conditions,

and as an ideal benchmark to test theories.

Research on microgravity combustion is also of importance because it offers a unique capability for experimentalists to establish an ideal flow environment and to extend the range of test conditions that can be studied, *i.e.* low-velocity flows, low heat losses and purely diffusive transport regimes [30], [31]. Buoyant flows complicate the execution and interpretation of experiments on Earth, since buoyant motion triggers the onset turbulence and unsteadiness. Absence of gravity allows the development of new insights into the fundamental phenomena of smouldering combustion.

Furthermore, microgravity environments provide ideal benchmark cases against which existing theories and new theories can be tested [31]. These theories often neglect buoyancy effects and/or assume one-dimensional flow in situations where in reality buoyant effects induce two- or three-dimensional behaviour. Microgravity continues to offer the unique ability to test truly one-dimensional flow experiments in combustion science. A numerical model of smouldering in microgravity does not need to model the buoyant transport of heat and mass inside the porous fuel and is therefore simpler and requires fewer assumptions.

V. Governing Equations

The set of governing equations presented here accounts for the most complete description of the transport mechanisms in smouldering combustion. This model has been shown to reproduce the most important features of the process and can predict the thermal and species structure of the reaction-front, the onset of smouldering ignition, the propagation rate and the temperature profiles. Only an overview is presented here. A detailed discussion can be found in [32], and other supporting references are [1] [33] [34] [35] [23] and [36].

The governing equations consists of the conservation of energy of the solid (1), energy of the gas (2), continuity of the gas (3), solid species (4) and gas species (5):

$$\frac{\partial h_s'''}{\partial t} = \nabla \cdot (k_s \nabla T_s) + \tau_{gs} (T_g - T_s) - \rho_0 \sum_i \dot{\omega}_i \Delta h_i \quad (1)$$

where h''' is the enthalpy per unit volume, ρ_0 is the initial density of the solid and t is the time. T is the temperature, with the subscript s for solid and g for gas. The temperature can be calculated from the corresponding enthalpy dividing it by the specific heat. The conservation equation includes the transport terms (in order of appearance on the right hand side) of heat transfer by conduction, between gas and solid matrix, and the source term of heat released by chemical reactions on the solid surface. The conductivity k_s includes the radiative conductivity in the optically thick

limit, which can be estimated using electron-microscopy photos of the porous matrix [20], [32]. The transfer of heat between gas and solid matrix is quantified via the efficient coefficient τ_{gs} . The reaction rates $\dot{\omega}_i$ and heats of reaction Δh_i are defined according to the kinetic mechanism assumed (see Section 4) and the kinetic parameters of the fuel.

Similarly, for the gas, the conservation equation becomes:

$$\begin{aligned} \frac{\partial}{\partial t} (\phi h_g''') &= \nabla \cdot (\phi k_g \nabla T) + \\ &+ \nabla \cdot \left(\phi \rho_g \frac{K}{\mu} c_{pg} (T_g - T_0) \nabla p \right) - \tau_{gs} (T_g - T_s) \end{aligned} \quad (2)$$

where ϕ is the porosity, c_{pg} the specific heat, p the pressure, K the flow permeability of the matrix, μ the viscosity. This equation takes into account the transport of heat by convection, conservation of momentum by Darcy's law in which the gas velocity is calculated as a linear function of the pressure gradient in the porous medium. No energy released by any gas reaction is included since a smouldering process that is far from transitioning to flaming is driven only by heterogeneous reactions on the surface of the solid.

The gas continuity is given by:

$$\frac{\partial}{\partial t} (\phi \rho_g) = \nabla \cdot \left(\phi \rho_g \frac{K}{\mu} \nabla p \right) + \rho_0 \sum_i \dot{\omega}_i \nu_{g,i} \quad (3)$$

where the reaction rates $\dot{\omega}_i$ and yields $\nu_{j,i}$ are defined according to the kinetic mechanism assumed and the kinetic parameters of the fuel. Buoyancy-induced flows are not included here but can be added using the Boussinesq approximation.

The conservation of the solid species is:

$$\frac{\partial m_j}{\partial t} = \sum_i \dot{\omega}_i \nu_{j,i} \quad (4)$$

The conservation of the gas species is:

$$\begin{aligned} \frac{\partial}{\partial t} (\phi \rho_g y_i) &= \nabla \cdot \left(\phi \rho_g \frac{K_x}{\mu} y_{O_2} \nabla p \right) + \\ &+ \nabla \cdot (\phi \rho_g D_{diff} \nabla y_{O_2}) - \rho_0 \sum_i \dot{\omega}_i \nu_{O_2,i} \end{aligned} \quad (5)$$

The most important gas species in smouldering is oxygen, which feeds the combustion process. Also important for emission and toxicity studies and for the transition to flaming are the gas product species. The pressure of the gas phase can be calculated using the ideal gas law once the gas composition is known.

To complete the mathematical representation of the problem, initial and boundary conditions need to be provided. In general, the most important conditions will be those describing the ignition protocol, the influx of oxygen and the heat losses at the boundaries with the exterior domain.

Fig. 8 shows the numerical results from integrating Eqs (1)-(5) for a 1D rod made of polyurethane foam [32]. These results have been validated against experimental measurements and shown to capture the ignition, propagation and front structure in both forward and opposed propagation modes [23].

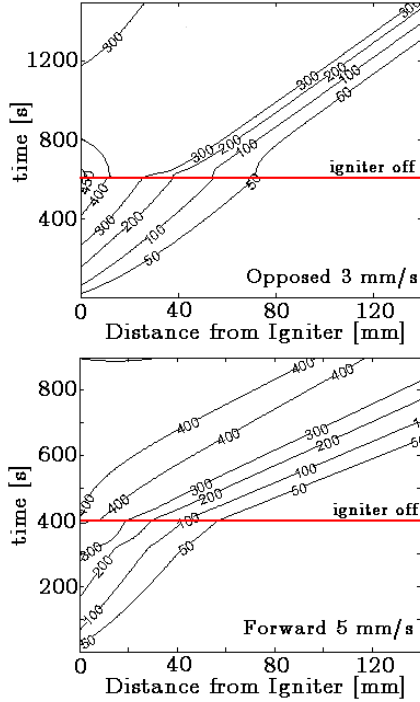


Fig. 8. Numerical results for temperature contour lines as a function of time and space in a 1D rod of polyurethane foam and 140 mm in length [32]. Top) Opposed smouldering with an inlet airflow of 3 mm/s; and Bottom) forward smouldering with an inlet airflow of 5 mm/s. The slope of each contour lines gives the propagation velocity

VI. Simplified Analysis

The complexity of the smouldering process requires the use of approximations in the theoretical models and simplifications in the experiments (see Section 4 for ideal experimental environment) to study the fundamentals. The propagation rate of self-sustained smouldering is typically controlled by two mechanisms: oxygen transport and net heat losses [1]. This can be shown by conducting a simple global energy balance at the smouldering front. This yields a simple mathematical representation of the propagation that serves to quantify the controlling mechanisms involved in the process.

In a control volume that contains the smouldering front, the propagation rate is determined by the balance between the heat released per unit mass of oxygen

reacted, the energy required to heat the virgin fuel and the incoming air to the smoulder temperature, and the heat losses to the environment [27], [29]. Assuming that all oxygen is consumed, the application of such an energy balance into mathematical terms provides the following expression for the smouldering propagation velocity in opposed configuration [29]:

$$u_{sml} = \frac{\dot{m}_{O_2}'' Q_{sml} - \dot{m}_g'' c_{pg} (T_{sml} - T_0) - \dot{q}_{loss}'' \frac{A_L}{A_c} + \dot{q}_{ig}''}{\rho_s c_{ps} (1 - \phi) (T_{sml} - T_0)} \quad (6)$$

The heat transferred from the igniter \dot{q}_{ig}'' can be neglected when studying self-sustained smoulder because the propagation occurs far from the igniter influence. For the typical range of gas velocities, the energy required to heat the incoming airflow to the smoulder temperature ($\dot{m}_g'' c_{pg} (T_{sml} - T_0)$) is small in comparison with the other energy terms. Consequently, in the above expression, Eq. (6), the two major terms determining the smoulder propagation velocity are the heat released by the reaction ($\dot{m}_{O_2}'' Q_{sml}$) and the heat losses to the external environment ($\dot{q}_{loss}'' \frac{A_L}{A_c}$). The heat loss coefficient $\frac{A_L}{A_c}$ expresses the ratio of the lateral area to the cross-sectional area at the smoulder front. The properties of the solid ($\rho_s c_{ps} (1 - \phi)$) only scale the magnitude of the velocity. Then, considering only the major terms, Eq. (6) simplifies to:

$$u_{sml} = \frac{\dot{m}_{O_2}'' Q_{sml} - \dot{q}_{loss}'' \frac{A_L}{A_c}}{\rho_s c_{ps} (1 - \phi) (T_{sml} - T_0)} \quad (7)$$

According to Eq. (7), the propagation velocity in the oxidizer-limited regime is linearly proportional to the mass flux of oxidizer, as it has been verified experimentally [37], [27], [29]. It is seen in Eq. (7) that the effect of the heat losses to the external environment is to hamper smouldering propagation. The heat losses term includes the effect of the size of the fuel sample through the ratio $\frac{A_L}{A_c}$. This ratio reflects that heat loss is proportional to the surface area whereas heat generated is proportional to the volume. As the sample is made smaller, the ratio $\frac{A_L}{A_c}$ increases, and the effect of the heat losses increases until smoulder propagation cannot occur below a critical size. The critical size for smouldering propagation can be analyzed by making Eq. (7) equal to zero (limit of no propagation). For a slab of square cross-sectional area, side length L and smouldering front thickness δ , the ratio $\frac{A_L}{A_c}$ becomes equal to $\frac{4\delta}{L}$. The rate of heat loss can be expressed as the function of a global heat-losses coefficient U_{loss}

and the temperature gradient with the exterior. Then, setting u_{smf} in Eq. (7) to zero and rearranging the expression, the critical sample size L_c is expressed as:

$$L_c = \frac{4\delta}{Q_{smf}} \frac{U_{loss} (T_{smf} - T_0)}{\dot{m}_{O_2}''} \quad (8)$$

The expression Eq. (8) can be used to provide an estimate of the critical size. The smoulder-zone thickness δ , the smoulder temperature T_{smf} and the heat of smouldering Q_{smf} depend on the smouldering properties of the fuel. For example, for polyurethane foam the required parameters are available from Bar-Ilan et al. [29] [28] and yields the critical size of 160 mm. The analysis of experimental studies of smouldering indicate that the critical size for rectangular polyurethane foam samples under natural convection is 150 mm [38]. Thus, for a polyurethane-sample which size is below this critical value, achieving self-sustained smouldering requires the reduction of the heat losses or the increase of the heat generated, or both. The former can be accomplished by thermally insulating the sample and the latter by increasing the oxidizer flux [16], [17].

VII. Smouldering Phenomena

VII.1. Fires in the Built Environment

Fire statistics draw attention on the frequency and danger of smouldering fires. They are the leading cause of fire deaths [3] and [39] with more than 25% of the annual fire-deaths. During 2001 alone, there were an estimated 31,200 smouldering fires in structures and US\$386 million in property damage [3] in the USA alone. A fire-initiation scenario that is particularly common is when a weak source of heat (e.g. a cigarette) ignites a piece of porous combustible material (e.g. upholstered furniture). This can lead to a smouldering fire that lasts for a long period of time (hours or even days), spreading slowly until critical conditions are attained and flames suddenly erupt.

The inherent danger of smouldering fires in the built environment stems from four particular characteristics [40]: 1) they can be initiated by weak sources of heat, too weak to immediately start a flaming fire; 2) they produce relatively cooler plumes of smoke which composition and lack of buoyancy makes detection difficult by standard fire detection devices; 3) gases produced by smouldering pose a toxic hazard; and 4) they can abruptly transition to a flaming fire.

Smouldering intrinsically emits products of incomplete oxidation and thus emits a mixture of asphyxiant and irritant gases and particulates at a higher yield than flaming fires [10]. The productions rate is lower and the growth slower than flaming fires but it

poses a serious threat to sleeping, incapacitated, trapped or otherwise immobilized occupants. The studies of Hilado *et al.* [41] on mice addressed the lethal toxicity of smouldering gases from a wide range of polymers. Mice were exposed to the smouldering gases from a piece of upholstery. With cotton fabric and polyurethane foam cushion, 12% of the mice died in the 90 min of the experiment and an additional 40% died in the following 14 days after the exposure was discontinued. With cotton fabric and cotton cushion, all the mice died during the first 35 min of experiment due to CO poisoning. Quintiere *et al.* [42] studied the hazard to humans of smouldering fires in enclosure due carbon monoxide. They determined that life-threatening conditions from CO doses occurred in most cases in the 50-150 minute range of the experiment. They also noted that the time to transition to flaming occurred within the same time window.

The ability of standard smoke detectors to activate in the presence of a smouldering fire is undermined since smoke from smouldering fires behaves differently to the smoke generated by flaming fires [40]. This is due to two main reasons: (a) the low temperature and weak plumes of smoke thereby produced; and (b) the smoke composition. Smoke detectors for flaming fires are typically designed and installed taking into account that the hot products of fires move up with the flame-induced buoyant flows and depend on the convective movement of combustion products from the fire to the detector. The positioning of these detectors is based on the need to minimize this travelling time. In an enclosure, the hottest gas and the greatest concentration of smoke collect at the highest locations. It is at these locations that smoke detectors are generally installed. However, the low heat release rates of smouldering fires and the resulting weak plumes imply that the gaseous combustion products are quickly cooled by the ambient air and therefore do not follow the same path as flaming fires. As a result, smoke from a smouldering fire takes considerably longer times to move to the smoke detector system [43], [44]. The plume may never reach detectors situated on the ceiling but may disperse or become stagnant at a lower level. Smouldering intrinsically emits smoke made of products of incomplete combustion and thus the composition is different from the smoke from flaming fires. The size of the smoke particulates and their spatial distribution in the fire plume from a smouldering source varies greatly from flaming fires. Because conventional smoke detectors are usually calibrated using flaming sources, they might not work properly with smouldering sources [45], [46].

There are several works in the literature comparing the effect of fire retardants on flaming against the effect on smouldering [40]. Some suggest that fire retardant treatments to reduce flame ignition also reduce smouldering ignition [47]. Many flame retardant promote the char formation that is considerably richer in

carbon content per unit mass than the original fuel. It has often been experimentally observed that materials with good resistance to flaming ignition have poor resistance to smouldering ignition and vice versa [48, 49, 50, 47, 17]. By enhancing the charring tendency, flaming combustion rates may be reduced, but perhaps at the expense of creating a source of smouldering combustion that would not otherwise have existed [51]. Inhibition of smouldering combustion requires different types of chemical retardant mechanisms than those required for inhibition of flaming combustion. The analysis in [52] of polyurethane foams shows that flame-retarded foams transition to flaming over a wider range of conditions than non flame-retarded foam this is primarily due to the higher yield of char of the former [49]. Wang et al. [50] studied wood ignition and showed that Borax tends to reduce flame spread but promotes smouldering, conversely boric acid suppresses smouldering but has little effect on flame spread. This conflictive interaction of current flame-retardants with smouldering and flaming ignitions poses a dilemma in fire safety and requires further research.

VII.2. Aerospace Fire Safety

Smouldering combustion is a fire-safety concern in the aerospace sector, including space flights. The aircraft industry suffers many smouldering incidents every year and although most do not grow beyond the point of origin or are detected on time, avoiding major disruptions, on some occasions smouldering has led to fatal accidents. One example is the 1998 Swissair flight 111 aircraft fire [53] which, according to investigations, was caused by faulty wiring which resulted in smouldering ignition of adjacent polymer insulation sheathing. The smouldering fire transitioned to flaming after some time.

There is concern for an accidental fire occurring in a space-based facility [54], [55]. In the closed environment of a spacecraft or extraterrestrial base, with no avenue for escape, a fire to be greatly feared [56]. Should a fire occur in a space facility, there is a strong probability that it would be a smoulder-originated fire [4]. The Space Shuttles have registered on average one charred-cable incident for every ten missions [57], [58]. A charred cable is symptomatic of smoulder-prone conditions and could lead to sustained smouldering or ignition of nearby fuels. The MIR orbital station and other USSR/Russian spacecraft have also suffered several smoulder-related incidents [59]. The impact of smouldering during a space mission is also critical from the points of view of the impact on the environmental health of the astronauts [60] and the difficulty to detect and extinguish a smouldering fire [61]. These topics need to be assessed in the context of long-term space habitation. With the currently orbiting International Space Station and future long-term missions (i.e., mission to the Moon and Mars), there is an increased

interest in the study of smouldering in reduced gravity because of the need to pre-empt the possibility and to minimize the effect of a smoulder-initiated fire during the operation of a space-based facility. Thus, it is of great interest to understand and characterize the smouldering behaviour of materials used in these facilities under the expected ambient conditions of absence of gravity, but also of reduced pressure and increased oxygen concentration.

VII.3. Wildland Fires

Smouldering of the forest ground fuels does not have the visual impact of the flaming front but is nonetheless an important factor in wildfires and the subsequent damage to the forest. Large smouldering fires are rare events at the local scale but occur regularly at a global scale. Once ignited, they are particularly difficult to extinguish despite extensive rains or firefighting attempts and can persist for long periods of time (weeks and up to years; [6], [62]), and spread over very extensive areas of forest and deep into the soil. By propagating below the surface, smouldering fires offer the means for flaming combustion to re-establish during wildfires in unexpected locations (e.g. across a fire break) and at unexpected times (e.g. long after burn out of the flaming front). These fires represent a large contributor to biomass consumption and a significant source of combustion emissions to the atmosphere [6], [63], [11].

The effects of smouldering fires on the landscape can range from the small scale (pockets of burning in superficial layers or the root of a single tree), to the large scale (burning of a hill-top or the destruction of the root network of a complete forest stand). In general, smouldering fires have a severe impact on the local soil system, because the burning fuel is the organic portion of the soil itself. The prolonged heating from the slowly propagating fire can kill roots, seeds and plant stems and the affected layers of soil sustain large losses of biomass. This coupled with exposing of underlying layers increases the likelihood of long term damage and erosion.

Forest fuels prone to smoulder during wildfires can be divided in two categories; thick fuels and organic soils. Natural thick fuels are stumps, snags, downed logs, large branches and roots [64]. These are characterized by having a significantly greater thermal time than finer fuels, which favours the slow burning of smoulder combustion. Organic soils are hummus, duff, peat, coal seams and others. Smouldering fires of organic soils can burn in shallow or deep fronts. Each has different dynamics. A shallow front burns near the free surface and are open to the atmosphere, thus having large supplies of oxygen available but exposed to convective heat losses. A deep subsurface fire burn many meters below the ground, and thus have a limited supply of oxygen but are insulated from heat losses to

the atmosphere. In this section, only shallow fuels are discussed and deep fires are treated in section 7.4.

It has been measured that smouldering can consume around 50% or more of the total burned biomass in temperate and boreal fires [65], [63], and in Amazonian tropical-woodland fires [66]. Bertschi *et al.* [63], Rabelo *et al.* [64] and Carvalho *et al.* [67] report high fuel-consumption fractions by smouldering fires. Smouldering of forest fuels is also responsible for a significant fraction of the pollutants emitted into the atmosphere during a wildfire. Bertschi *et al.* [63] studied the emissions from smouldering biomass fuels and calculated the emission from real wildfires. Based on their results and compared to the emissions from the flaming phase of a tropical savanna fire, smouldering produces 130% more CO and 670% more hydrocarbons, but 15% less CO₂ and no NO_x. Compared to the emissions from a boreal fire, smouldering produces 30% more CO and 20% more hydrocarbons, but 13% less CO₂ and no NO_x. Many smoke management problems in the US associated with prescribed fires involved smouldering emissions [68].

The changes to the soil produced by smouldering fires in organic soils are driven by two factors: the high temperatures reached and the large loss of soil mass. The most important physical change produced by smouldering fires is that affecting the stability of the ground. The removal of soil layers at the surface leads to enhanced erosion and the destruction of deeper layers can lead to structural collapse. Over-hangs, holes in the ground and pan-shape voids around tree bases are commonly produced during smouldering fires and can lead to local subsidence of the soil and damage to roots, threatening tree stability and disturbing hydrological dynamics. Heating of the soil by wildfire produces changes of chemical nature (loss of carbon, nitrogen and organic phosphorus) and biological nature (modification of nutrient availability, perturbation of microbial dynamics and plant species). In general terms, flaming fires produce very high temperatures away from the ground for short periods of time. Smouldering fires, however, lead to enhanced heat transfer to the soil for much longer durations (i.e. in the order of one hour) that can lead to sterilization of the soil [5], [69]. The longer duration and the higher heat transfer to the forest floor by smouldering has been identified as an important factor in fire mortality (comparable to damage to tree crowns by flaming fires) [70].

The moisture and the organic content have been identified as the main controlling parameters for smouldering ignition of biomass. Frandsen [71] determined that the smoulder-ignition limits of Canadian boreal peat are a moisture content lower than 110% (dry base) and an mineral content lower than 82%. Contents higher than these were shown to result in no ignition.

In the organic layers of the ground, the smoulder front propagates downward and laterally consuming the

fuel (Fig. 8). The front structure is similar to a forward-smouldering configuration: the drying and the pyrolysis fronts move ahead of the oxidization front which stays in contact with the oxygen in the open air.

A recent case of a smouldering fire causing major damage to the landscape and the ecosystem is a wildfire that occurred in a 40 year old, 15 ha plantation of lodgepole pines in Rothiemurchus near Aviemore, Scotland, during July 2006 [5]. The flaming fire was extinguished by the fire service within 3 days, but the peat underneath the forest continued to smoulder for more than 40 days despite the occasional rains (see Fig. 9).



Fig. 9. Photographs of adjacent forest stands from the July 2006 Rothiemurchus peat fire in Scotland, UK [5]. The fire involved flames for three days and smouldered for six weeks. Top) Stand not affected by the fire showing the trees and the peat layer. Bottom) Stand of trees trunks charred by the flames and the soil destroyed by smouldering fire

To stop the smouldering spread, the fire service dug a fire-break trench 5 m wide and 0.5 to 2 m deep at the perimeter of the burning areas to remove the peat and expose the mineral soil. Fig. 3 shows photographs of adjacent forest stands after the fire. While the flaming fire scorched the trees up to 1 m from the floor and consumed some of the grass, the smouldering fire burned the peat up to depths of 0.5 to 1m removing large quantities of the soil. The root systems and tree bases were by far the most affected areas by smouldering. Many smouldering pan-shape voids were seen around forest stands and single trees. These were formed by the burning of large portions of soil in approximately circular areas 0.5 to 3m around the tree bases and exposing the mineral soil layers beneath. A

dependence of peat consumption patterns on the distance from the base of the trees was also observed in several areas of the forest (not shown in Fig. 9), in a similar pattern to that noted by Hille and Stephens [72] and Miyanishi and Johnson [73]. Near the bases of trees, where crown cover reduces the rainfall and roots take up water, there is a much higher degree of peat consumption and the fire spread following the roots. This suggests that the fire pattern in Rothiemurchus was largely influenced by the moisture distribution of the peat.

The transition from smouldering to flaming is also observed in forest fires. Logs can naturally burn for long periods of time oscillating between flaming and smouldering combustion after the flame front has passed [64]. Smouldering can also re-ignite previously extinguished wildfires. For example, this mechanism led to the re-ignition of the 1991 Oakland Hills Fire, California [74]. The re-ignited fire destroyed nearly 2,000 homes and caused up to US\$10 billion in damages. Hot embers are another method by which wildland fires can spread due to smouldering. These embers are lofted by the fire plume and transported some distance away from the originating fire front [75]. Once landed, the hot ember heats the underlying litter, underbrush or grass and can initiate a smouldering fire, which could transition to flaming.

VII.4. Subsurface Fires

Smouldering fires of peat and coal can penetrate many meters below the ground (see Fig. 10) and can cause large perturbations in the global atmospheric chemistry and a long term safety hazard to local population.

When active, the burning of ground and subsurface layers can last for long periods of time and emit large quantities of combustion products causing the deterioration of the air quality. Carbon emissions from peat fires are equivalent to approximately 3,000 times the normal flux due to natural decomposition at ambient conditions [11]. After the 2002 study of the Borneo fires [6], subsurface fires have started to be seen as an emerging threat, posing a global risk with social, economic and environmental consequences in both the short and the long terms.

Peat is an accumulation of partially decayed vegetation matter. Peatlands cover more than 3% of the Earth's land surface. They are important ecosystems for a wide range of wildlife habitats supporting biological diversity, hydrological integrity and carbon storage.

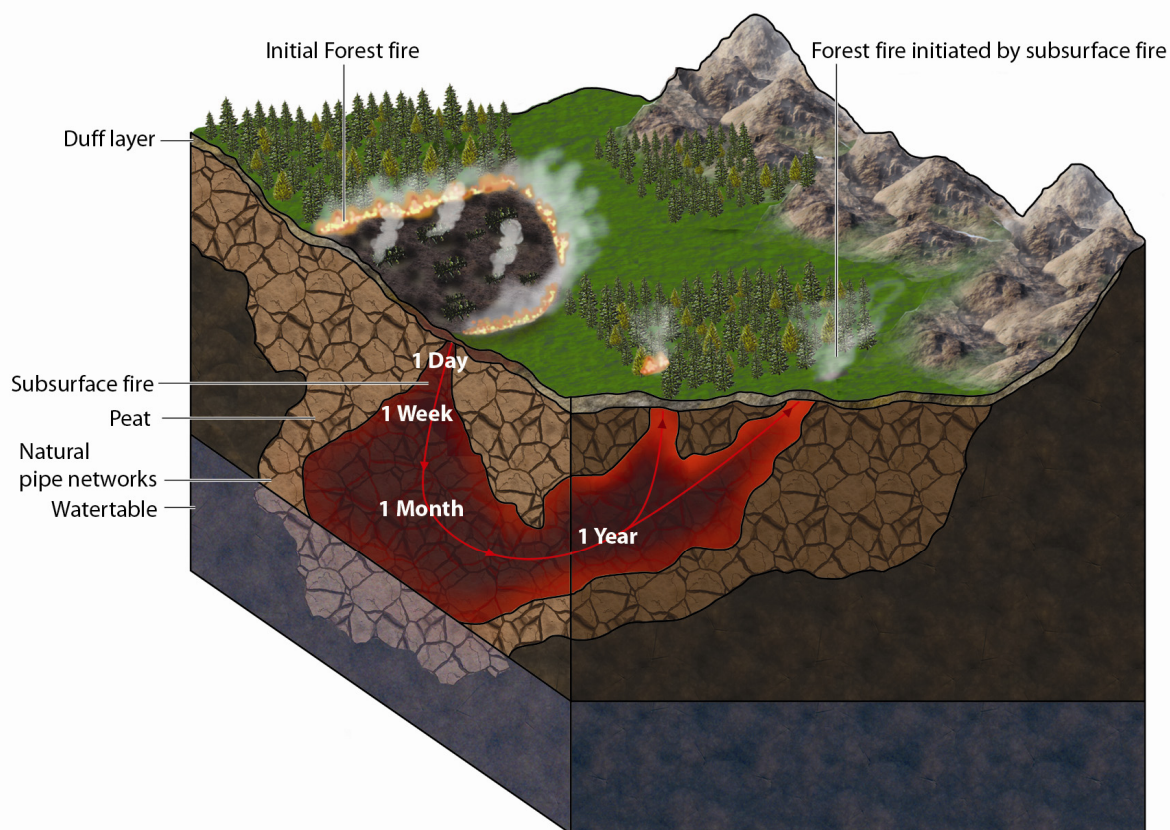


Fig. 10. Illustration of a subsurface fire initiated at the surface that propagates into the ground and emerges months later (illustration by E. Burns 2008 and commissioned by G. Rein)

Peatlands play an important role in the global carbon balance and recent environmental changes, such as climate change and human activities including drainage, peat harvesting and air pollution have raised questions regarding the long term stability of these carbon sinks.

The largest peat fires registered to date took place in Indonesia during the El Niño dry season of 1997 (previously occurred in 1972, 1974, 1982, 1991 and 1994, and later repeated in 1998, 2002, 2004 and 2006) and lasted for several months, destroying over 2,441,000 ha of peat with a loss of ground layers between 0.2 and 1.5 m deep [6]. Smouldering accounted for 80% of the emissions to the atmosphere.

The smoky haze covered large parts of South East Asia for weeks, disrupting shipping and aviation and causing large economic losses, long term damage to the environment and healthcare problems. It has been estimated that the 1997 fires released between 0.8 to 2.6 Gton of carbon emissions into the atmosphere, equivalent to 13-40% of the global fossil fuel emissions for that year [6].

Coal seams and coal mines and other fuel accumulations like landfills also burn in smouldering mode. Thousands of underground coalmine fires have been identified around the world [7]. Some of the oldest and largest coal fires in the world occur in China, the United States, and India. Elusive, unpredictable and cost prohibitive, coal fires may burn indefinitely, choking the life out of a community and its environs while consuming a valuable natural resource. Fires lasting more than 46 years are well documented [76].

In China alone, subsurface fires account for 2 to 3% of the annual world emission of atmospheric CO₂ [7]. Associated financial costs run into millions of dollars from loss of coal, closure of mines, damage to 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, but the fire continues to burn after more than forty years. It is currently being monitored with the front advancing approximately 20 m/year [76]. In 2005, the State of Colorado, USA, reported more than 30 active subsurface fires [77], involving 2% of all known abandoned coal mines in the state.

The primary controlling mechanisms of subsurface smouldering fires are the net fuel load, the oxygen transport, (predominantly dictated by the distance to a free surface and the permeability of the medium) and the heat losses (predominantly by water evaporation and conduction). Thus, the fuel properties affecting these mechanisms are, the moisture and inert contents, organic composition, bulk density, flow permeability, and the presence of cracks or deep channels. These properties dictate the smouldering dynamics controlling the ignition, depth, duration, and extent of smouldering fires. Subsurface fires are fed by small quantities of air flowing through fractured strata, cracks, natural pipe

networks [78], openings or mines shafts and galleries, which permit oxygen to circulate to the subsurface. The reduced heat losses and the high thermal inertia of the underground material, together with the high fuel availability and the small oxidizer flow promote long-term smouldering combustion and allow for creeping but extensive propagation both in depth and in area. These fires prove difficult to be detected and frustrate most efforts to be extinguished. Little technical research has been undertaken on the subject and as a result, the understanding of how to tackle these fires is very limited [79].

VII.5. Technological Applications

There are beneficial applications of smouldering combustion to technological advances in energy, environment science and forest management. An overview of those noteworthy is included here.

Smouldering of fossils fuels in the subsurface is of interest for optimal exploitation and cleaner use of energy sources. In-situ combustion in oil fields is a method of thermal recovery in which a forward smouldering fire is generated in one side of the reservoir and is fed by injecting a gas containing oxygen [14]. Part of the oil is cracked and burned and converted into lighter hydrocarbons, carbon monoxide, carbon dioxide and water at high pressure. As the smouldering front moves, heat is transported ahead and reduces oil viscosity, in turn displacing it and creating a flow of oil towards the production well. In-situ oil combustion is being used more often for oil recovery when traditional-extraction methods become inefficient or too costly. Underground coal gasification is an in-situ process carried out in deep coal seams (deeper than 30 m) using injection and production wells drilled from the surface, which enable the coal to be converted into product gas for power generation [80]. The coal seam is ignited via the injection well and a forward smouldering front is fed by injecting a gaseous mixture containing oxygen. The products of combustion at high pressure are collected at the production well. Hydrogen, carbon monoxide, and methane are useful as gas fuels produced by this process. Underground gasification allows development of new sources of energy from coal that could be cleaner than traditional coal burning.

In the field of environmental science, smouldering is of interest in waste treatment, soil contaminant remediation, and biochar production and storage.

Smouldering of tires can be employed for tar and energy production, fostering the recycling of tires and partially avoiding their waste [81]. Smouldering combustion can be used for remediation of contaminated soils [15] and associated laboratory experiments (see Fig. 11) show that the smoulder front can be controlled to consume most of the liquid contaminant and clean the porous matrix soil. This is a promising environmental technology.

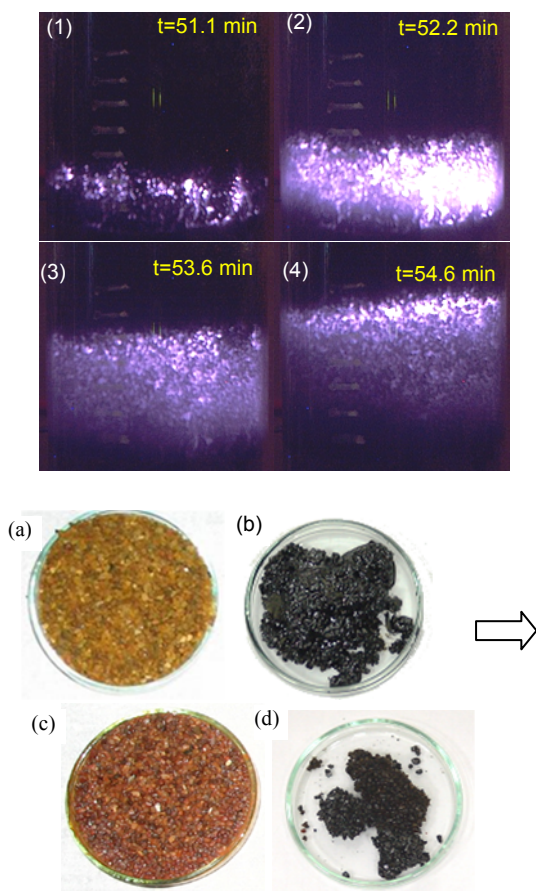


Fig. 11. Smouldering combustion as a remediation technology for contaminated soil [15]. (Top) Series of images showing the onset and propagation of the visible front in soil contaminated with 25% coal tar (Images show an area of about 30x30 mm of the sample. Ignition was initiated at $t=50$ min). (Bottom) Comparison between samples of soil before and after the treatment: (a) Clean soil, (b) soil mixed with fresh coal tar, (c) treated soil from the reactor core, and (d) treated soil from the periphery of the reactor

Biochar is a fine-grained, highly porous charcoal produced from biomass that helps soils retain nutrients and water. Charcoal is rich in carbon content and a long-term stable solid resisting degradation, and thus, can be used to lock carbon in the soil [82]. Biochar is of increasing interest because of concerns about global warming being caused by emissions of CO_2 and other greenhouse gases. On the one hand, smouldering combustion can provide energy-efficient conversion of biomass into biochar by the pyrolysis. Thus, one process that promotes biochar conversion with the advantage of minimal or zero energy costs is a smouldering process where the energy supply is released from the slow oxidation of a part of the biomass itself. Small reactors, easy to operate and to maintain, can be designed to be run by local communities. On the other hand, biochar can sustain a smouldering combustion and thus smouldering fires present a significant hazard where biochar is to be stored in large quantities or at high concentration [83]. If a smouldering fire were to occur in a biochar field, a

fire could propagate through the surface and subsurface layers destroying the biochar and releasing the stored carbon as gas emissions. This is about the only hazard that could lead to an accidental release of the stored carbon to the atmosphere.

In forest management, controlled smouldering fires can be used to reduce shallow layers of natural fuels at slow propagation rate [84]. These fires have two benefits when kept in very shallow layers: they are easy to control and result in little damage to the forest stand.

VII.6. Other Smouldering Phenomena

Smouldering combustion is referred in the literature by other names. It is referred to as filtering combustion [85], a term used for surface combustion in porous metal matrixes, glowing combustion, which is an intense smouldering process that has heated the solid surface to the point that it radiates to the environment in the visible spectrum. Other names are found in fire safety practice, where the issue of smouldering fires in residential environments is called 'the smoking problem' [3]. A phenomenon that is intrinsically linked to smouldering combustion is the self-heating of a solid fuel [86]. In this case, the heterogeneous oxidation reactions and heat losses governing self-heating are of similar nature to those in smouldering combustion and if the process is strong enough it may lead to the ignition of a smouldering front or/and the transition to a flaming fire. Other names are deep seated fires in landfill sites under overextraction conditions (i.e. when air is being entrainment into the pile lagging fires in the process industries, low oxygen combustion in the biochar community and fire flooding or fireflood in in-situ combustion by petroleum industry.

Peat fires under anomalous climate conditions are also responsible for the rare event, first reported in 1999, of a smouldering wild-urban interface fire. This occurred in St. Petersburg, Russia during a spell of unusually hot, dry weather [87]. Peat fires south of the city burned for weeks during the summer period and haze covered five districts. The smouldering fire was seen 300 m from the concrete residential buildings in 10 m deep peat lands.

An unusual case of subsurface fire is the burning of the debris of the World Trade Center. After the attack, fire and subsequent collapse of the Twin Towers on September 11th, 2001, the immense pile of debris left on the site smouldered for more than five months with occasional burst of flames near the free surface [88]. It resisted attempts by the fire fighters to extinguish it until most of the rubble was removed. Outdoor pollutant levels in lower Manhattan returned to urban background levels after about 200 days [89]. The effects of the gaseous and aerosol combustion products on the health of the emergency workers were patent but the details are still a matter of debate. There is very little information on this fire.

VIII. Concluding Remarks

Smouldering combustion is studied by a number of rather isolated disciplines but which fundamentals remain mostly unknown to the scientific community. This paper provides an overview of smouldering problems in the different disciplines, in an attempt to bridge the gaps between them and bring together current and future research efforts.

From a fundamental scientific point of view, the most studied smouldering materials to date are cellulose and polyurethane foam. The most carefully conducted and comprehensive experiments of smouldering combustion are those of NASA conducted in microgravity and ideal flow conditions. But this is not enough to foster a multidisciplinary approach to smouldering. The study of the state of the art shows that current body of knowledge cannot provide good understanding. More experimental and theoretical studies are needed, especially to explore the issues of ignition, combustion emissions and extinction and the transition to flaming.

Fundamental research in these topics will facilitate further applied research in the fields reviewed in this paper and will allow better tackling the problem of gas emissions from subsurface fires, the loss of carbon pool and how to extinguish them. These topics will become even more important if, as climate experts predict, warmer and drier summers over large areas of the planet might be expected in the future which would bring an increased subsurface fire frequency.

Moreover, the production and safe storage of biochar, in-situ oil recovery and in-underground coal gasification are promising technological solution to solve current energy and environmental problems but that required further scientific development to allow optimized operations of the technology, increase efficiency and reduce the economic and environmental costs. The prospects of new opportunities for science and engineering in smouldering combustion are noticeable, but a much larger international research effort is required to increase the number of multidisciplinary studies.

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References

- [1] T.J. Ohlemiller, Modeling of Smoldering Combustion Propagation, *Progress in Energy and Combustion Science 11* (1985), 277-310.
- [2] T.J. Ohlemiller, *Smoldering Combustion*, (SFPE Handbook of Fire Protection Engineering, 3rd ed., Massachusetts, 2002, pp. 2.200–2.210)
- [3] J.R. Hall, *The Smoking-Material Fire Problem*, (Fire Analysis and Research Division of The National Fire Protection Association, November 2004, Massachusetts).
- [4] J.S. T'ien, H. Shih, C. Jiang, H.D. Ross, F.J. Miller, A.C. Fernandez-Pello, J.L. Torero, D.C. Walther, *Mechanisms of Flame Spread and Smolder Wave Propagation*, Microgravity Combustion: Fire in Free Fall, H.D. Ross (ed), (Academic Press, 2001, pp. 299-417).
- [5] G Rein, N Cleaver, C Ashton, P Pironi, JL Torero, The Severity of Smouldering Peat Fires and Damage to the Forest Soil, *Catena 74* (2008), 304-309.
- [6] S.E. Page, F. Siegert, J.O. Rieley, H.-D.V. Boehm, A. Jaya, S. Limin, The amount of carbon released from peat and forest fires in Indonesia during 1997, *Nature 420* (2002) 61-61.
- [7] G.B. Stracher, T.P. Taylor, Coal fires burning out of control around the world: thermodynamic recipe for environmental catastrophe, *International Journal of Coal Geology 59* (2004) 7-17.
- [8] FIREDOC, online bibliographic database, Building and Fire Research Laboratory Research Information Service, National Institute of Standards and Technology, Gaithersburg, MD. http://www.bfrl.nist.gov/bfirlris/firedoc_info.htm
- [9] K.N. Palmer, Smoldering Combustion in Dusts and Fibrous Materials, *Combustion and Flame 1* (1957) 129-154.
- [10] D.A. Purser, *Toxicity Assessment of Combustion Products*, (SFPE Handbook of Fire Protection Engineering, 3rd edition, Massachusetts, 2002, pp. 2.83-2.171).
- [11] G Rein, S Cohen, A Simeoni, Carbon Emissions from Smouldering Peat in Shallow and Strong Fronts, *Proceedings of the Combustion Institute 32* (2009) 2489-2496.
- [12] D.C. Walther, A.C. Fernandez-Pello, D.L. Urban, Space Shuttle Based Microgravity Smoldering Combustion Experiments, *Combustion and Flame 116* (1999) 398-4
- [13] D. Drysdale, 2009, *Ignition of Liquids*, SFPE Handbook of Fire Protection Engineering (4th ed.), Chapter 18, Quincy, Massachusetts.
- [14] I.Y. Akkutlu, Y.C. Yortsos, The dynamics of in-situ combustion fronts in porous media, *Combustion and Flame 134* (2003) 229-247.
- [15] P. Pironi, C. Switzer, G Rein, JI Gerhard, JL Torero, A Fuentes, Small-Scale Forward Smouldering Experiments for Remediation of Coal Tar in Inert Media, *Proceedings of the Combustion Institute 32* (2009) 1957-1964.
- [16] O. Putzeys, A. Bar-Ilan, G. Rein, A.C. Fernandez-Pello, D.L. Urban, 2007, The role of the Secondary Char Oxidation in Smoldering and its Transition to Flaming by Ultrasound Probing, *Proceedings of the Combustion Institute 31* (2007) 2669-2676.
- [17] O. Putzeys, AC Fernandez-Pello, G Rein, DL Urban, The Piloted Transition to Flaming in Smoldering Fire Retarded and Non-Fire Retarded Polyurethane Foam, *Fire and Materials 32*, (2008) 485–499.
- [18] S.D. Tse, A.C. Fernandez-Pello, K. Miyasaka, Controlling Mechanisms in the Transition from Smoldering to Flaming of Flexible Polyurethane foam, *Proceedings of the Combustion Institute 26* (1996) 1505-1513.
- [19] A. Tewarson, *Generation of Heat and Chemical Compounds in Fires*, (SFPE Handbook of Fire Protection Engineering, 3rd Edition, Massachusetts, 2002, pp. 3.82-3.164).

- [20] G. Rein, C. Lautenberger, A.C. Fernandez-Pello, J.L. Torero, D.L. Urban, Application of Genetic Algorithms and Thermogravimetry to Determine the Kinetics of Polyurethane Foam in Smoldering Combustion, *Combustion and Flame* 146 (2006) 95-108.
- [21] M. Grønli, M.J. Antal, G. Varhegyi, A round-robin study of cellulose pyrolysis kinetics by thermogravimetry, *Industrial and Engineering Chemistry Research* 38 (1999) 2238-2244.
- [22] T. Kashiwagi, H. Nambu, 1992, Global kinetic constants for thermal oxidative degradation of a cellulosic paper, *Combustion and Flame* 88 (1992) 345-368.
- [23] G Rein, AC Fernandez-Pello, DL Urban, Computational Model of Forward and Opposed Smoldering Combustion in Microgravity, *Proceedings of the Combustion Institute* 31 (2007) 2677-2684.
- [24] D.A. Schult, B.J. Matkowsky, V.A. Volpert, A.C. Fernandez-Pello, Forced forward smolder combustion, *Combustion and Flame* 104 (1996) 1-26.
- [25] J.L. Torero, A.C. Fernandez-Pello, 1996, Forward smolder of polyurethane foam in forced air flow, *Combustion and Flame* 106 (1996) 89-109.
- [26] D.A. Schult, B.J. Matkowsky, V.A. Volpert, A.C. Fernandez-Pello, Propagation and extinction of forced opposed flow smolder wave, 1995, *Combustion and Flame* 101 (1995) 471-490.
- [27] J.L. Torero, A.C. Fernandez-Pello, M. Kitano, Opposed forced flow smoldering of polyurethane foam, *Combustion Science and Technology* 91 (1993) 95-117.
- [28] A. Bar-Ilan, G. Rein, A.C. Fernandez-Pello, J.L. Torero, D.L. Urban, 2004b, Forced Forward Smoldering Experiments in Microgravity, *Experimental Thermal and Fluid Science* 28 (2004) 743-751.
- [29] A. Bar-Ilan, G. Rein, D.C. Walther, A.C. Fernandez-Pello, J.L. Torero, D.L. Urban, The effect of buoyancy on opposed smoldering, *Combustion Science and Technology* 176 (2004) 2027-2055.
- [30] C.K. Law, G.M. Faeth, Opportunities and challenges of combustion in microgravity, *Progress in Energy and Combustion Science* 20 (1994) 65-113.
- [31] M.D. King, H.D. Ross, Overview of the NASA Microgravity Combustion Program, *AIAA Journal* 36 (1998) 1337-1345.
- [32] G. Rein, Computational model of forward and opposed smoldering combustion with improved chemical kinetics, PhD. Thesis, Department of Mechanical Engineering, University of California at Berkeley., 2005 <http://repositories.cdlib.org/cpl/fs/ReinPhD05>.
- [33] C. Di Blasi, Mechanisms of two-dimensional smoldering propagation through packed fuel beds, *Combustion Science and Technology* 106 (1995) 103-124.
- [34] SV Leach, G Rein, JL Ellzey, O Ezekoye, JL Torero, Kinetic and Fuel Property Effects on Forward Smoldering Combustion. *Combustion and Flame* 120 (2000) 346-358.
- [35] G Rein, A Bar-Ilan, AC Fernandez-Pello, JL Ellzey, JL Torero, DL Urban, Modeling of One-Dimensional Smoldering of Polyurethane in Microgravity Conditions, *Proceedings of the Combustion Institute* 30 (2005) pp. 2327-2334.
- [36] A.B. Dodd, C. Lautenberger and A.C. Fernandez-Pello, Numerical examination of two-dimensional smolder structure in polyurethane foam, *Proceedings of the Combustion Institute* 32 (2009), pp. 2497-2504.
- [37] F.E. Roger, T.J. Ohlemiller, A. Kurtz, M. Summerfield, Studies of the Smoldering Combustion of Flexible Polyurethane Cushioning Materials, *Journal of Fire and Flammability* 9 (1978) 5-13.
- [38] J.L. Torero, BRE Centre for Fire Safety Engineering, The University of Edinburgh, Personal communications about unpublished results conducted in 1993.
- [39] S. Brereton, R.M. Laing, Analysis of injury and death from burning upholstered furniture, *New Zealand Medical Journal* 105 (1992) 429-32.
- [40] J.L. Torero, 1999, Smoldering: The Fire Scenario, internal report, University of Maryland. <http://hdl.handle.net/1842/2644>
- [41] C.J. Hilado, D.P. Brauer, E.M. Olcomendy, A. Furst, Toxicity of gases from Smoldering combustion, *Proceedings of the West Pharmaceutical Society* 22 (1979) 199-200.
- [42] J.G. Quintiere, M. Birky, F. Macdonald, G. Smith, An analysis of smoldering fires in closed compartments and their hazard due to carbon monoxide, *Fire and Materials* 6 (1982) 99-110.
- [43] H. Hotta, Y. Oka, O. Sugawa, Interaction between hot layer and updraft from a smoldering fire source - Part I An experimental approach, *Fire Science and Technology* 7 (1987), pp. 17-25.
- [44] J-I. Watanabe, T. Tanaka, Experimental Investigation into Penetration of a Weak Fire Plume into a Hot Upper Layer, *Journal of Fire Sciences* 22 (2004) 404-420.
- [45] B.J. Meacham, V. Motevalli, Characterization of smoke from smoldering combustion for the evaluation of light scattering type smoke detector response, *Journal of Fire Protection Engineering* 4 (1992), pp. 17-28.
- [46] G.W. Mulholland, T.J. Ohlemiller, Aerosol characterization of a smoldering source, *Aerosol Science and Technology* 1 (1982) 59-71.
- [47] P.J. Wakelyn, P.K. Adair, R.H. Barker, Do open flame ignition resistance treatments for cellulosic and cellulosic blend fabrics also reduce cigarette ignitions?, *Fire and Materials* 29 (2005) 15-26.
- [48] F.E. Rogers, T.J. Ohlemiller, Smolder Characteristics of Flexible Polyurethane Foams, *Journal of Fire and Flammability* 11 (1980).32-44.
- [49] C.Y.H. Chao, J.H. Wang, 2001, Comparison of the Thermal Decomposition Behavior of a Non-Fire Retarded and a Fire Retarded Flexible Polyurethane Foam, *Journal of Fire Science* 19, (2001) 137-155.
- [50] Q. Wang, J. Li, J.E. Winandy, Chemical mechanism of fire retarding of boric acid on wood, *Wood Science Technology* 38 (2004) 375-389.
- [51] C.L. Beyler and M.M. Hirschler, *Thermal Decomposition of Polymers*, (SFPE Handbook of Fire Protection Engineering, 3rd Edition, Massachusetts, 2002, pp. 1.110-1.131)
- [52] C.Y.H. Chao, J.H. Wang, Transition from smoldering to flaming combustion of horizontally oriented flexible polyurethane foam with natural convection, *Combustion and Flame* 127 (2001) 2252-2264.
- [53] F. Fiorino, Lessons From Swissair Crash, *Aviation Week & Space Technology* 158 (2003), 62.
- [54] H. Palmer, Closing Address, *International Microgravity Workshop, NASA LeRC*, Cleveland, OH, January 25, 1989.
- [55] G.M. Faeth, Closing Address, *Space Station Freedom Modular Combustion Facility Assessment Workshop*, NASA LeRC, Cleveland, OH, May 17, 1989.
- [56] R. Friedman, *Fire Safety in Extraterrestrial Environments*, NASA Technical Memorandum 1998-207417, Lewis Research Center, Cleveland, OH, May 1998.
- [57] T. Paulos, F. Issacci, I. Catton, G.E. Apostolakis, *Proceedings of 2nd Probabilistic Safety Assessment and Management Conference*, Ed. G.E. Apostolakis, San Diego, CA, Vol. 3, pp. 099-15-099-20, 1994.
- [58] G.A. Ruff, *Research Needs in Fire Safety for the Human Exploration and Utilization of Space*, Proceedings and Research Plan, NASA CP-2003-212103, 2003.
- [59] J. Oberg, *Star-Crossed Orbits: Inside the U.S.-Russian Space Alliance* (McGraw-Hill, New York, 2001).
- [60] R.D. Irons, T.W. Clarkson, J. Schulz, R. Eberhardt, B. Weiss, P. Todd, G.W. Morgenthaler, G. Oberdorster, M.J. Utell, Hazard identification and risk assessment in the extended spaceflight environment, *Acta Astronautica* 33 (1994) 277-287.
- [61] F.J. Weinberg, F.B. Carleton, D. Dunn-Rankin, Development of electrically charged extinguishant dispersions for use in microgravity, *Combustion Science and Technology* 175 (2003) 2161-2179.
- [62] H. Svensen, DK Dysthe, EH Bandlien, S Sacko, H Coulibaly, S Planke, *Geology* 31 (2003) 581-584.
- [63] A. Bertschi, R.J. Yokelson, D.E. Ward, R.E. Babbitt, R.A. Susott, J.G. Goode, W.M. Hao., Trace gas and particle emissions from fires in large diameter and belowground biomass fuels,

- Journal of Geophysical Research* 108 (2003) 8.1-8.12.
- [64] E.R.C. Rabelo, C.A.G. Veras, J.A. Carvalho, E.C. Alvarado, D.V. Sandberg, J.C. Santos, Log smoldering after an amazonian deforestation fire, *Atmospheric Environment* 38 (2004) 203-211.
- [65] W.H. Frandsen, Burning rate of smoldering peat, *Northwest Science* 65 (1991) 166-172.
- [66] J.B. Kauffman, D.L. Cummings, D.E. Ward, Fire in the Brazilian Amazon, 2, Biomass, nutrient pools and losses in cattle pastures, *Oecologia* 113 (1998) 415-427.
- [67] E.R. Carvalho, C.A. Gurgel Veras, J.A. Carvalho, Experimental investigation of smoldering in biomass, *Biomass and Bioenergy* 22 (2002) 283 – 294.
- [68] C.C. Hardy, R.D. Ottmar, J.L. Peterson, J.C. Core, P. Seamon, (eds), *Smoke Management Guide for Prescribed and Wildland Fire* (Natural Wildfire Coordination Group, Natural Interagency Fire Center, Idaho, 2001).
- [69] A. Simeoni, J. Garcia, G. Rein, Description of Subsurface Fires and Some Experimental Consideration on their Dynamics, *Russian Physics Journal (in press)* (2009).
- [70] S.L. Stephens, M.A. Finney, Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion, *Forest Ecology and Management* 161 (2002) 261-271.
- [71] W.H. Frandsen, Ignition probability of organic soils, *Canadian Journal of Forestry Research* 27 (1997) 1471-1477.
- [72] M.G. Hille, S.L. Stephens, Mixed conifer forest duff consumption during prescribed fires: tree crown impact, *Forest Science* 51 (2005) 417-424.
- [73] K. Miyanishi, E.A. Johnson, Process and patterns of duff consumption in the mixedwood boreal forest, *Canadian Journal of Forest Research* 32 (2002) 1285-1295.
- [74] P.J. Pagni, Causes of the 20 October 1991 Oakland Hills Conflagration, *Fire Safety Journal* 21 (1993) 331-339.
- [75] R.A. Anthenien, S.D. Tse, A.C. Fernandez-Pello, On the trajectories of embers initially elevated or lofted by ground fire plumes in high winds, *Fire Safety Journal* 41 (2006) 349-363.
- [76] M.A. Nolter, D.H. Vice, Looking back at the Centralia coal fire: a synopsis of its present status, *International Journal of Coal Geology* 59 (2004) 99-106.
- [77] S. Renner, *Status of Fires at Abandoned Underground Coal Mines in Colorado* (Colorado Division of Minerals and Geology, Denver, 2005).
- [78] J. Holden and T.P. Burt. Piping and pipeflow in a deep peat catchment, *Catena* 48 (2002) 163-199.
- [79] G.J. Colaizzi, Prevention, control and/or extinguishment of coal seam fires using cellular grout, *International Journal of Coal Geology* 59 (2004) 75-81.
- [80] M.S. Blinderman, D.N. Saulov, A.Y. Klimenko, Exergy optimisation of reverse combustion linking in underground coal gasification, *Journal of the Energy Institute* 81 (2008) 7-13.
- [81] J.P. Vantelon, B. Lodeho, S. Pignoux, J.L. Ellzey, J.L. Torero, Experimental observations on the thermal degradation of a porous bed of tires, *Proceeding of the Combustion Institute* 30 (2005) 2239-2246.
- [82] J. Lehmann, A handful of carbon, *Nature* 447 (2007) 143-144.
- [83] G Rein, Gains and Threats from Smoldering Combustion to Biochar Production and Storage, *International Biochar Initiative, Biochar, Sustainability and Security in a Changing Climate*, Newcastle, Sept 2008. <http://hdl.handle.net/1842/2511>
- [84] H.H. Biswell, *Prescribed Burning in California Wildlands Vegetation Management* (University of California Press, Berkeley, 1989).
- [85] A.G. Merzhanov and B.I. Khaikin, Theory of combustion waves in homogeneous media, *Progress in Energy and Combustion Science* 14 (1988) 1-98.
- [86] B. Gray, *Spontaneous Combustion and Self-Heating* (SFPE Handbook of Fire Protection Engineering, 3rd ed., Massachusetts, 2002 pp. 2-211-2-228)
- [87] A. Badkhen, Underground Fires Smoke Out City Residents, *St. Petersburg Times* 483, Friday, 16 July 1999.
- [88] J. Beard, Ground Zero's fires still burning, *NewScientist*, 3 December 2001.

- [89] J.D. Pleil, W.E. Funk, S.M. Rappaport, 2006, Residual Indoor Contamination from World Trade Center Rubble Fires as Indicated by Polycyclic Aromatic Hydrocarbon Profiles, *Environmental Science & Technology* 40 (2006) 1172-1177.

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