Smoldering - The Fire Scenario

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There are certain fire initiation scenarios that are particularly common, one of great significance is a fire initiated from the ignition of a porous fuel, one well known example is that of fires originating in cigarettes. Nearly 40% of the deaths due to fire can be traced to cigarette induced smolder of upholstered furniture [1,2,3] and the mechanisms that control the process that transforms the weak smolder reaction occurring in the cigarette to a fire are still mostly unknown. The statistics that link the origins of fires to smoldering combustion are not very precise but many examples show that this type of fire initiation scenario is very common. Clarke and Ottoson [4] pointed that fires started in upholstered items, such as furniture and mattresses, represent the single largest cause of fire deaths in the United States. A commonly accepted sequence of events is that of ignition caused by a cigarette leading to smoldering for a long time period (that could last for hours) and finally followed by flaming. After flaming occurs lethal conditions can be attained very fast [5]. Flaming accelerates the process but is not a necessary event, in many cases smoldering furniture releases toxic gases very slowly, but this can be enough to kill occupants if they are asleep and exposed to such gases for a long time [6]. Although initiation by smoldering is most common in residential fires it can also occur in dump sites where smoldering of waste can lead to flaming with disastrous consequences for the environment. A good example is a 1990 fire that occurred in an underground dump site of tree stumps that affected the environmental conditions over Baltimore, the mechanisms leading to the development of that fire are still unclear but can be traced to smoldering tree stumps.

Smoldering of upholstered furniture has been a subject of numerous studies. In most cases full scale tests have been conducted to determine the burning characteristics of different materials used in furniture. Early work conducted by Hafer and Yuill [7] showed that smoldering of upholstered furniture under many different configurations and environments could lead to lethal conditions in less than 2 hours. Thirty tests were conducted with beds and upholstered chairs using various combinations of materials and ignition sources in a closed test chamber with realistic leakage. Ignition characteristics for different sources, cigarettes (one, two or three), matches and methenamine pills were recorded. The different hazardous conditions resulting from smoldering, smoldering that transitions to flaming and flaming ignition where determined by means of temperature, light obscuration, CO, CO_2 oxygen and selected noxious gases measurements. This work provides a survey of the different issues involved in realistic smoldering fires and addresses in a comparative way the hazards involved in flaming and smoldering. Following this work a series of large scale tests were conducted concentrating on issues such as flame spread [8], fire retardants [9], time to flaming ignition and flash-over [10] and the influence of ventilation on burning upholstered chairs [11]. These studies address the issue of smoldering but they concentrate mostly on flaming ignition. The results, although relevant when addressing the hazardous aspects of smoldering, have provided very little insight to the fundamental understanding of this particular combustion process.

Large scale tests are generally dependent on the specific experimental conditions therefore Hafer and Yuill [7] recommended the development of a small scale test to rate bedding and furniture with respect to the degree of fire hazard. Following this recommendation Rogers et al. [12] studied, by using a standardized small scale sample, the ignition of upholstery containing polyurethanes and cellulose based fabrics. It was observed low intensity heat sources and prolonged exposure favored ignition. This combination leads to charring as opposed to tarring and ensures in-depth heating of the poorly conductive foam. It was noted that most polyurethanes do not smolder readily needing, in most cases, a cover fabric that is itself capable of smoldering. High permeability and large surface area were deemed necessary to ensure sufficient oxygen supply and positive net heat flux from the reaction to the environment. It was emphasized that total inhibition of external (buoyant or forced) air inflow results in extinction, however, the oxygen supply necessary to support smolder is surprisingly small. Further information on insulation and buoyant air entrainment needed for ignition of a smoldering reaction was provided by Cantwell [13]. Cantwell [13] used cotton layers to and a hot nichrome wire to ignite a polyurethane foam sample. It was observed that the cotton layers provided insulation to the reaction and breaking the ash layer (left by the burning cotton) will result in extinction. To increase the insulation effect, the number of cotton layers was increased but the result was again extinction. By using a laser sheet to image the flow at the interface it was qualitatively determined that air entrained by buoyancy, through the cotton linen, was necessary for a succesfull ignition process. The cotton layers provided insulation but also blocked the passage of air towards the smolder reaction in the polyurethane foam, resulting in competing effects. It is important to note the dominant role of buoyancy in this process.

The idea of a small scale test to asses the flammability of upholstered furniture was further developed by Gann et al. [14] who used a bench scale test coupled to a numerical model to rank the potential of different cigarettes to ignite upholstered furniture. This work provides an extensive review of the different studies related to smolder ignition of upholstered furniture. The study conducted by Gann et al. [14] was motivated by the "Cigarette Safety Act of 1984" which encouraged the modification of cigarettes to have a minimum propensity to ignite upholstered furniture or mattresses. Thus, the main focus is on the statistical determination of the parameters that will have an effect on the interaction between a burning cigarette and a material representative of upholstered furniture. Full scale tests are successfully compared with three different bench scale tests (flat configuration, cigarette in a crevice, cigarette in a crevice with a welt cord) in an attempt to establish a protocol that will allow to rank the cigarettes under conditions more controlled than those of full scale tests.

Although not the main objective of the study by Gann et al. [14], an important contribution of this work is the development of a semi-empirical model that predicts the heat flux and heating zone of a cigarette (both functions of the smolder velocity) and its effect on the ignition of a substrate (upholstered furniture). To model the heat flux from the cigarette it was deemed necessary to determine the maximum surface temperature and the propagation velocity of the smolder reaction. The smolder velocity together with an average net heat of combustion provides the total heat released by the cigarette and the maximum surface temperature allows to differentiate what fraction of the total heat released is heat convected from the cigarette towards the substrate.

Empirical data and modeling assumptions of Muramatsu [15,16] were used to obtain the smolder velocity and the heat of combustion. It was noted that, the model predicted well the smolder velocity, the maximum temperature and their dependencies on the cigarette radius, packing density and moisture content, but significant discrepancies observed between the experimental and calculated dependencies of the maximum temperature and smolder velocity on the oxygen partial pressure. This discrepancy precluded the authors from using the maximum temperature, as given by Muramatsu et al [15,16] to calculate the heat flux from the cigarette to the substrate instead they use a linear fit of the experimental data provided by these authors together with their own experimental data. The shape of the heat source is assumed to be fixed but moving at a constant velocity which corresponds to the smolder velocity predicted by Muramatsu et al. [15,16]. A detailed numerical model (CIG25) was presented as an alternative to the above approach but it was not used to study a smoldering substrate due to the complexity of its implementation.

The interaction between the cigarette and the substrate is very complex. Cigarette and substrate exchange heat, compete for oxygen and condensation of the combustion products (i.e. water) on either can change the net heat flux between cigarette and substrate. It was noted that experiments show that this complex interaction results in a decrease of approximately 17% in the burning rate of the cigarette. This empirical value was used in the model to evaluate the net heat flux of the cigarette towards the substrate.

The substrate is modeled as a semi-infinite solid with an exposed surface where the net heat flux is the balance between the heat source (cigarette) and the heat losses (convective and radiative). The lack of an analytical solution for a moving source forces the authors to resort to a numerical solution. The numerical solution to the substrate problem was coupled to both the semi-empirical representation of the cigarette as extracted from Muramatsu et al. [15,16] and to the CIG25 code obtaining very similar results when tested with an inert substrate (calcium silicate insulation). The results obtained did not correlate well with the experiments but the importance of this work relies mainly in the methodology. The work of Gann et al [14] provides the first attempt to model a realistic smoldering ignition scenario, it addresses the adequate issues and identifies the appropriate variables. To the knowledge of the authors, no follow-up to this work was made.

The last review that treated smoldering as a fire related problem was written by Ohlemiller [1] who summarized the issues that relate smoldering with fires. The paper provides a comprehensive overview of the relevance of smoldering to the fire problem but it does not provide a detailed description of the existing work on the subject. Previously, Quintiere et al.[2] had compiled all smoldering fire experiments conducted in closed rooms and buildings. The experiments reviewed included only those conducted in closed rooms or rooms with realistic "leaks." The fire scenarios attempted to be realistic therefore mattresses, chairs, blankets where used as fuels and ignition was generally accomplished by means of cigarettes. The materials involved where mostly polyurethane foams and cellulosic materials. The main objective of this work is to provide a hazard criterion for smoldering fires. Three different elements are isolated as being the controlling parameters of that determine the level of risk of a smoldering fire:

- **CO Production Rates** - CO appears to be the principal hazardous agent of smoldering fires, with other products generated only increasing the hazard. Exposure to CO results in the formation of carboxy-hemoglobine (COHb) which displaces oxyhemoglobine from the blood starving the body from oxygen. Quintiere et al [2] used two different integral exposure levels, a 4.5% - min. and a 18%-min., as being critical life threatening conditions. It was noted that 42% of the experiments attained the 4.5%-min. exposure level and 10% the 18%-min. threshold before transition to flaming occurred. This integral exposure levels are well accepted criteria that determine hazard (4.5%-min.) and incapacitation (18%-min.). Quintiere et al. [2] added that life threatening conditions occurred always in the first 200 minutes of the experiment with most cases in the 50-150 minute window. The experiments and proposed model showed a weak influence of the room volume on the time to attain a critical dose.

- **Smoke Movement** The energy released by smoldering fires is very small compared to flaming fires, therefore cooling represents a significant factor in smoke movement. As the gases cool they will not be driven by buoyancy and tend to follow the natural ventilation of the building. Quintiere et al. [2] use a model proposed by Zukoski [17] for a closed room with a small fire to correlate the data obtained from the smoldering experiments. The model seemed to predict well the time required for a close room to fill with combustion products but there is no guarantee that it will properly describe a real smoldering fire subject to the natural ventilation of a building. A later study by Hotta et al. [18] showed that heating a room ceiling caused a significant deflection in the smoke plume. A series of experiments with smoldering sources (cotton, beechwood) with different ceiling temperatures showed that a 2-3oC temperature increase at the ceiling stopped the penetration of smoke from the smoldering source. This work has a great impact in the area of fire detection since most smoke detectors are placed at the ceiling an rely on buoyant transport of the combustion products. Cooper [19] used the experimental results of Quintiere et al [2] and a mathematical model for simulating the environment in enclosures to address life safety in buildings under smoldering and flaming fire conditions. The model assumes that buoyancy drives the high temperature products towards the ceiling forming a thin stable stratified upper layer. It was noted that the model predicted well the behavior of the upper layer for flaming fires but in the case of smoldering the heat of combustion required for good agreement between experimental and model temperature distributions is an order of magnitude larger than those commonly found in the literature. The author does not make any further remarks on the validity of its assumptions but the results show again a strong lack of knowledge concerning weak plumes originating from smoldering materials.
- **Transition to Flaming** Once a smolder reaction transitions to flaming the heat release and CO production rates increase dramatically. The critical levels of exposure are attained in a

few seconds, therefore the time to flaming represents an adequate parameter to asses the risk of a smolder fire. Quintiere et al [2] showed that from all the tests reviewed 18% resulted in transition to flaming after the 4.5%-min. exposure level was attained, 42% transition to flaming before and 40% never transition to flaming.

The conclusions to the work of Quintiere et al. [2] point out the lack of quantitative information that will allow to predict the hazard of a smoldering fire. It is noted that the heat of reaction for smoldering is still not well documented. The heat release and the CO production rates are generally lacking and therefore adequate comparison between models and experiments is not possible. Of greater importance is that the event of transition from smoldering to flaming has been treated as a random event, therefore modeling has to ignore flaming when evaluating the hazard of a smoldering fire.

A different aspect of smoldering combustion as a fire related problem was addressed by Meacham and Motevalli [20], who studied the smoke produced by smoldering sources. The motivation of this work relates to early fire detection of smoldering fires. Meacham and Motevalli [20] used a scattered light detection instrument consisting of a Galium-Arsenide solid state laser as a source and photodiodes as scattered light receivers to study the effect of fuel location and angle of incidence on the intensity of the scattered light. The fuels used were rubber, cotton, Douglas-fir and computer printer paper, all burning in smolder mode. It was observed that the scattered intensity depended on the fuel and the relative location of the detector with respect to the smoldering source. According to Mie scattering theory the intensity of the scattered light and the angular distribution is a function of the composition of the smoke which tends to vary significantly from fuel to fuel [21]. As mentioned before, the plume originating from a smoldering fuel is weak therefore the smoke does not stratify in a homogeneously mixed layer close to the ceiling, as with flaming fires, instead smoke is randomly distributed throughout the chamber. This implies that the intensity of the scattered light will be dependent on the distance between the detector and the smoldering fuel. It was observed that the detectors placed at 20^o were the least sensitive to the fuel location. Meacham and Motevalli [20] conclude that there is a lack of pertinent data on particle size, number concentration and refractive index for smoke emanating from smoldering fires. The only significant work in this area is that by Mulholland and Ohlemiller [22] who characterized the smolder products of cellulosic insulation (wood fibers) by means of three parameters mass flow rate, number flow rate and size distribution. They observed that the average size of smoke particles emanating from the "fire scale" smoldering insulation was 2-3 μm which is an order of magnitude larger than particles common of flaming fires [23] and four times larger than particles from small smoldering cigarettes. It was noted that flaming fires produce solid particles with high optical absorption and C/H ratio, in contrast non-flaming fires lead to liquid droplet pyrolyzate aerosols that tend to coagulate in the plume. The large size of the aerosol from smoldering fires requires a significantly larger concentration to trigger ionization detectors, this conclusion served as a basis for Meacham and Motevalli [20] to choose a light scattering detection instrument for their study. Mulholland and Ohlemiller [22] also observed that the residual char left by a smolder reaction serves as a filter for the combustion products, therefore the mass flow of aerosol exiting the fuel decreases significantly as the smolder reaction propagates deeper into the sample. The study by Mulholland and Ohlemiller [22] shows that there are significant differences between the combustion products of smoldering cellulosic insulation and those typical of lamming fires and that the reaction front location together with the fuel permeability will determine the fraction of those products that will reach the surface. These findings are of great importance in the area of fire detection but the observations are limited to one single fuel therefore can not be generalized to all smoldering fires.

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