PHYSICS-BASED MODELING OF WILDLAND-URBAN INTERFACE FIRES

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Abstract

This paper addresses the development of a practical physics-based model for fires in the wildland-urban intermix. These fires arise when wildland burning invades the built environment. Fire models for ignition and spread must consider individual fuel elements of both vegetation and structures in order to assess fire risk of developed properties. Successful prediction of wildland fire spread has been accomplished through "operational" mathematical models based on empirical correlations for wildland fuels. They fail, however, when the fire spreads to the built environment where the empirical correlations no longer apply. Property owners and communities need guidance in managing the urban forest and built environment to decrease the risk of losses to wildfire. The Oakland and Berkeley Hills fire of October 21, 1991, and the Los Alamos fires of May 2000 are examples of community-scale fires that attracted national attention in the US. The potential fuel loadings for various land uses demonstrates that structures generally provide much higher loadings than wildlands do. While this comparison is useful, it could also be misleading since generally, not all of the potential fuel in either the wildland or the built environment will burn. Furthermore, often the time scales for ignition and the heat release rates for the wildland fuel and the fuel in the structures will be widely disparate, and these differences will influence both the spread rate of the fire and its persistence. Although the NIST computational model known as the Fire Dynamic Simulator (FDS) was developed to study building fires, its use is extended to study community-scale fires spread. The FDS model utilizes higher resolution data including the local topography, placement of buildings and vegetation, ignition and burning characteristics of fuels, and meteorological conditions to provide a time dependent simulation of fire spread in neighborhoods of structures and trees. The simulation requires quantification of fire effects, such as the burning characteristics of individual trees and buildings, that are not used in the operational models of fire spread. The burning of single fuel elements is quantified by large-scale laboratory fire tests and full-scale field burns

Background

The protection of structures in a community from destruction by fire is a national concern. Building codes and standards address the ways in which our communities can be built and the materials that can be used to reduce the threat of fire. Annually in the U.S. there are more than 300,000 fires that originate in homes. In addition, nearly 10 percent of the land and over one-third (42 million) of the homes in the U.S. today belong to the Wildland Urban Interface (WUI). The WUI is used to refer to both areas where housing abuts heavily vegetated areas (interface) and those areas where houses and vegetation are intermingled (intermix). If current trends in housing continue, the WUI will grow rapidly.

Experiments and case studies of WUI fires conducted by Cohen (2000) have shown that, under the conditions of these experiments, fuels, either vegetation or structures, within about 40 meters distance from a home constitute the major threat for ignition. At this “neighbourhood scale,” models and the computational resources are adequate to allow simulation of the details of fire behaviour. These models require detailed data on the topography, local meteorology, building layouts and elevations, three-dimensional distributions of natural fuels, and the material properties of both the natural fuels and the structures. Predictions include the major features of fire spread that threatens structures. The results can be used to understand the risk to communities on a property-by-property basis.

WUI Fuels

In the WUI, structures and vegetation are intermixed and their 3D distribution must be taken into account. As both the duration and intensity of burning structures is much greater than for vegetation, WUI fires cannot be studied accurately as a type of 2D fuel bed through which fire spreads. Furthermore, the intense burning of WUI fires cannot be characterized as burning along a line or boundary. WUI fires are area fires in which structures can burn independently from the vegetation. Figures (1a, b) show respectively a damaged area from the Oakland Hills, CA fire and burning during the Summerhaven, AZ fire. In both fires, it is obvious that trees and structures ignite and spread fire differently. In some areas homes burn while surrounding trees are uninvolved. The fact that it is common in WUI fires to find homes totally destroyed adjacent to vegetation that is untouched illustrates the complicated nature of the WUI fire events.

Only two references were found that discuss substantive technical issues related to wildland and community fires (Maranghides 1993) and (Chandler et al. 1983). Maranghides attempts for the first time to combine analyses of ignition and spread of a fire in a vegetation fuel bed, commonly employed in current operational models, with a model for ignition of a structure. This simple and interesting physics-based approach is found to be limited by a lack of data, a problem also discovered by the authors of the present study.

In the second (Chandler et al. (1983), Chapter 8 entitled, “Fire at the Urban-Forest Interface,” makes several very important observations. First, the authors note that fuel loadings in buildings are typically many times those in a forest: “the heaviest likely fuel load in the forest is less than the lightest load for a structure.” Next they observe that fuels in buildings include a variety of combustibles whereas forest fuels are exclusively cellulosic. The authors also point out several important differences between burning in a structure and burning forest fuels. Moisture, which is a very important factor in ignition and burning intensity, is controlled within a building, but is determined in wildlands by environmental factors such as the sun, wind and precipitation. Radiation from an indoor fire is trapped inside the building whereas most radiation in a wildland fire escapes. Similarly, most convective heat is trapped in an indoor fire whereas it is lofted into the atmosphere in a wildland fire. Finally, oxygen is severely limited in an indoor fire whereas it is virtually unlimited in a wildland fire.

The first point concerning the potential fuel loading differences between structural and wildland fuels is illustrated in Figure 2. In this figure, land use has been divided into four basic categories: wildland, rural, suburban and urban. The number of structures per hectare is plotted as the abscissa, and the ratio of the estimated vegetation energy load to the structure energy load is the ordinate. In this diagram, wildland covers the upper left corner of the diagram, where the number of structures is small and the vegetation energy load is relatively high, whereas the urban area occupies the lower right corner. Also shown on this plot are several fires for which we estimated, from information available, the potential energy load per hectare where the fires did their greatest damage to the built environment, whether the fires began there or elsewhere. Note that the Oakland Hills fire of 1991 and the Los Alamos/Cerro Grande fire of 2000, fall directly in the category of suburban fires and are good examples of community-scale or wildland-urban interface fires. Greater details about this analysis are available from (Rehm et al. 2002).

In the suburban and urban setting, the key quantity is the density of houses -- together with the combustible material in these houses -- in determining fuel loading and fire behavior. The density of trees, shrubs and ground cover (grass) may still be important for determination of the fire behavior, but clearly house density as a fuel is critical.

An estimate of the heat release rate (HRR) during a house fire in the Oakland and Berkeley Hills fires was made by Trelles (1995) and by Trelles and Pagni (1997). According to these estimates, a house burns at a peak rate of 45 MW for 1 hour (yielding about 160 GJ), and then dies down over another 6 hour period. The die-down of the fire is approximated as two steps, one 10 MW for 3 h and the last as 5 MW for 3 more hours. The total burn time is 7 hours, and the total energy released by the house is 324 GJ. If, as assumed also, there is brush around each house which releases another 5 MW for one hour, then an additional 18 GJ of energy will be released. If the house is assumed to be 15 m by 15 m by 5 m, then we estimate the total potential fuel loading per unit area to be of order 1.44 GJ/m^2, the peak HRR per unit plan view area to be of order 0.20 MW/m^2, the HRR per unit exterior surface area to be order 0.08 MW/m^2 and the volumetric HRR to be of order 0.04 MW/m^3.

For comparison Figures 3a and b show the burning of a small (6.2 m by 5 m by 2.5 m) wood frame out building in Odenton, MD ignited by burning vegetation. Measurements of the total heat flux were made 16.6 m from the building. Assuming uniform hemispherical heat flux and 30 percent radiative fraction from the fire a preliminary estimate of the total heat production of the fire was calculated. From this analysis of the data, the building fire was found to produce a sustained HRR of nominally 23 MW ± 7 MW estimated uncertainty for 5 minutes. Using that value, the peak HRR was

0.74 MW/m^2 per unit plan view area; 0.26 MW/m^2 per unit exterior surface area; and 0.30 MW/m^3 per unit volume. These peak values are much greater than the values for homes cited in the study of the Oakland Hills fire, but the fire duration is much shorter.

The widely different burning characteristics of petroleum based home furnishing materials (shingles, foam, plastics and synthetic fabrics and carpets) compared to wood materials can change the characteristic HRR for a home by an order of magnitude. Chandler et al (1983) describe the concept of an "ideal" burning rate, which was first introduced by Tewarson and Pion (1976). The "ideal" burning rate is the rate at which the energy required to produce a unit mass of fuel gas is equal to the energy released by burning the fuel gases in air. At the "ideal" burning rate, energy lost from the burning surface equals that supplied from the flame and other sources. Tewarson and Pion (1976) tabulate the ideal burning rates for several fuels. Liquid hydrocarbons have ideal heat release rates per unit area ranging between 0.7 and 3.0 MW/m^2. The corresponding rate for wood is about 0.26 MW/m^2.

The fuel-bed burning used in operational models suggests the use of the plan view area basis for comparing the burning of structures and wildland fuel. However, characterization of burning structures for WUI fire modeling remains to be resolved.

WUI Fire Model

For wildland fires, mathematical models are regularly used to predict the likely burn development for expected meteorological conditions. These models, which are known as operational models, have largely developed through empirical correlations over the past few decades. In the United States, they include the Rothermel model, (Rothermel 1972), and models known as BEHAVE, (Andrews and Bevins 1999), and FARSITE, (Finney and Andrews 1999), with the last one being the most recent and most highly developed.

Generally, these operational models have served well as long as the fires are confined to wildlands. They are based on the assumption that the fuels can be represented by continuum 2D beds, which may be inhomogeneous and anisotropic, but nevertheless are continuous. Thus these models can address horizontal variation of fuel beds, but cannot address 3-dimensional structure of fuels. Fire spread to buildings and transitions from ground to crown fires are among the fire phenomena that cannot be analyzed using these models.

When the built environment becomes involved in a fire, as in the Oakland and Berkeley Hills fire of October 21, 1991, or more recently the Los Alamos fires of May 2000 and Summerhaven, AZ of June 2003, these operational models are ineffective. The operational models cannot predict the spread of fire because the building fuel loads are larger and discrete. In these community-scale fires, buildings, as well as large individual trees, must be regarded as discrete fuel elements. At a fundamental level, the physical mechanisms controlling fire spread are very different than those in wildland fires. The empirical correlations upon which the wildland-fire models have been developed are no longer valid. No validated predictive models of fires in an urban or urban/wildland setting exist to our knowledge.

Over the past 25 years, the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) has been developing a physics-based mathematical and computational model, the current version known as the Fire Dynamics Simulator (FDS), to predict fire spread in a structure. Over the past few years, it has also been used to predict smoke and hot gas plume behavior produced by outdoor fires. FDS is well documented and is widely used by fire protection engineers around the world. BFRL is extending the model to include fire spread from structure to structure and generalizing FDS to include a means to predict fire spread in both continuous and discrete natural fuels. The current model, as well as its generalization, is both computationally and data intensive. For any specified region to be modelled, high-resolution, three-dimensional data to describe the geometry, fuels, and the ignition and burning characteristics are required. In addition, more recently, it has been used to predict wind fields in the built environment with one to ten meter resolution over regions measuring up to one kilometer or so on a side. All of these simulations require only a current high-end PC running overnight. The code can be downloaded free of cost from the URL: http://fire.nist.gov. It consists of two components, a computational fluid dynamics (CFD) code, called FDS, written in Fortran 90 for computation of fire-driven flows, and an OpenGL graphics program known as Smokeview for visualization of results, see (McGrattan et al. 2000), (McGrattan and Forney 2000), and (Forney and McGrattan 2000).

A second fire modeling effort for wildland fuels alone is underway at the Los Alamos National Laboratory under the direction of Dr. Rodman Linn (2002). Both models can address the 3D structure of fuels. Linn's model is currently being used to understand fire behavior in wildland fuels. Both models will need extensive 3D data on the properties of wildland fuels in order to calibrate and validate the model assumptions.

FDS has been used to construct a simulation of burning and fire spread in the WUI that is useful for analyzing the fire hazards associated with a structure and its surroundings. In FDS, structures and vegetation must be characterized as separate fuel elements with individual ignition and burning properties. As each element in the model can be modified, the value of actions taken by owners or land managers to reduce hazards can be analyzed. It is expected that when properly validated, using data yet to be obtained, FDS will be able to duplicate the well known fire spread characteristics in ground fuels, but will also have the capabilities of quantifying transitions of fire spread between fuel types. This includes the phenomena of transitions from ground fire to tree-crown fires as well as ignition and burning of structures intermixed with vegetation. Such a tool will be of value to community planners, building code authorities and firefighters.

The capabilities of the FDS model can be demonstrated by an example. Figure 4 shows a series of frames from an FDS simulation of fire spread on a parcel of land. These frames were obtained using the Smokeview visualization software, also developed at NIST. Four structures, many trees, and shrubs have all been included in this simulation. It can be seen that simulations of fire events on the “neighbourhood scale” are now possible. For the simulation, ignition and burning characteristics for each of the fuel elements – ground surface, shrubs, trees and the homes were selected. The selection of these properties was guided by experiments and other experience. From a single ignition point, the model predicts where and how rapidly the fire will spread. It considers heat transfer by convection and radiation, sensible and latent heat of pyrolysis absorption by material, ignition conditions for materials, the consumption of mass by burning, smoke generation, smoke blocking of radiation from fires, and the effect of wind. Fire spread by brands is not included in the current model. It is known that structures have a greater ignition delay time and total burning time than wildland fuels. The long burning structures distributed over an extended area produce plumes that can substantially change the wind patterns and therefore the spread of the fire front at some distance from the structures (Trelles and Pagni 1997).

Even though the graphical representation of the result is realistic, it should be remembered that underlying the pictures at every position (to the limit of the cell size in the computation) the gas and surface temperatures, gas velocity, heat flux, and materials burning can be quantified for each time step in the simulation. There is an enormous amount of detailed information available from the model. It is common to view the results as computer generated simulations and gain insight from the viewing as one would from seeing an actual fire event.

The “neighbourhood scale” fire simulations using FDS have the capability to provide authorities with insight about the fire safety in communities. The simulations can also be used to assess the impact of changing local regulations. The physical science basis for the FDS model provides confidence that even without the benefit of comparison with full-scale urban fire experiments, it is capable of providing relative quantitative results between alternatives and accurate predictions of trends.

Conclusions

Through the capabilities to simulate the major features of WUI fires, we are beginning to develop an understanding of the mechanisms by which fires progress in a community where both structures and wildland fuels exist. Except for investigations of actual community fires, we have not previously had a technology that was capable of providing the fire safety insight that can be obtained from physics-based, high temporal and spatial resolution simulations. Many fire-properties of vegetation and structures remain to be measured in ways that permit the description of the ignition and burning of individual trees, shrubs, and structures. All methods of fire propagation, including spread by brands, need to be quantified to build a complete and accurate model of the WUI fire. Available experimental data for fire spread can provide a basis for evaluation and validation of the high-resolution fire models.

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Figure 1a. Spotty damage to homes and vegetation at the periphery of the 1991 Oakland Hills fire area.

Figure 1b. Homes in Summerhaven, AZ burn amid tall trees during 2003 Aspen fire. (Photo Courtesy of KTVK NewsChannel 3, Phoenix, Arizona)

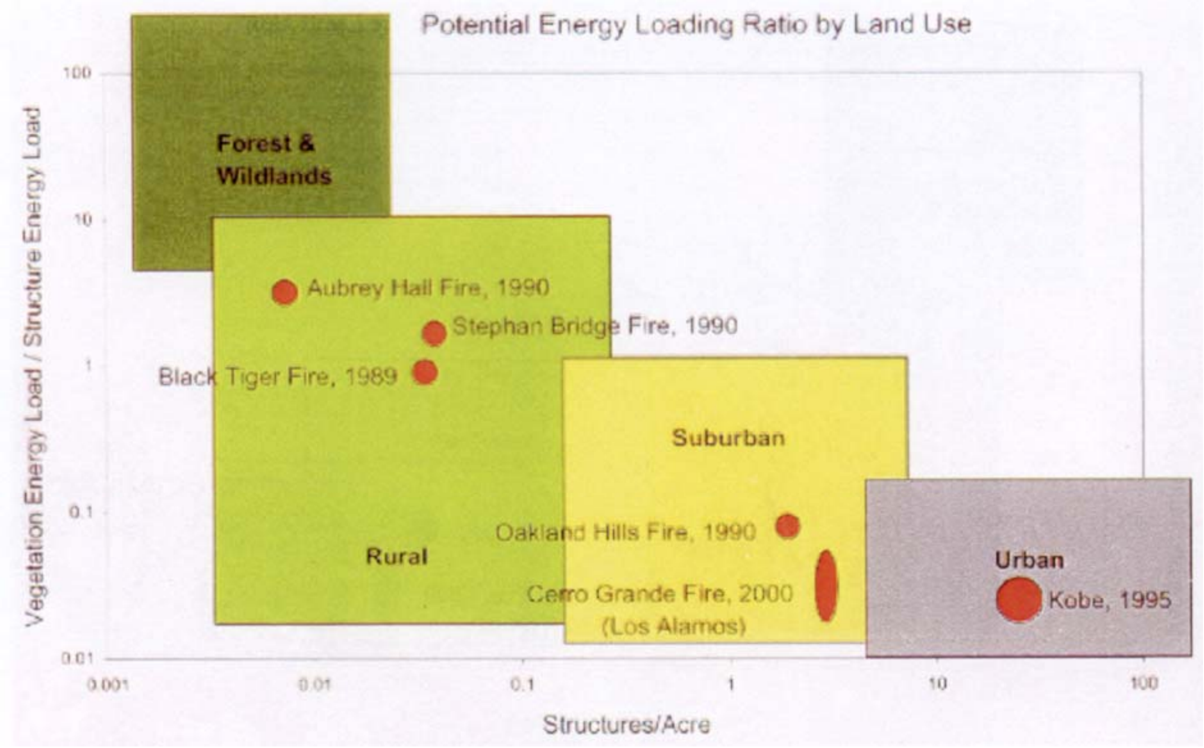

Figure 2. Potential energy loading by land use. Also shown are six specific fires including the Oakland Hills fire of 1991 and the Los Alamos/Cerro Grande fire of 2000.

Figure 3a. Small building ignition

Figure 3b. Full involvement

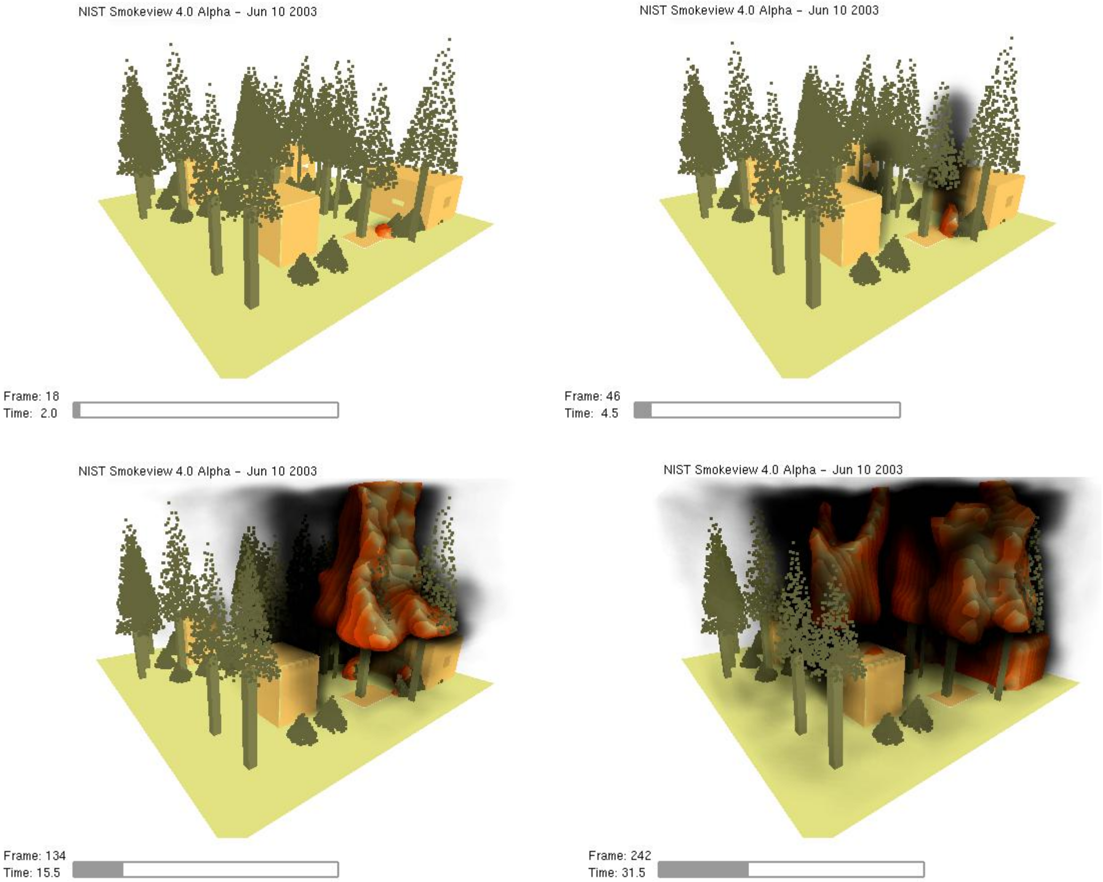

Figure 4 Selected frames from FDS / Smokeview simulation of “neighbourhood scale” fire spread from a single ignition. The fire spreads from ground fuels, through ladder fuels to the tree-crowns. Structures are ignited by heat flux from the burning vegetation.