5.3 IMPROVED MODELS OF FOREST AND WILDLAND-URBAN-INTERFACE FIRES

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1. Introduction

In 1997, Frank Albini [1] presented a talk entitled, "An Overview of Research on Wildland Fire," at the Fifth International Symposium on Fire Safety Science, Melbourne, Australia. The attendees, members of the International Association for Fire Safety Science (IAFSS), were mostly engineers and scientists concerned with fires in structures and included the first author of this paper! In his talk/paper, Albini discussed a much wider variety of issues than we do here. We discuss only issues related to conceptual and mathematical model development, and experimental validation of these models. However, for these issues, quotes from Albini's paper demonstrate the differences between the wildland-fire and the structure-fire communities, and, unfortunately, how little progress has been made in communication between these communities over the past ten years!

Albini is justifiably regarded as an intellectual leader in the wildland-fire community, and many of his papers were published in journals regularly read by members of the structure-fire community! Therefore, his 1997 talk is taken seriously by both communities. The present paper could be regarded as an attempt to update Albini's original assessment of the status of fire modeling.

In the next section of this paper, we review the research and development of conceptual and mathematical models of fire in the structure-fire community, in which we have been active. This development includes both verification by analytical procedures and validation against experimental and empirical evidence. We then turn to the development of wildfire models, with the expectation that the lessons learned during these structure-fire model-development efforts might encourage a similar development process within the wildland-fire community!

2. A history of models for structure fires

Early studies on modeling fires included scientific and engineering leaders known for their expertise in heat transfer and fluid dynamics, such as Hoyt Hottel, Geoffrey I. Taylor, Phillip Thomas and Howard Emmons. Each contributed technical insights and historical perspectives on fire research during its formative years in papers published in the Proceedings of the First International Symposium on Fire Research, sponsored by the National Academy of Sciences - the National Research Council, and held in Washington, 9-10 November 1959. The published volume of these proceedings was entitled, the "International Symposium on the Use of Models in Fire Research," which is remarkable because it appears to be the first and *only* symposium emphasizing the use of models in the conduct of fire research! The papers in this volume connect mathematical modeling and fire research in various application areas technically and historically. Contributors include scientists/engineers from the U.S. Bureau of Mines, the U.S. National Bureau of Standards and the U.S. Forest Service, as well as university and government researchers from England, France, Canada, and Japan, with interests in wildfire as well as structure fires!

In his description of the stimulation of fire research in the United States after 1940, Hottel [2] helps explain the current the fragmentation of fire-research activities remaining today. The penultimate statement in this paper suggests the difficulty of the subject; Hottel states: "A case can be made for fire being, next to life processes, the most complex of phenomena to understand."

Another paper in this volume by Thomas [3] reviewed the early developments in the modeling of fires in compartments. He distinguished fire from combustion by noting that combustion systems have taps for the observer to control the continuous supply of fuel and air. Fire, on the other hand, has no such taps and allows for (or, in fact, requires) positive feedback between the essential components of fire: HEAT, FUEL, and OXYGEN. Thomas illustrated this distinction by invoking the so-called "fire triangle," an early and often-used schematic diagram for fire, reproduced here in Figure 1. The diagram labels the corners of this triangle as the three critical components of fire, HEAT, OXYGEN and FUEL. Two of the sides are labeled to show the interactions, or feedback between these critical components: the side connecting HEAT and OXYGEN is described as "Buoyancy-induced flow," while the side connecting HEAT and FUEL is described as "Thermal feedback to produce gaseous fuel." Thomas cited a 1964 paper by fluid mechanician B. Morton,

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who remarked on the ability of a fire to entrain its own air supply and to produce fuel vapors needed to sustain burning from the solid or liquid as essential characteristics of fire.

Thomas also discussed models in general, noting there are two types, scaled physical models and mathematical models. He defined the word "model," as a "'representation,' and, as in the visual arts, some representations are more complete or more idealized than others: neither an engineer's nor an architect's drawing is a complete representation but they allow certain purposes to be fulfilled and certain conclusions to be drawn." Alternately, Marc Kac, the famous New York University applied mathematician, described a mathematical model as a caricature. If well done, even a very simple caricature can be recognized immediately. Similarly, a mathematical model can be simple or complex, but captures the essence of the phenomenon being modeled! In Figure 2, three caricatures of a house are drawn; each can be recognized immediately as a house. But the level of detail increases greatly from right to left in the diagram, illustrating a second import feature of a mathematical model; more elaborate models are required as more detailed questions are asked about the phenomenon!

The early modeling of fires in structures progressed by the study of fires in compartments, where many of the processes can be approximated for engineering purposes by submodels that are connected through the laws of conservation of mass and energy. Because each submodel occupies a region or zone of the compartment, these models have become known as "zone models." The models acquired predictive value because each submodel could be calibrated and validated using data from laboratory experiments, they were computationally tractable based on the computational resources of the day, and they satisfied the conservation laws.

Significant progress modeling compartment fires began during the 1970s. One of the earliest studies was reported in two parts in 1972 by Harmathy [4]. An important series of studies of compartment fires was presented by Quintiere [5]-[9], beginning in the 1970s and culminating in a review in 1984. Quintiere [10] subsequently published a general, clear and useful textbook entitled, "Principles of Fire Research," in 1997. Other relevant studies were reported by Friedman [11] and Thomas [12]. A very useful general text on fire dynamics, culminating in a summary of the state of zone modeling of compartment fires is "An Introduction to Fire Dynamics," by Drysdale [13].

A fire in a compartment is generally regarded to evolve in the following fashion. First there is ignition, and then growth and spread of the fire in the compartment. The fire acts as a pump, taking ambient air and combustion products, heating them and pumping them into an upper layer, which first forms and then fills the room from the top down. Openings, such as windows and doors, allow the heated air and combustion products to escape and fresh air to enter, often establishing a period of nearly steady-state burning in which the fire pumps smoke and hot gases out and draws fresh air in through the openings. It is during this period that the mmodeling Finally, the whole compartment seems to be consumed in flames, a process known as flashover, and, while it may continue to supply smoke and hot gases to spread the fire elsewhere, the contents of the compartment, including the compartment itself, is regarded as lost.

In compartment fires, there is often a time during which a nearly steady-state fire burns, pumping smoke and hot gases out and drawing fresh air in through the openings. Time-average patterns of the flow during this period can be described quantitatively by several parameters: the heat release rate (hrr) of the fire, the volume of the compartment, and the area of the openings (windows and doors) to the outside. The physical processes in various regions or zones of the enclosure are characterized by balances between different physical processes, and can be usefully and quantifiably approximated by submodels, which can then be connected into a model for the overall behavior of the compartment fire, known generally as a "zone model," see for example, Quintiere [10], Drysdale [13], Birk [14], and Jones et [15], for example.

This formulation of the zone model results in a set of discrete, nonlinear algebraic equations, while a slowly time varying (or quasi-steady) formulation results in a nonlinear, usually stiff set of ordinary differential equations. Both formulations can usually be solved by standard numerical methods. Practically, zone models satisfy the conservation of mass and energy, while conservation of momentum is discarded.

Alternately, models that start with mathematical statements of mass, momentum, energy and species conservation (the "field equations"), and are discretized for computer solution using the techniques of Computational Fluid Dynamics (CFD), are known as field models. The Fire Dynamics Simulator (FDS) of McGrattan [16], the Wildland-Urban-Interface Fire Dynamics Simulator (WFDS) of Mell and Rehm [17] and FIRETEC of Linn et al [**?**] are representative examples of the field-model approach (and of references); this approach is both widely known and widely used. We will not discuss this approach further here.

3. Importance of Models of Fire in Structures

First, Albini observed that while the interests of attendees, i.e "are focused mainly upon fire in manmade structures, many of its studies are relevant to, and applied in, modeling of wildland fire phenomenology. But the converse does not seem to be the case. Results of wildland fire research are seldom cited in the literature of fire safety research as it is done by this audience." He further elaborated on this asymmetry in awareness of the research of one group by the other, noting, "the learning burden in this process will probably be greater for wildfire specialists than for traditional fire safety science researchers because the latter group strongly favors mathematical modeling of physical processes while wildland fire research traditionally incorporates a significant component of empiricism, often only weakly supported by conceptual models of underlying physical processes."

While Albini discussed the importance and value of research and of understanding both wildland and WUI fires, he also cautioned that there are several pitfalls. For example, he stated that a major problem in the federal funding of wildland fire research arises because the subjects of fire effects and fire behavior compete for research funds. Since land managers, who are very influential in selection of the research projects and who are also expected to bring forth usable results in a timely fashion, research projects that rely heavily on empiricism are selected with fire effects greatly favored over those considering fire behavior. About wildland fire research, he further stated that, "I hope that in offering these snippets, I will offend as few of my colleagues as possible and entice as many new investigators as possible to this challenging, intriguing and poorly funded field of research." Apparently, these funding realities have severely restricted the development of physics-based mathematical models of wildfire behavior and almost totally eliminated research on WUI fire!

Finally, Albini noted that, "Interest by the general public in matters of wildland fire safety has grown with increased exposure of affluent society to the hazards posed by building flammable structures in flammable wildland settings." This quote is very important because it explicitly recognizes structures, if ignited, as part of the fuel system for the fire. The prevailing view regarding structures in land-management agencies seems to be that structures are surrounded by wildland fuel and isolated from other structures (see the schematic pictures in the recent GAO report cited below)! When a wildfire encounters an individual structure, the structure either resists the thermal insult, or it ignites. Either way, according to this way of thinking, the structure is no longer of interest for determination of the wildfire behavior. In contrast, by this statement, Albini recognizes explicitly that structures are part of the fuel system, and implies that the fire behavior with the structure included, will be different than the fire behavior without the structure!

The objective of this paper is to trace the history of physics-based mathematical modeling of fires in structures, with the hope that this progression might illuminate possible approximations that could be introduced to improve physics-based modeling of wildfire and/or WUI fires without resorting to a complete "field-model" description of these phenomena. Another way of stating this objective is to ask the question, "What would a generalization of the Rothermel model look like that was: (a) physics based, (b) more complex and detailed, than the Rothermel model, but not as complex, mathematically and computationally on the one hand and data-wise on the other, as a field model. Another way of stating these requirements is to ask what a follow-up, more physics based, model to that of the Rothermel model, would look like?

4. Structure-Fire Modeling and Outdoor Fire Behavior

Studies of CFD-based models of smoke transport and fire behavior developed by researchers in the structure-fire community have been described in reports, publications and at wildfire-community meetings. Some of these descriptions have included suggestions for the potential application of these models to smoke dispersion and fire behavior predictions in wildland and WUI settings. However, the magnitude of the effort and of the cost of extending these models and of systematically generating and/or collecting required input data for them continues to be a major deterrent to undertaking the required research and development. Despite significant success of these models in structural fire applications, they continue to be regarded by many as impractical and too computationally expensive.

Here we suggest an alternate, more simplified physics-based model (analogous to the zone models familiar in the structure-fire community), recognizing that the approximations made may seem very limiting at first, but that further development of these models is often made in subsequent studies.

A recent NIST report by Evans et al. [19] presented the results of an experimental study of the burning of individual Douglas-fir conifers of heights, 1.2 m, 2.4 m, and 3.7 m (4 ft, 8 ft and 12 ft). The purpose of these experiments was to examine the ignitability of an individual conifer, to measure the temporal behavior of the heat release rate once the tree was ignited, and to determine the scaling of the HRR as a function of tree height. To our knowledge, such a study had not been carried out before. For these experiments, it was found approximately that the HRR increased linearly with time to a peak and then decreased linearly to zero, yielding a nearly triangular HRR profile. The triangular HRR is characterized by two parameters, its peak and duration; the duration was found to be approximately 90 s for the burns in this study, whereas the peak was then the total heat released divided by the duration. Of course, the peak, duration and ignitability depend upon the moisture content of the burnable portions of the conifer, but the duration did not seem very sensitive to the moisture for the relatively dry trees in these tests.

Additional, as yet unreported, burns at NIST of nominally 4.9 m (16 foot), relatively dry confers seem to confirmed these general conclusions. Particularly, it was found that the burning duration remains on the order of only one to two minutes! However, as yet unreported, but also experimentally unconfirmed, simulations carried out at NIST of much larger burning conifers, 18 m (59 ft) and 36 m (118 ft), indicate that the burn durations could increase to 600 s (10 min) and 1400s (23 min) respectively, with peak HRR for both of about 60 MW, for Douglas firs of 30

While these latter results, if confirmed, could modify the arguments below, we will assume that burn durations for most conifers, if sufficiently dry, are of the order of a few minutes. If this statement is approximately correct, then the thermal coupling between individual burning conifers, on the one hand, and grass and structure fires on the other, whose duration is measured in hours, will be very small! By contrast, the thermal coupling between the grass fires and the structure fires could be substantial!

Below, we estimate the heat release rate (HRR) for a circular grass fire in the absence of wind using the empirical correlation for the rate of spread (ROS) of Australian grass fires determined by Cheney et al [20] and used by Mell et al [21] to compare with results from an effort to model these fires using computational fluid dynamics (CFD) techniques. Then we estimate the number of house fires required as a function of time to produce HRRs comparable to these circular grass fires. (In principle, it may also be possible later to determine an approximate 3D structure for each house-fire plume, again in the absence of any ambient wind, from previous analytical studies of Baum and McCaffrey [22], and these plume-wind fields can be superimposed to estimate the collective wind field generated by the grass and structure fires.)

The correlation of Cheney et al [20] for the grass-fire rate of spread (ROS) includes effects of both moisture and ambient wind on the ROS. If we assume low moisture and no wind for simplicity, the ROS is 0.165 m/s. Then a spot ignition yields a circular fire whose radius R grows linearly with time t as $R(t) = R_s t$, and for which the heat release rate H_r also grows linearly with time, $H_r(t) = 2\Pi R(t) R_s h w$, where, from Mell et al, $h = 15.6$ MJ/kg is the mass based heat of combustion, and $w = 0.3$ kJ/m^2 (to within ten percent for both values given by Mell et al) is the vegetative fuel loading. Therefore, approximately, $H_r(t) = 0.8t$ MW.

By comparison, Trelles and Pagni [23] estimated the HRR for an average house in the Oakland Hills fire, 1991, to have a time history yielding about 45 MW peak for 1 hour, 10 MW for 3 hours and 5 MW for 3 hours. Hence, according to the estimate above, the HRR for the circular grass fire after one minute is approximately equal to the peak HRR for one house. After the minute, the grass fire would have a diameter of about 20 m and cover an area of over 300 square meters. Furthermore, since the grass-fire HRR grows linearly with time, it would grow at a rate equivalent to having one additional house burning at peak rate added each minute.

While there are several caveats associated with this very simple analysis, it begins conceptualizing a WUI fire by comparing the HRR from a burning wildland fuel with the HRR from a structure fire,. One very important limitation is that it is assumed in both cases that there is no wind, and an ambient wind is known to enhance fire spread in either case. We believe that some useful and enlightening physics-based, but not CFD based generalizations of this simple idea could also be undertaken.

Finally, a very different physics-based and computationally oriented, but not CFD dependent, approach to crown fires has recently been published by Butler, Finney, Andrews and Albini [24]. It is based on many studies of Albini and colleagues, and is a good illustration of an alternate modeling approach which we are suggesting here. Their approach, while still fairly computationally oriented, combines several submodels to represent the overall process of crown-fire spread. Apparently, Albini still is attracted to this "challenging, intriguing and poorly funded field."

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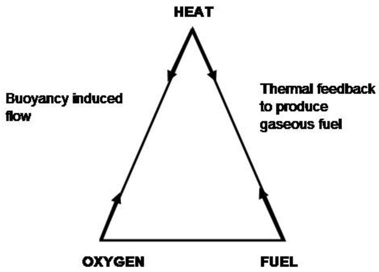

Figure 1: **Fire Triangle as shown by Thomas [12]. The arrows along each side go both ways.**

Figure 2: **Mathematical models are caricatures that capture the essence of the phenomenon of interest. They can be more elaborate (left) or less (right) depending upon the questions asked of the model and resources devoted to it.**