MODELING IGNITION OF STRUCTURES IN WILDLAND/URBAN INTERFACE FIRES

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ABSTRACT

With the Occurrence of large fire losses in the wildland/urban interface areas, assessing the fire hazard of structures that exist among the wildland fuels is necessary. A USDA Forest Service research team is developing a physics-based model to assess potential hazards of structures in given wildland fire scenarios. This model integrates a wildand fire module, a flame heat transfer module, and an ignition module. The model examines the major pathways that can lead to ignition: (a) pure radiative heat transfer from the flame (b) flame impingement, and (c) contact with burning brands. This paper describes the three modules of the model with special emphasis on the ignition module. The ignition module predicts piloted ignition of materials based on bench-scale ignition data. Model calculations showed that flame radiation from wildland fuel may not be the primary source of structure ignition. Laboratory experiments showed that flame impingement for sufficient length of time ignited wood materials but did not guarantee sustained burning after the flame source was removed. Additional research is needed to accurately model ignition that is due to burning brands.

BACKGROUND

With increasing presence of structures in the Wildland/Urban Interface (WUI) areas, the increasing loss of structures because of wildland fires becomes a national problem. Planners, developers, fire agencies, and home owners need a way to consistently assess the hazards to make decisions regarding fire safe construction methods, materials, site, vegetation clearance, and numerous other factors.

To minimize subjectivity and reliance on anecdotal experience, the Structure Ignition Assessment Model (SIAM) being developed uses a physics-based analytical approach as much as possible. The structure of SIAM has been described by Cohen et al.[1] and will only be discussed in general here. The structure of SIAM is outlined in Figure 1. Three modules make up SIAM: (a) a fire behavior module, (b) a heat transfer module, and (c) a structural response module. An additional module calculates the generation of burning brands and ignition potential based on brand classification and material susceptibility to brands.

Note that SIAM only addresses ignitability, not survivability. This decision was made because of the complexity of the latter. Survivability depends greatly on the logistics and suppression tactics at the time of the fire. The model does not deal with the human factors and simply views ignition as the essential criterion for structures to burn.

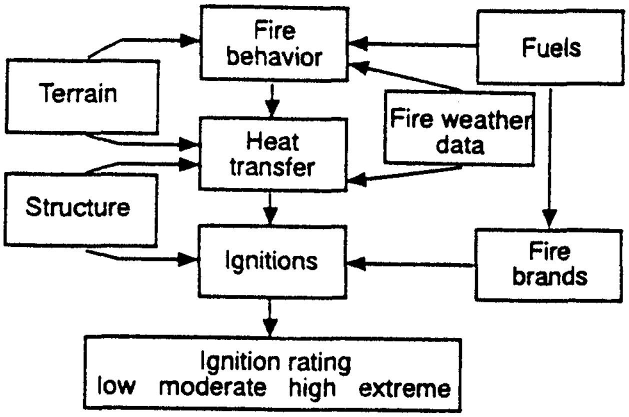

Figure 1 — The Structure Ignition Assessment Model (SLAM) process.

First the paper describes the physics used in the ignition module. The second part is an analysis of the importance of pure radiation from flame. The subsequent part considers flame impingement, and the last deals with the importance of burning brands and possible ways to model ignition by brands.

IGNITION MODULE

Ignition of materials in a fire is predominantly piloted ignition. Piloted ignition is defined in ASTM E 176 standard terminology as initiation of combustion as a result of contact of a material or its vapors with an external high energy source such as a flame, spark, etc.[2] The term piloted is used to distinguish this mode of ignition from smoldering and spontaneous ignition. The piloted mode of ignition is most prevalent in growing fires where the materials are heated by radiative and/or convective heat sources and ignition sources (flames, sparks) are present.

Piloted ignition of solids is a complex phenomenon because of many controlling factors. Some external factors are the heating history, orientation of the material, and dilution of the volatiles with entrained air. Internal factors include material thickness, thermophysical and chemical properties, and how they change as a result of heating.

The need to model fire growth within structures has spurred development of test methods to measure ignitability and calculation methods to relate ignition time of a material to its thermophysical properties and external factors such as heat flux. The data obtained from these tests can then be used to predict piloted ignition of materials.

Presently, there are three main approaches to predict piloted ignition. The first approach assumes a certain amount of energy must be delivered to the solid before it ignites. An example is the "heat soak" concept used by Smith[3] with data from the Ohio State University (OSU) calorimeter.[4] The second approach assumes an ignition temperature for each solid exists. Ignition occurs when surface temperature of the solid exceeds this critical temperature. An ignition and flame spread theory is discussed by Quintiere et al.[5] The theory is based on a thermally thick solid, and ignition occurs when surface temperature exceeds a calculated ignition temperature. The theory is used to deduce material properties such as thermal inertia, critical ignition flux $\dot{q}_{cr}''$ etc., from experimental data. Note that the ignition temperature calculated here! is theoretical and can be very elusive in experimental validation. The third approach assumes a minimum mass flux of volatiles from the pyrolyzing solid. This criterion for ignition is used in models that include kinetics of pyrolysis to calculate mass loss rate. Such a model was described by Parker.[6]

SIAM uses an approach similar to the first approach mentioned above for simplicity. The model uses correlation of ignition time t_{ig} with the imposing flux $\dot{q}_e''$ obtained from bench-scale tests. Ignition is then predicted based on the flux history and the established relationships. Most of the background work to develop these correlations was done in an effort to develop a compartment wall fire model. In this work, piloted ignition data were compiled from three different apparatuses: the Cone Calorimeter,[7] Lateral Ignition and Flame Travel (LIFT) apparatus, and the OSU apparatus used at the USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.*

Basically, the ignition tests involved holding a fixed radiant flux to a vertical sample. Time to ignition t_{ig} was obtained as a function of heat flux. There are various ways of correlating ignition time and heat flux. Janssens[9,10] compared several methods of ignition data reduction and proposed to plot $(1/t_{ig})^{0.547}$ versus the radiant heat flux. Different powers were found to be appropriate for different materials. For wood materials, Janssens method seemed to work quite well. Therefore, that method is adopted for data correlation here. For thermally thick materials, this relationship is found to be linear, as shown in Figure 2 with Douglas-fir plywood as the example. There was good agreement between the three apparatuses. Therefore, data from the three devices were pooled together. The regression relationship can be described in the form

$$(t_{ig})^{-0.547} = a\,\dot{q}_e'' + b \tag{1}$$

For Douglas-fir plywood, a=0.006006 and b=-0.0789 with an R^2 value of 0.97. The intercept of the regression line with the abscissa is the critical heat flux for ignition $\dot{q}_{cr}''$ which turns out to be 13.1 kW/m^2. For most wood materials, the critical flux was found to be around 12 to 13 kW/m^2.

It follows that for ignition at constant heat flux

$$(\dot{q}_e'' - \dot{q}_{cr}'')^{1.828}\, t \geq a^{-1.828} \tag{2}$$

Figure 3 shows a curve that describes Equation (2). The product of the coordinates of any point on this curve is equal to the constant on the right side of the equation. The area below the curve is no ignition zone, and the area above the curve is ignition zone.

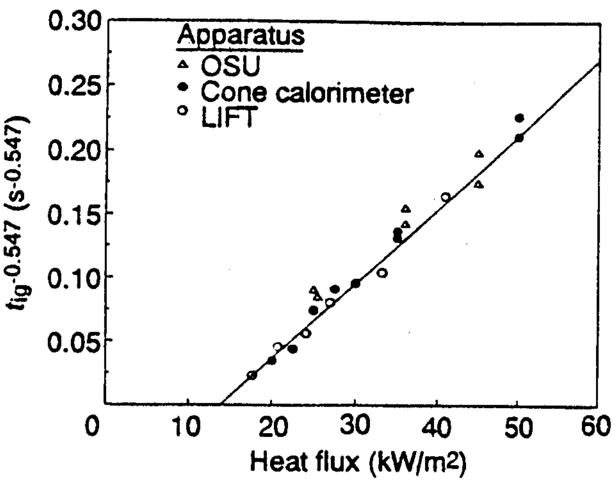

Figure 2–Piloted ignition data of Douglas-fir plywood. t_{ig} ignition time.

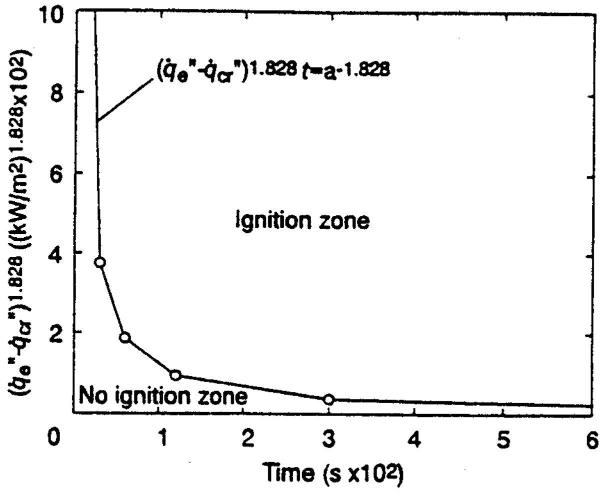

Figure 3–Heat flux criteria for ignition of Douglas-fir plywood. $\dot{q}_e''$ imposing flux, $\dot{q}_{cr}''$ critical heat flux, t time, a constant.

Using the heat soak concept that a minimum amount of energy equivalent to the constant on the right side of Equation (2) must be met for ignition to occur, it follows that ignition in the case of transient heat flux will occur if

$$\int (\dot{q}_e'' - \dot{q}_{cr}'')^{1.828} dt \geq a^{-1.828} \tag{3}$$

IGNITION FROM RADIATIVE HEAT TRANSFER

In the context of SLAM, the fire behavior model assumes that the fire will approach a structure from each of its sides. As the fire burns through the fuel bed at calculated flame front velocity, the heat transfer module will calculate the incident heat flux to the structure. A resultant flux-time history curve is then obtained.

The ignition module treats the two separately because they are not always additive. Except for the case of flame impingement, either radiative or convective heat transfer dominates at any one time. First, let us consider the case of pure radiative heat transfer.

Radiation from the flame is calculated as a function of flame height, depth, and distance to the structure.' The inherent assumption in SIAM is that the flame will start from the distance pertinent to each fuel type and approach each side of the structure at the spread rate pertinent to each fuel type. Let us consider an "extreme" case of a very large flame approaching a structure.

Vegetation fire information:

Flame length (height)	15 m
Flame depth	9 m
Fire line length	30 m
Spread rate	0.15 m/s
Flaming residence time	60 s

Structure dimensions: 4.9 by 6.1 m

SLAM calculation of radiant flux:

Time (s)	Distance (m)	Radiant flux (kW/m^2)
0	14	13.4
20	11	18.6
40	8	27.0
60	4.5	41.5

The flux and time history of this flame radiation scenario is compared with the minimum value of energy for ignition for Douglas-fir plywood in Figure 4. As shown, the radiative heat flux only becomes significant at a distance of 14 m, and the integral of flux history is barely adequate to ignite the plywood, even in this extreme case.

IGNITION FROM FLAME IMPINGEMENT

In the previous section, we looked at pure radiant heat flux to a surface. The SIAM model also considers cases where the flame convection column intercepts the structure. The model calculates that

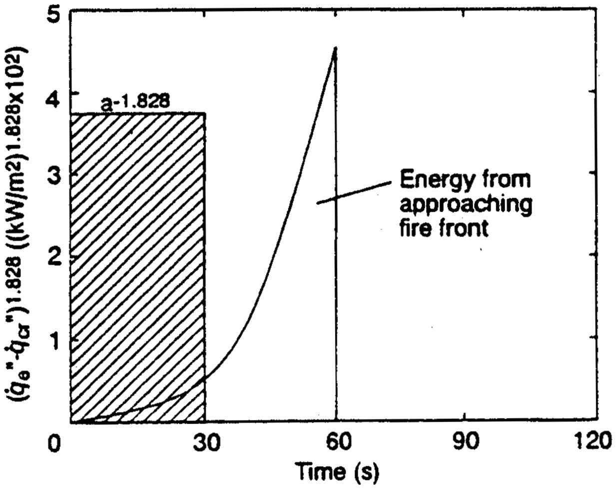

Figure 4– Heat flux criteria for ignition of Douglas-fur plywood. Example of a transient flux case. $\dot{q}_e''$ imposing flux, $\dot{q}_{cr}''$ critical heat flux, a constant.

$\dot{q}''_{cr}$ may be exceeded if there is flame impingement. To get a feel for ignitability of wood materials when exposed to flame impingement, a set of laboratory experiments were done in which mock wall sections were exposed to a propane flame from a burner. A commercial hardboard siding with a thickness of 11 mm and an ovendry density of about 620 kg/m^3 was used. It was factory prefinished and coated with an off-white primer. The material was conditioned prior to the tests to obtain a moisture content of about 9% in all tests.

Bench-Scale Tests of Siding

A series of bench-scale experiments were conducted to characterize the hardboard siding material in terms of ignitability and rate of heat release. Samples were tested in the OSU apparatus and also in a LIFT apparatus. Ignition time as a function of flux for this material is given in Figure 5. Ignitability data seem to be apparatus dependent. Heat release rate obtained with the OSU apparatus at three levels of heat flux is given in Figure 6. Based on our experience, the ignitability and heat release rate of this material is rather typical of wood products.

Wall Tests

Sections of walls covered with the same hardboard siding were exposed to a square burner source adjacent to the wall. The burner is constructed as a sand box with a 0.305- by 0.305-m sand diffusion area, and the top of the burner is 0.305 m above the floor. Propane (at least 99% purity) was metered to the burner to produce two burning programs: Program A, 40 kW for a duration of 10 min and Program B, 160 kW for 2 min. The burner was placed with one side flush against a vertical section of a wall. The wall and burner assembly were placed under a collection hood that is part of the Forest Products Laboratory room fire facility.'' The hood and duct assembly were already instrumented to measure heat and smoke release rate. A schematic of the wall and burner setup is shown in Figure 7.

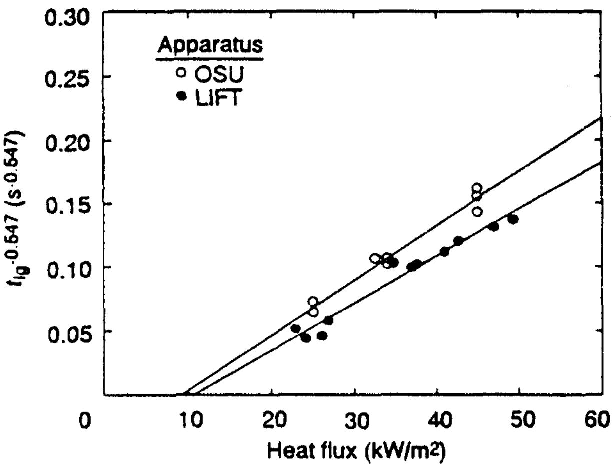

Figure 5–Ignition data of hardboard siding. t_{ig} ignition time.

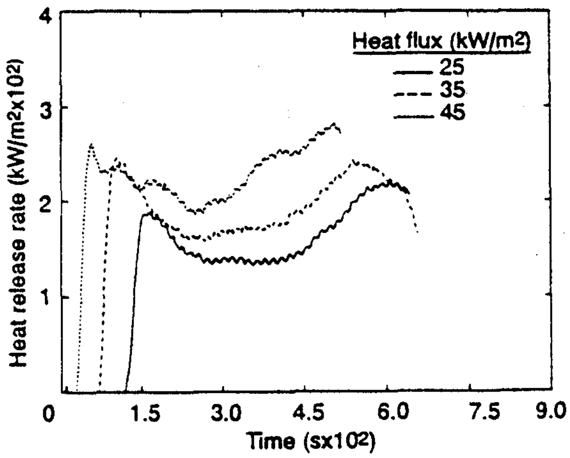

Figure 6–Heat release rate of hardboard siding.

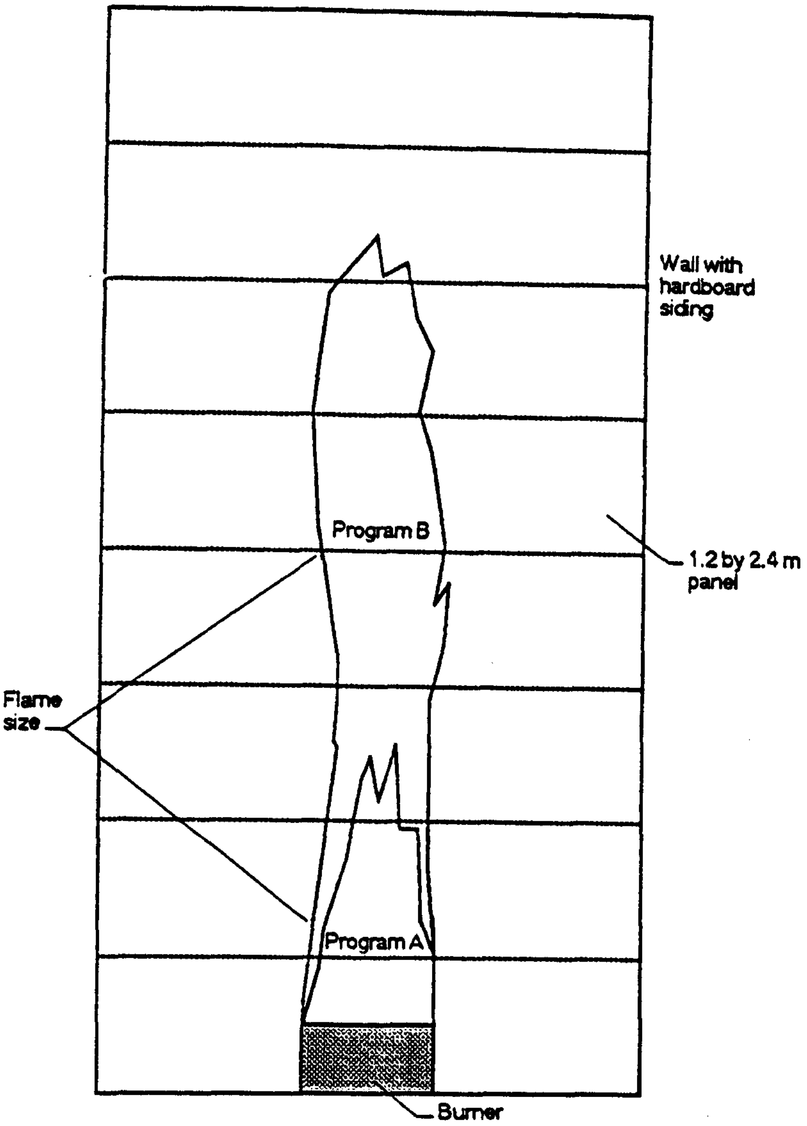

Figure 7 — Experimental setup of wall tests. Burner Programs A and B shown.

Four tests were carried out as a 2 x 2 matrix with two burner programs and two siding configurations. The siding material (0.3 m wide) was nailed to plywood panels to form either flat or lap siding. In case of the lap siding, the reveal was 0.25 m. The measured heat release rates including that from the burner flames from the four tests are shown in Figure 8. In all cases, the wall fire self-extinguished after the burner flame was turned off. A fan was turned on after the flame extinguished to force air into the still-hot surfaces to observe any kindling effect by wind. Some descriptive observations of the tests are given here:

Test 1. Burner program A, flat siding. The area behind the burner ignited at about 1 min. There was a very small amount of upward and lateral flame spread. When the burner was off (10 min), flaming ceased. Upon exposure to wind caused by the fan, smoldering combustion accelerated and eventually ignited the plywood substrate.

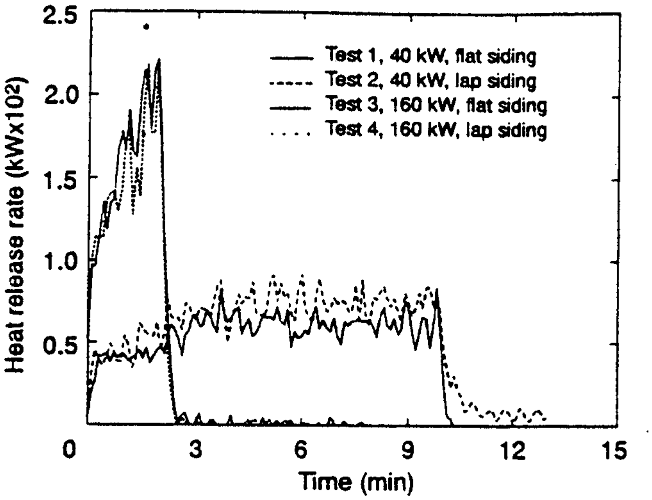

Figure 8—Heat release rate from hardboard siding exposed to burner flames.

Test 2. Burner program A, lap siding. Ignition of the area behind the burner flame was also at about 1 min. There was more significant lateral flame spread along the lower edges of the laps, resulting in a "Christmas tree" bum pattern. Following burner extinction, flaming combustion along the bottom edges of the laps continued for about 5 min. The fan was turned on and smoldering eventually ignited the plywood substrate.

Test 3. Burner program B, flat siding. After the 160-kW burner flame was extinguished (2 min), the panels also ceased flaming. No smoldering was observed when wind was added.

Test 4. Burner program B, lap siding. Ignition and flaming of the lower edges of the laps were more significant than in test 3. There was some smoldering of the lower edges of the laps after the burner was off. but it did not continue even with the fan on.

These tests showed that flame impingement for sufficient length of time (approximately 1 min) ignites a typical hardboard siding material. Upon removal of the source, flames self-extinguished. The wall continued to smolder and burned if aided by wind in the case of the 40 kW flame for 10 min but did not continue in the case of the 160 kW flame for 2 min exposure. Therefore, it appears that the duration of flame impingement may be the dominant factor for continued burning. In fact, bench-scale experiments with this material exposed in the OSU apparatus for different time periods, withdrawn to the point of self-extinguishment, and then rekindled by applied wind confirmed this point. There was a minimum time of exposure required before smoldering ignition could be initiated. The minimum time corresponded well with the burnthrough time of the material. The effect of wind-aided smoldering plays a significant role in continuation of fire spread and should be further investigated.

IGNITION VIA BURNING BRANDS

As digcussed in the previous two sections, radiation in this context is not the primary source of ignition although it may assist other ignition pathways. Flame impingement may lead to ignition if sufficient time is allowed. Considering the transient nature of wildland fuel fires, it is unlikely that flame impingement is a major pathway either. In reality, structures exposed to wildland fires but distant from the flame sources have burned down readily in many cases. That leads us to believe that ignition by burning debris plays a very important role in the ignition of structures.

At the present time, the SIAM assumes that brands are generated mainly as a function of the fuels and that they will be present everywhere. Not enough is known about brand size, distribution, viability, and transport properties to be incorporated in a physically rigorous way. A qualitative method uses fuel models from the National Fire Danger Rating System [12] and fire severity condition to classify brand generation. The brand generation index is then taken into account with the fire rating of materials that are susceptible to brand ignition (such as roof covering). Because of the lack of understanding in this area, plus the random nature of brand transport, more laboratory and field tests are needed to fill the knowledge gaps before some reliable method to assess hazards can be derived.

CONCLUDING REMARKS

Development of the SIAM model so far indicates that it is feasible to calculate whether piloted ignition of the structure occurred. Preliminary runs of the model showed that it required very large wildland fires with relatively long residence times to ignite wood structures via radiative heat transfer. Field experiences showed that structures have been destroyed with much smaller fire size and faster flame spread rate. This observation reinforces the significance of ignition modes other than through flame radiation. The other conceivable modes of ignition are flame impingement and burning brands. Ignition by brands, however, is still the most difficult to model because of its random nature.

The model development has shed some light on the way structures may ignite. However, a great many questions can only be answered by real-life experience. Although many actual fires have occurred, little information is useful from "eyewitness" accounts. Often, the witnesses are not trained or have duties that prevent detailed observations. Therefore, our current efforts are being focused on setting up both laboratory and field tests to observe first hand the pathways of ignition. The laboratory tests include ignitability of various materials under wider ranges of conditions (moisture contents, with or without finishes, configurations, etc.) and the collapse of windows when exposed to a fire flame/plume. Our planned field tests of structures exposed to controlled wildland fire will be invaluable to fill the knowledge gaps of structure ignition.

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