WildFire Ignition Resistance Estimator (WildFIRE) Wizard Software Development Report

David Werth, Savannah River National Laboratory

Monica Phillips, Savannah River National Laboratory

Casandra Robinson, Savannah River National Laboratory

Tim Smail, Federal Alliance for Safe Homes

Nick Gupta, Savannah River National Laboratory

Jack Cohen, RMRS Fire Sciences Laboratory

Kaushik Biswas, Oak Ridge National Laboratory

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Executive Summary

This report describes the development of a software tool, entitled "WildFire Ignition Resistance Estimator Wizard" (WildFIRE Wizard, Version 2.10). This software was developed within the Wildfire Ignition Resistant Home Design (WIRHD) program, sponsored by the U. S. Department of Homeland Security, Science and Technology Directorate, Infrastructure Protection & Disaster Management Division.

WildFIRE Wizard is a tool that enables homeowners to take preventive actions that will reduce their home's vulnerability to wildfire ignition sources (i.e., embers, radiant heat, and direct flame impingement) well in advance of a wildfire event. This report describes the development of the software, its operation, its technical basis and calculations, and steps taken to verify its performance.

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1.	Introduction

This report describes the development of a software tool, entitled "WildFire Ignition Resistance Estimator Wizard" (WildFIRE Wizard, Version 2.10). This software was developed within the Wildfire Ignition Resistant Home Design (WIRHD) program, sponsored by the U. S. Department of Homeland Security, Science and Technology Directorate, Infrastructure Protection & Disaster Management Division.

The goal of the WIRHD program is to provide a tool enabling homeowners to take preventive actions that will reduce their home's vulnerability to wildfire ignition sources (i.e., embers, radiant heat, and direct flame impingement) well in advance of a wildfire event.

This goal is realized in the development of WildFIRE Wizard, an easy-to-use software tool that will allow any professional or homeowner to estimate a home's vulnerability to the ignition sources associated with a wildfire and provide mitigation steps that can be taken, making it possible for a flaming front to pass the home with a lower probability of ignition. The software integrates the structural and material features of the home and external items within the home ignition zone (HIZ), including the ignition sources. Structural and material features of the home interact in different ways with each ignition source. For example, homes can be constructed to be highly resistant to radiant heat, yet may be readily ignited by embers blown from large distances.

2.	Purpose and Scope

WildFIRE Wizard allows an individual to input specific home structural features and materials along with vegetation and landscaping arrangements. The software provides recommendations for reducing the risk of home ignition (from both flames and embers), and these include the removal of flammable vegetation near the home, clearing of pine needles and other debris from the roof and gutters, and the use of screened windows.

WildFIRE Wizard is intended to identify a home's vulnerability to wildfire and has the potential of enabling homeowners to mitigate a home's vulnerability. This software is not intended to be a computational model for simulating or predicting what will happen to the home when approached by a wildfire, although it does involve numerical modeling of the interaction between the home and burning vegetation and structures. Instead, the software is a tool that can highlight vulnerabilities of the home and dangers in the homeowner's yard that can be remedied. To run more efficiently, the software makes several assumptions about the types of threats and their characteristics, and the ember ignition calculation relies on estimated probabilities. These assumptions and probability values were made to intentionally over-estimate ignition potential.

3.	Overview of WildFIRE Wizard

WildFIRE Wizard is composed of two interacting elements: (1) the graphical user interface (GUI) which receives inputs from and provides outputs to the user and (2) "Enhanced SIAM" which performs calculations based on user inputs and predetermined values. Figure 1[1] provides a graphical representation of WildFIRE Wizard.

4.	Enhanced SIAM

4.1.	Background

The calculation portion of the software is based on further development of the Structure Ignition Assessment Model (SIAM)[2], originally created by the U. S. Forest Service for the purpose of rating potential for ignitions based on a structure's ignition resistance characteristics and its potential fire exposure. SIAM assessed potential ignitions by establishing relationships between structure design and fire.[3] The model included convective and radiant heating of a panel (i.e., a one-dimensional wall) and did not include material thermal properties. SIAM allowed a user to input specific characteristics of the fire, weather, topography, structure, and fuels. In addition to the required user inputs listed above, the model required that the user have extensive wildfire knowledge and experience to be able to input parameters describing the fire and the surrounding vegetation, including the following:

- Reaction intensity (ir, a measure of how rapidly heat is released from the fuel in BTU/ft.^{2}/min, and used to calculate flame height and tilt).

- Heat content (hl, a measure of the total heat stored in the fuel in BTU/lb, and used to calculate flame tilt).

- Burning time (brntime, the total time between a portion of the fuel igniting and burning out, in seconds).

- Rate of spread (ros, ft./minute).

An overview of the components of SIAM is provided in **Error! Reference source not found.**. Shaded gray boxes indicate user inputs.

The original version of SIAM was developed for the purpose of assessing potential structure ignitions during wildfires burning in vegetation and structures and was based on worst-case estimates of direct effect of flames and firebrands.

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[1] All figures are provided in Appendix A of this report.
[2] Cohen, 1995.
[3] Cohen, Saveland, 1997.

From the user inputs, the model calculated the imposed heat flux on a panel by a single prescribed burning object and determined whether that flux would lead to ignition or window breakage. The total time it takes for the fire to burn through the fuel was calculated (based on the fuel depth and the burning time), then looped over incrementally. At each time step, the distance between the flame front and the structure was reduced by an amount based on the rate of spread, and the net imposed heating at each time step was calculated. This flux was then used in the calculation of the flux time product (FTP), a cumulative function serving as an index for ignition. If the FTP value exceeded an empirically determined threshold, ignition was assumed to have occurred. Window breakage was determined using the same FTP calculation but having a different threshold.

The Savannah River National Laboratory (SRNL) converted the DOS-based model into a Windows-based product that both a knowledgeable fire professional as well as a homeowner with no wildfire knowledge or experience can use to determine the ignition potential of a home. The new version, referred to as "enhanced SIAM," receives user inputs via a GUI developed by the Federal Alliance for Safe Homes (FLASH). The GUI allows the homeowner to select features of his or her home and yard, placing the structure and flammable objects (i.e., threats) within an area approximately 200-ft. from each side of the home (which includes the 100-ft. home ignition zone (HIZ)). Inputs include the size and shape of the home; materials of construction; structural features of the home; the position, size, and type of any objects within the HIZ. Enhanced SIAM then runs calculations multiple times, determining the heat flux imposed against the different parts of the home by each threat. The heat fluxes are used to obtain the overall ignition potential, which then goes into a report issued via the GUI to the user.

4.2.   Wildfire Properties and Assumptions in Software

This software is not intended to model the behavior of a wildfire. The tool has been developed to assess the vulnerabilities of the structure (house) to wildfire and the threats in the surrounding HIZ. Assumptions relating to the fire's properties and characteristics, environmental conditions, and the threats in the HIZ include the following:

Fire:

- The flame is assumed to be a constant, 1200 Kelvin gray body emitter over its entire dimensions.[4]

- The wildfire is assumed to start heating the home very early in the simulation. In reality, a home would be 'shaded' from a wildfire in the forest by trees between the home and the fire. This assumption eliminates such shading from consideration.

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[4] Cohen, 1995.

- The wildfire approaches the home from each side independently. That is, the assessment is completed four separate times, once for each side of the home.

- The flame is assumed to always approach the home from the opposite end of the fuel on all sides.

Environmental Conditions:

- A moderate wind speed of 10 miles/hour (converted to m/s in the software) is assumed to be representative of a range of wind speeds, and the outdoor temperature is specified to be 90 °F. A low value of fuel moisture (3% for all fuel types except mulch, which is 10%) is assumed to represent dry, easily ignitable fuel.

Threats:

- The tool considers the following to be threats to the home: forests, dry grass, neighboring homes, combustible sheds, combustible fences, combustible playsets, trees, shrubs, pine needles and mulch. Each threat is assigned a set of values describing its size, its location, and its burning properties, including the reaction intensity, heat content, burn time, rate of spread, fine fuel moisture content, and fuel temperature.

- Neighboring homes are forced to become fully involved at once, avoiding the period when the fire gradually engulfs the home.

- All flammable materials in the HIZ burn at the same time because how and in what sequence the flammable materials adjacent to a structure will burn cannot be predicted.[5]

4.3.   Operation of the Software

Enhanced SIAM takes into account the above assumptions, home feature characteristics and threats and performs calculations using this information. Home features and threats are described in Sections 4.4.1 and 4.4.2.

Figure 1 provides a flowchart of enhanced SIAM and how it processes inputs from the GUI. Once inputs are received, HomeB (see Figure 3) determines which (i,j,k) reference points belong to each side of the home (designated as sides A, B, C, and D, with A being the front) and records these values. Each side of the home is separated into panels (i.e., non-coplanar wall faces), and the software then addresses all threats to each panel followed by calculations for each side of the home. The final function addresses embers, and an output report is provided to the user.

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[5] Cohen, Saveland, 1997.

Figure 4 shows an example of the way the HIZ is displayed, with a home (in dark blue) and a single threat (a field of dry grass). Note that the home comprises three substructures, each of a different height. Using side A as an example, the next function (called Panels) divides each wall of side A into a series of panels and records information about the panel's location and shape (Figure 4). The function then loops over all panels, looping again in turn over all threats for each panel. The first function in this second loop (called SIAMPrep) reads in the panel data and the data for the threat and prepares an input file for the heat flux calculation. It does this by calculating the distance between the threat and the panel, and these data, along with the burning characteristics of the threat, are written as output. The function also isolates the portion of the threat to which each side of the home can be exposed. For example, Side A in Figure 4 can see the entire grass field, while Side D (the left side) can only see the leftmost portion.

The function SIAMQ is then called and reads this input and performs all heat flux calculations. This function first establishes the initial conditions: the angle of the flame (calculated using the assumed wind speed and fuel moisture), the flame length (calculated with the reaction intensity) and the total burning time (calculated using the amount of fuel and the burning rate). Then the fire simulation begins, starting with the flame at the far end of the fuel and moving closer to the home with each time step (with a distance calculated with the rate of spread). At each step, the radiative and convective fluxes are both calculated and recorded with the number of the panel and the threat. This function is run for each threat. After all threats have been processed, the inner loop ends, and the heat fluxes for all the threats (for this panel) are recorded.

These data are then used by two additional functions that determine the response of the panel to the imposed heating. Continuing to use Panel 1 of Side A as an example, the first function (called SIAMTemp) reads in all the previously recorded flux values, calculates the total heat flux (summed over all threats) at each point on the panel at each time, and calculates the panel temperature for both windows and siding, recording the temperature values. If vinyl is the siding type, the temperature calculation is also used to predict if the vinyl melts (recording the time at which it does so), exposing the wood behind it.

The second function (SIAMftp) also reads in the heat flux data from each threat and sums these to get the total heat flux at each point of the panel. It also reads in the melting time data. Then, the FTP calculation is performed for panel points designated as wood or melted vinyl (the latter only for the period after the melting time) and records these data.

After all panels have been exposed to all threats and the panel loop terminates, the temperature and FTP data are recorded for all panels of the wall. Another function (SideAssessor) reads all the aforementioned data and records as output the parts of the wall that are expected to ignite (when the FTP exceeds the designated threshold) or experience window breakage (when the window temperature exceeds a threshold). This information forms the basis for the user report. Additionally, another function

(ThreatAssessor) evaluates and rates the degree to which each threat contributed to the net heat flux.

Finally, the ember function (Ember) is run, which reads in the roof and deck data, along with an assumed ember exposure rating of 100% (worst case), and calculates the cumulative probability of ignition due to embers.

4.4.   Components of Enhanced SIAM

4.4.1.   Home Feature Characteristics

Home features addressed by enhanced SIAM include roof material, roof features (i.e., dormers, chimneys, skylights, vents, and gutters), siding, windows, and doors. The roof material and roof features are used in determining ember ignition probability. Properties of siding, windows, and glass doors are used in radiant and convective heat calculations. For wood siding, the FTP ignition threshold was taken from experiments performed by Cohen in 2004. For vinyl siding, the density and heat capacity were taken from the PMIC report produced for Oak Ridge National Laboratory.[6] For window glass, the required properties are the cooling rate and the temperature at which the glass is assumed to break. The cooling rate was determined from a PATRAN[7] simulation, and the glass breaking temperature was obtained from the tests performed at the Insurance Institute for Business and Home Safety (IBHS).[8]

Home features input by the user are coded for transmission to enhanced SIAM according to the table in Appendix B. The table also specifies how home feature characteristics are used by enhanced SIAM.

4.4.2.   Threats and Associated Properties

The following features within or near the HIZ are considered to be threats to the home: forest, dry grass, small home, medium home, large home, shed, fence, playset, small tree, medium tree, large tree, small shrub, medium shrub, large shrub, pine needles, and mulch. Each threat is assigned a set of values describing its size, its location, and its burning properties, including the reaction intensity, heat content, burn time, rate of spread, fine fuel moisture content, and fuel temperature. These standard flame characteristics are provided in Table 1, and the list is largely generated from the Rothermel fire spread model used in U. S. operational fire management systems.[9] These are used to calculate the flame length, the rate at which the flame front approaches the home, and the time any portion of the threat will be burning.

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[6] PMIC, 2010.
[7] PATRAN is a software package designed to simulate the heat transfer between any arrangement of radiating and receiving surfaces.
[8] IBHS, 2011.
[9] Rothermal, 1972; Albini, 1976; Cohen and Deeming, 1985.

The original threat list comprised only grass, a shrub, a tree, and pine needles, with the material properties taken from the original SIAM. This was expanded to allow a full menu of threats to be available to the homeowner. The new threats were developed as modifications of the existing threats. For example, the small, medium, and large trees were simply assigned different burning times (as well as different sizes) as the original tree. A medium tree will burn for 40 seconds (the same as the original tree), while the small and large trees will burn for 20 and 60 seconds, respectively. Similarly, the three shrub sizes differ only in their burning times (used to get the total time of exposure): 10, 20, and 30 seconds for the small, medium, and large shrubs, respectively.

For a large burning object, its properties were also created by modifying existing values. A forest is a collection of trees, so the burning properties are the same. It is

Table 1. Material properties of the threats

Properties	Forest	Dry Grass	Small home	Medium home	Large home	Shed	Fence	Playset
ir	20000	3516	981	4424	10683	981	20000	20000
hl	8000	8000	8000	8000	8000	6000	6000	6000
brntime	40	15	1200	1200	1200	1200	20	20
ros	N/A	426	N/A	N/A	N/A	2000	100	100
ffm	3	3	3	3	3	3	3	3
temps	90	90	90	90	90	90	90	90

Properties	Small tree	Medium tree	Large tree	Small shrub	Medium shrub	Large shrub	Pine needles	Mulch
ir	20000	20000	20000	14042	14042	14042	1343	1100
hl	8000	8000	8000	6000	8000	10000	8000	9000
brntime	20	40	60	10	20	30	20	40
ros	100	100	100	330	330	330	200	20
ffm	3	3	3	3	3	3	3	10
temps	90	90	90	90	90	90	90	90

Table Notes:
ir: reaction intensity (BTU/ft.^{2}/min)
hl: heat content (BTU/lb)
brntime: burn time (seconds)
ros: rate of spread (ft./minute)
ffm: fine fuel moisture (percent)
temps: fuel temperature (degrees F)

up to the user to expand the forest graphic to create a wide forest area.

The three neighboring home types are assigned reaction intensities (used with the heat content to calculate the flame length) that will produce flame heights that approximately match the height of the burning home and were all assigned a longer burning time (20 minutes) to account for the time it might take for flames in a fully involved home to extinguish.

The fence and playset were assigned the same values used for a small tree but with a reduced heat content of 6000 BTU/lb versus 8000 BTU/lb for a tree. This reflects the smaller amount of wood fuel in the former. Similarly, a shed has the same values as a small home (and is smaller in size) but with a reduced heat content (again, reduced to 6000 BTU/lb from 8000 BTU/lb). Mulch is similar to pine needles but with a longer burning time, a greater heat content, a smaller reaction intensity, and a smaller rate of spread.

All threats are coded for transmission to enhanced SIAM according to the table in Appendix B. The table also specifies how the threat properties are used by enhanced SIAM.

4.4.3. Flame Representation

Enhanced SIAM reads in the material burning properties from Table 1 and converts them into the flame characteristics used in the heat flux calculations. Three key parameters are initially calculated: the flame depth, the flame length, and the flame tilt (the flame width is calculated from the threat size). These all are subsequently used to calculate the locations of the flame front relative to the home and the flame emissivity. Equations for flame representation are summarized in Table 2.

Table 2. Equations for Flame Representation

Equations	Definition of Terms
Equation 1 $fldpth = ros \cdot brntime$	fldpth = flame depth (constrained to remain at or below the fuel depth) ros = rate of spread brntime = burn time
Equation 2 $flgth = 0.0775 * (ir/fldpth)^{46}$	flgth = flame length ir = reaction intensity
Equation 3 $flht = 25 * (2.32 - 0.055*ffm) * (2.02 + 0.014*ffm) * (ir*fldpth/hl)/uwind$	flht = flame height ffm = fine fuel moisture hl = heat content uwind = wind parameter
Equation 4 $\alpha = \tan^{-1}\left(0.7087 * uwind \middle/ \sqrt{flht} \right)$	α = flame tilt angle ffm = fine fuel moisture

4.4.4.   Slope Representation

The software uses the slope of the terrain to determine if a wall of the home will be partially (or completely) shaded from a flame that lies over the edge. The user inputs the distance between the wall and the edge of the slope, the angle of slope, and whether or not the wall is partially beneath the ground (as for a home built into a hillside).

The distance between the home and the edge of the slope may be specified by the user to be between 0 and 100 ft. The maximum distance of 100 ft. was chosen even though an approaching flame front appears to be on level ground when the slope edge is at a distance of much less than 100 ft. from the home. Seven options are provided for slope angle:

- - 30°, - 20°, - 8°: Negative slope values indicate that the slope of the land is downward toward the home.

- 0°: Zero slope indicates that the home is located on level terrain.

- + 30°, +20°, + 8°: Positive slope values indicate that the slope of the land is upward toward the home.

The slope angle options are taken from the 2012 International Wildland-Urban Interface Code.

4.4.5.   Heat Transfer Calculations

The software applies two methods to determine the heat flux imparted from a burning object to the panel: radiant heating and convective heating.

The wall panel is subdivided into a grid of 1 ft. x1 ft. squares, and the flame front is also divided into smaller squares. Each square of the home then receives an amount of radiant heating from each square of the fire, summing over all of the fire squares. The view factor (Equation 6) describes the way that two surfaces exchange heat as a function of areas of the squares ($A_{i,j}$), the distance R between them, and the angles ($\theta_{i,j}$) between their normals and the line joining their centers (if $\theta_{i,j}=0$, the two surfaces face each other directly and the heat transfer will be at its maximum). As the program loops over the burning time of the threat, the radiant heat flux is calculated at each one-second time step.

Enhanced SIAM assumes all of the threats in the HIZ burn, unless they are there for aesthetic value only. The heat flux of each individual threat is added together over the period of time it takes all of the threats to burn. The total heat flux is projected onto the wall of the home for each given interval and compared against predetermined values to determine if a home feature fails. Failure of a feature is considered by the software to be (1) if a window breaks or (2) if any siding ignites.

Table 3 below summarizes the radiant heat calculations. These equations are taken from Incropera and DeWitt (1996).

Table 3. Radiant Heat Calculations

Equation	Definition of Terms
Equation 5 $$q''_{rad} = \varepsilon_1 \sigma T^4$$	q''_{rad} = Radiant Heat Flux (W/m^2) ε_1 = emissivity of the flame σ = 5.6703 10^{-8} (W/m^{2}K^4) Stefan-Boltzmann constant T = Absolute temperature (K)
Equation 6 $$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j$$	F_{ij} = View Factor A = Elemental area of squares i and j R = Distance between elements i and j $\theta_{i,j}$ = Angles between their normals and the line joining their centers (if $\theta_{i,j}$=0, the two surfaces face each other directly, and the heat transfer will be at its maximum). i and j indices = correspond to the radiating and receiving surfaces (i.e., the fire and the wall)
Equation 7 $$q_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\dfrac{1-\varepsilon_1}{\varepsilon_1 A_1} + \dfrac{1}{A_1 F_{ij}} + \dfrac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$	q_{12} = Net radiation exchange between surfaces 1 and 2 ε_2 = emissivity of the wall (set to 0.9 for common siding types) T_1 = flame temperature of 1200K T_2 = wall temperature (assumed at be 300K) A_1 = Area of flame A_2 = Area of wall

The next heat flux is convective being caused by flames or hot air touching the wall. This is calculated (Equation 8) through a flux-gradient approximation by which the difference between the flame temperature and the wall temperature is calculated, and this is converted to a heat flux through the application of a proportionality constant (h).

This factor was derived using data from the testing performed by Intertek Testing Services[10] in which a flame was applied to a sample, and a constant was selected that resulted in a heat flux that produced ignition at a time comparable to the experiment (see Section 4.5). The software must first determine if flames or hot air touch the home, using the flame angle and the position relative to the home. It then calculates the temperature, T_{flame}, assuming that hot air exiting the flame column cools as it rises (according to an algorithm developed by Chandler et al., 1983), to go into Equation 8. The convective heat calculations are summarized in Table 4.

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[10] Intertek, 2010.

Table 4. Convective Heat Calculations

Equations	Definition of Terms
Equation 8 $$q_{conv}^{''} = h(T_l - T_2)$$	q''_{conv} = Convective heat flux (W/m^2) h = 58.42 kW/m^{2}K, calculated proportionality constant (see Section 4.5.2) T$_1$ = flame temperature T$_2$ = wall temperature
Equation 9 $$T_1 = 3.8\, x\, \frac{fli^{\frac{2}{3}}}{\omega} + 300$$	fli = Byram's intensity (Byram, 1959) ω = distance from the flame tip to the point on the wall where the heat flux is to be calculated (z(k))
Equation 10 $$fli = 260\, x\, flgth^{2.17}$$	

If no flame contact occurs, but the hot air column contacts the wall, ω is calculated as the distance from the flame tip to the wall (cnvln), added to the distance up the wall from the contact point (hcnv) to the point z(k). Figures 5 through 8 pictorially show an angled flame front approaching a wall. If flame contact does occur, the software first calculates the distance over which the flame column contacts the wall (flcol), assuming the total flame length remains constant (Figure 7). Then, ω is calculated as the distance between z(k) and the height of the contact point (hcnv), minus the flame column distance (flcol). (A value of ω lower than zero indicates a point within the flame column). T$_1$ is constrained to remain at or below 850K, and for maximum heat transfer, T$_2$ is assumed to remain constant at a relatively low value of 32°C (305K).

The software then calculates the effect of the imposed heating on the wall and determines if there is ignition or window breakage. For wood, this involves the calculation of the FTP index, using the heat flux as input (see Section 4.5). For vinyl, an explicit equation is used to calculate the temperature at each time (see Section 4.5), which is compared to the melting point of vinyl to determine if the siding material melts. For glass, a similar equation is used, with breakage assumed if a temperature threshold is exceeded.

4.4.6.   Ember Probability

Ember ignition is based on a probability, determined by the user inputs, rather than an explicit calculation. The process of ember ignition of a home involves the production of embers, their transport to the home and their collection on the home in sufficient quantity and size to ignite the home. To simplify the procedure, only the latter process requires input from the user. (The former two are accomplished with a default value.) Embers are known to collect on a home along edges, within roof valleys, at interfaces between structural components and features, and in other locations where the natural flow of air is interrupted allowing embers within that airflow to drop out. Because these are also locations where pine needles and other flammable debris naturally accumulate, the potential for ignition due to ember collection can be great.

Roof features of concern for debris and ember collection include the roof covering, skylights, dormers, gutters, vents, and chimneys. Decks attached to the home can also trap debris and cause the siding to ignite or melt. Ignition probabilities have been assigned to each of these features. The software first calculates the home's ember *reception* probability, which is the likelihood that embers hitting the home will collect. It first determines the total 'edge' length in feet of each of the following home features that are receptive to embers: dormers, chimneys, skylights, gutters, and wood decks.

Roof features, except for gutters and vents, are assumed in the software to be of a specified length and width representative of a wide range of typical roof features, and the edge length is simply the perimeter. Gutters are placed and sized by the user, and the resulting lengths are also used in the edge length calculation. Vents are individually counted, and the quantity is used in the calculation. Several roof feature examples are provided below:

- A chimney is assumed to be 2 ft. x 2 ft., which results in an 8 ft. perimeter.

- A dormer is assumed to be 5 ft. x 6 ft., which results in a 22 ft. perimeter.

- A skylight is assumed to be 3 ft. x 4 ft., which results in a 14 ft. perimeter.

- A home with two chimneys and two dormers will therefore have a total edge length of 60 ft. If a skylight were also present, the total edge length would be 74 ft.

Decks are placed and sized by the user, and the resulting lengths are used in the edge length calculation.

The executable then assigns a 'nook and cranny' (nc) reception probability [P(nc)] value for each foot of the total edge length (see Appendix D for more information), which will be used to calculate how efficiently each feature will collect embers. This probability is assigned by roof type and condition for roof features. A separate reception probability [P(p)] is assigned to various other features of the home that are characterized by their number (vents and broken windows), rather than by their size. Table 5 provides the P(nc) and P(p) assigned values for home features.

Two examples are provided below for clarification.

Example 1:

- Wood roof with debris, two dormers, and one chimney

- Total edge length = 52 ft.

- Probability of nonreception = $[1 - P(nc)]^{52} = [1 - 1\%]^{52} = 0.593$

- Reception probability = 1 - .593 = .407

Table 5. P(nc) and P(p) Assigned Values for Home Features

Roof Material and Condition	Reception Probability for Chimneys, Dormers and Skylights (probability compounded over all feet of the edge length)
Metal	0
Asphalt	0
Clay tiles – no debris	0
Clay tiles with debris	0.5% per ft.
Wood – no debris	0.5% per ft.
Wood with debris	1.0% per ft.
Other Home Features	**Reception Probability**
Wood deck	0.3% per ft. of deck touching home
Vents	0.5% for each vent
Broken windows	1.0% per ft.^{2} of windows
Metal gutters	0.3% per ft. if debris on a wood roof or tile roof
Vinyl gutters	0.4% per ft. if debris on roof (regardless of roof type)

Example 2:

- Wood roof with no debris, two dormers, and one chimney

- Total edge length = 52 ft.

- Probability of nonreception = $[1 – P(nc)]^{52} = [1 – .5\%]^{52} = 0.771$

- Reception probability = 1 - .771 = .229

The software also requires the ember *exposure* probability, which is the likelihood that the home will be threatened by embers. Appendix C describes a procedure for determining ember exposure probability; however, because the ember exposure a home will experience cannot be predicted, enhanced SIAM assigns the ember exposure probability for every home to be 100% (worst case). Using the examples above, if the home in example 1 was assigned an exposure probability of 100%, the total ember ignition probability would be calculated to be .407 x 100% = 40.07%, while the same exposure probability for the home in example 2 would yield an ignition probability of .229 x 100% = 22.90%.

4.5.   Material Testing

Enhanced SIAM requires data on the thermal and ignition properties of the various materials typically used as siding for the home.   To simulate the home ignition, the software must calculate the radiant and convective heat impinging on the home and the response of the siding material (e.g., melting or igniting). The calculations were partially validated through field testing,[11] but for home ignition, the full range of software calculations had to be evaluated.

To accomplish this, Intertek Testing Services was contracted to perform various materials tests.[12] These tests addressed (1) calculation of the heat fluxes and (2) the response of simulated siding materials to the imposed heating. Complete test details are provided in the official reports from Intertek[13] and the Oak Ridge National Laboratory (ORNL).[14]

To summarize, each test involved the application of a prescribed heating to a test sample. Each sample was instrumented with thermocouples on both the front and back sides of the siding and distributed to provide temperature readings over the sample face. Some tests also involved "floating" thermocouples mounted at a short distance from the sample to monitor temperatures of the air adjacent to the sample. This thermocouple placement facilitated monitoring of the sample temperature rise in response to the imposed heating. The test results were compared to the software calculation results for the purpose of either validating or modifying the way the software calculates heat flux from flames or simulates ignition. This information was then used to recode the software when the calculation results did not correspond to the test results.

The following sections describe several tests, their results, and how the software was either validated by the test or how the software algorithms were rewritten to be consistent with test data.

4.5.1.   Radiant Heat Testing

Radiant testing involved the use of a calibrated radiant panel that could be adjusted to impart a heat flux to the samples. The radiant panel comprised a thick metal sheet heated from behind by gas fired burners (Figure 9), and the desired heat flux was obtained by adjusting the fuel flow rate to the burners and the distance between the radiant panel and the samples. The radiant heat flux incident on the test samples was calibrated using a panel instrumented with five radiometers (Figure 9, top left). Heat flux calibration tests were performed both before and after the samples were tested at each desired radiant exposure (25, 40 and 50 kW/m^2). Figure 9 shows the pre- and post-test calibration plots for the 40 kW/m^2 radiant flux and shows little loss of

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[11] Cohen, 2004.
[12] Biswas, 2011.
[13] Intertek, 2010.
[14] Biswas, 2011.

calibration between measurements. These tests were primarily used to validate the simulated response of the samples. The results of testing on vinyl siding and cedar siding were studied since each of these is treated differently by enhanced SIAM.

Intertek Test 1

This test involved a wall sample (Figure 10, top) with vinyl siding exposed to a calibrated radiant panel initially producing an imposed heat flux of 40kW/m^2. Enhanced SIAM uses a simple but explicit heat equation to calculate the vinyl temperature, T, removing the coating when the melting temperature is exceeded. This is done according to , change in time.

.

Equation 11

$$T_{t+1} = T_t + (\frac{q''-C}{C_p})\Delta t$$

q", the imposed flux = 38.44kW/m^2 (as indicated by the panel calibration).

C_p, heat capacity = 1287 J/m^2/K.

C, prescribed cooling rate in kW/m^2.

Δt, change in time.

The cooling rate was determined from this experiment, in which readings from thermocouples mounted to the interior and exterior vinyl surface were averaged to get the interior vinyl temperature and compared to simulated temperatures calculated with various cooling rates. (After tests with a Newtonian cooling function, it was determined that a constant rate fit the data much better.)   The sample temperatures showed an approximately linear increase with time in response to the constant heating rate (Figure 10), at an average of 5.19º C/s. Different cooling rates were tested in the enhanced SIAM calculations, and 31.8 kW/m^2 was chosen as the optimum cooling rate yielding a temperature rise rate of 5.16º C/s (Figure 10). , change in time.

 was therefore recoded with the updated cooling rate, and code was modified so that the vinyl siding temperature rise occurs only when the imposed heat flux exceeds 31.8 kW/m^2.

This test was also useful for determining the melting point of the vinyl siding, which is used to determine when the siding has ablated and exposed the wood beneath it. The interior thermocouples revealed a sharp increase in temperature when the siding failed, and this tended to occur when the vinyl temperature reached between 230º C

and 310º C (as measured by the outer thermocouple). Therefore, a value of 270º C (543K) was used in the software.

Intertek Test 2

This test involved a wall sample with cedar siding exposed to a calibrated 38.44kW/m^2 radiant panel[15]. For wood siding, the software uses the FTP calculation of Cohen.[16] The radiant heating is used to calculate the FTP value according to Equation 12:

Equation 12

$$FTP = \int (q'' - q_c)^{1.828} dt$$

$q_c = 13.1 Kw/m^2$.

dt, time step = 1 second.

 As the FTP values crosses the value of 11500, ignition becomes increasingly likely until the value of 13500 is reached, when it is a certainty.[17] For as long as the heating is applied, the FTP value will increase until the heating stops or the ignition threshold is reached. The goal of this test was to determine if the threshold value obtained by the earlier research[18] is general enough to be used in the software. With q''= 38.44 kW/m^2, Equation 12 predicted ignition between 32 and 37 seconds, going from likely to certain ignition. In the test, ignition occurred approximately 28 seconds after exposure, which is close to the value predicted by the software.

4.5.2.   Convective Heat Testing

Convective heating is that imparted to the sample from either active flames or the hot air column above a flame front. Enhanced SIAM uses the temperature difference between the flame and the wall to calculate the flux. Results from these tests were used to help calibrate this process and provide further validation of the software adjustments made in response to earlier tests.

Intertek Test 6

This test was used to adjust the way the temperature difference caused by flame or hot air contact is converted into a heat flux. This test involved a wall sample with cedar siding exposed to a 100kW flame. The software calculates the heat flux by calculating a flame/air column temperature and assuming a wall temperature, then applying the flux-gradient equation (Equation 8).

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[15] The Intertek report lists the radiant panel exposure as 40 kW/m^2, which was not the actual recorded value. The actual value was 38.44 kW/m^2.
[16] Cohen, 2004.
[17] Ibid.
[18] Ibid.

As before, the cedar ignition was calculated with the FTP value. The ignition time from the experiment was 25 seconds, so the heat flux must be such that the FTP reaches the threshold at that time. Using the temperature values from the sensors (T_{flame} was obtained from the floating temperature sensor, while T_{wall} was set to 32 ºC to maintain a conservatively large heat flux), the temperature difference was determined, and the h term in Equation 8 was calculated with an algorithm in enhanced SIAM to get the heat flux. The FTP values calculated using this flux did not reach ignition at the proper time (~ 25 seconds), however, indicating that the software required adjustment. The heat flux calculation was simplified by assigning h a specific value of 58.42 kW/m^2/K, selected so that the value of FTP would be ~11500 at the same time ignition happened. This leads to an FTP curve that reaches 11500 at the same time as the actual ignition. Figure 11 shows the FTP curve with blue being the original value, red being the improved value, and orange being the FTP ignition threshold.

Intertek Test 10

This test involved a wall sample with cedar siding exposed to both a radiant panel producing 27.36 kW/m^2 (from the radiant panel calibration)[19] and a 100 kW flame. First, the convective heat flux was calculated using Equation 8, with the floating temperature probe providing the flame temperature as in Test 6 but using the altered h value. Then, to that flux, the radiant value was added to get the total heat flux. This total was entered into the FTP equation (Equation 12) and used to obtain the ignition time. The resultant time of 5.8 seconds was a little more than 3 seconds under the observed time of 7 to 10 seconds, validating the convective heat flux calculation.

Intertek Test 5

This test involved a wall sample with vinyl siding exposed to a 100kW flame. Thermocouples were again placed on both sides of the siding to monitor the temperature rise in response to the imposed heating. This was used to test two ideas obtained from the previous tests: (1) the way that a temperature difference between a hot flame and cooler sample is converted to a heat flux (i.e., validate the new, constant value for h (58.42kW/m^2/K) now used in Equation 8) and (2) the way vinyl heats up in response to the imposed flux (i.e., validate , change in time.
), especially the way the software simulates sample cooling by assuming a constant rate.

First, an attached external thermocouple (probe 10) was selected to represent the flame temperature (T_{flame}). This was used in Equation 8 to get the heat flux into the sample, again assuming a constant sample temperature (T_{wall}) of 32 ºC as is done in enhanced SIAM. Following this, the flux was used in , change in time.

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[19] The Intertek report lists the radiant panel exposure as 25 kW/m^2, which was not the actual recorded value. The actual value was 27.36 kW/m^2.

to calculate the sample temperature, and this was compared to the temperature from the thermocouple probes. As seen in Figure 12, the calculated temperature approximates well the range of actual temperatures from the probes, so the revisions to Equation 8 are justified.

4.6.   Verification of Enhanced SIAM

It is vital to determine that the software correctly receives and applies the user inputs to the appropriate equations, performs the heat flux calculations as intended, and that the output seen by the user reflects the software output. To accomplish this, the software was verified by a series of tests with carefully selected input expected to produce a known output.

4.6.1.   Layout of Home and HIZ Tests

This test determined that the software would take the user inputs about home and threat size and position and create enhanced SIAM input files that accurately list the resulting panel properties (size and location) and flame properties (location and distance from the panel).

As an input, a field of dry grass in front of the home was entered (refer to Figure 4) extending from 1ft. to 146 ft. across the 400-ft. width of the domain. Side A was subdivided by the software into 3 panels, each of a certain width, height, and distance from the threat. Panel 1 began at the 1ft. level (i.e., ground level) and 221 ft. from the $i = 0$ point (i.e., left side). The panel lies along the plane 200 ft. from the $j = 0$ point and is 10 ft. high and 20 ft. wide, all in accordance with the figure. As the script loops over all three panels and the single threat, it calculates for Panel 1 the properties shown in Table 6.

The first seven values describe the burning properties of dry grass. The next four values describe the position of the fuel relative to the wall, and the 'fueldst' is the calculated distance between the panel and the leading edge of the fuel. Figure 4 shows this to be 54 ft., and the input file matches the correct value. The final six values describe the size and shape of the fuel bed, as well as the height and width of the wall). The fuel depth (fueldp) of 145 ft. matches the expected value, and the xoffset indicates that the left edge of the grass lies 220 ft. from the left edge of the panel (Figure 4). This and similar tests indicate that the preliminary executables are correctly receiving the user inputs via the GUI and preparing the enhanced SIAM input file in accordance with the layout indicated by the GUI.

A second test was conducted to determine that the software was correctly adjusting these values for the slope. The test was run on the hillside home shown in Figure 13, with the home facing the downslope on Side A and the upslope side on Side C. The home comprises 2 blocks, a three story block and a two story block (seen from above in Figure 14). To this layout, two threats were added: a grass field and forest, positioned as shown in Figure 14. Two windows were added to the home, one on

each side. The Side C window is 10 ft. from the lowest level, but given that the depth is one story on this side, it should be represented as being level with the ground.

When this home was run by the software, the threat files in

Table 7 and

Table **8** were created for Side A. It can be seen that the different panels have different values of dset. Both indicate a 100% slope, with the home uphill from the fuel (updwn=1). The threat files in

Table 9 and Table 10 were created for Side C.

Table 6. Panel 1 Properties

Property	Term	Value
Reaction intensity	ir	3516.000
Heat content	hl	8000.000
Burn time	brntime	15.00000
Rate of spread	ros	426.0000
Fine fuel moisture	ffm	3.000000
Wind parameter	uwind	7.500000
Fuel temperature	temps	90.00000
Calculated distance between the panel and the leading edge of the fuel	fueldst	54.00000
Distance from home to the slope edge	dset	0.0000000E+00
Percent Slope	pcpslp	0.0000000E+00
Slope direction index	updwn	1.000000
Fuel width	fuelwd	400.0000
Fuel depth	fueldp	145.0000
Offset from left edge of panel	xoffset	-220.0000
Distance of panel from ground	zoffset	0.0000000E+00
Wall height	hstr	10.00000
Wall width	wstr	20.00000

Table 7. Side A, Panel 1

Property	Value
fueldst	4.000000
dset	40.00000
pcpslp	100.0000
updwn	1.000000

Table 8. Side A, Panel 2

Property	Value
fueldst	4.000000
dset	30.00000
pcpslp	100.0000
updwn	1.000000

Table 9. Side C, Panel 1

Property	Value
fueldst	5.000000
dset	60.00000
pcpslp	-100.0000
updwn	-1.000000

Table 10. Side C, Panel 2

Property	Value
fueldst	5.000000
dset	30.00000
pcpslp	-100.0000
updwn	-1.000000

The values of dset were calculated similarly as before, with the back of the 3-story block a full 60 ft. from the edge and the back of the 2-story block at a distance of 30 ft. Now, however, the values of pcpslp and updwn are negative to reflect the fact that the fuel is uphill from the home.

Figure 15 shows a plot of the radiative heating and resulting temperature of the two sides, revealing the effect of the hillside. Side A is fully illuminated with the window (the square in the temperature field) located as seen in Figure 15. For Side C, it can be seen that the panels were adjusted to account for the the lowest part of the wall being underground. The panels are shorter, and the window (seen in the temperature plot) is at ground level, representing a glass door.

4.6.2.   Radiant Heat Transfer Tests

A series of tests with the PATRAN radiant transfer software were done to verify enhanced SIAM's calculation of the radiant heat transfer. The tests involved a 2 m x 5 m flame radiating heat against a 40 m x 10 m wall. The different tests involved varying the flame tilt (0º or 30º from the vertical) and the slope of the terrain (0º or 20º). Both tilt and terrain affect the radiant transfer through the impact on the view factor, the shading of the lower part of the wall from a flame below the edge of the slope, and the vertical displacement of a flame on a hill relative to the home. The fire was positioned 30 m from the left edge of the wall and 30 m away. In the tests with

sloped terrain, the wall was 10 m behind the slope edge. The results of enhanced SIAM and PATRAN were compared according to their calculations of the view factor (Equation 6) and the radiant flux (Equation 7).

Figure 16 shows the enhanced SIAM and PATRAN results for the radiant heat flux for an untilted flame on level ground, and the close correspondence between the two is readily observable. (The peak flux value from enhanced SIAM was 413W/m^2, and the PATRAN heat flux value was 406 W/m^2). Table 11 shows how well the maximum view factors compared. Figure 17 shows the results when the flame was tilted 30º (as if the flame were driven by the wind), and the close correspondence between the two is again readily observable. Both plots show the reduced flux, with a lowered illumination pattern, as a result of the tilting (which increases the values of $\theta_{i,j}$ in Equation 6) and reduces the surface area radiating towards the wall. The view factors (Table 11) again show good agreement.

This was repeated for several configurations, adding sloped terrain, and placing the fire uphill or downhill from the wall. Table 11 shows a good match of maximum view factor for these experiments. Therefore, the radiant flux calculation in enhanced SIAM was verified.

Table 11 Comparison of Enhanced SIAM and PATRAN maximum view factors.

Condition	Enhanced SIAM Maximum View Factors	PATRAN Maximum View Factors
Untilted Flame, level ground	3.512e^{-4}	3.51e^{-4}
Flame tilted 30 º, level ground	3.41e^{-4}	3.41e^{-4}
Untilted flame, fire downhill	3.19e^{-4}	3.13e^{-4}
Tilted flame, fire downhill	2.39e^{-4}	2.31e^{-4}
Untilted flame, fire uphill	3.81e^{-4}	3.81e^{-4}

4.6.3.   Conductive Heat Transfer Tests

As described in Section 4.5, enhanced SIAM was recoded to match more closely the Intertek tests, which measured the temperature of a sample as a flame was applied. The software was also altered to allow for a flame and hot air column to intersect and rise alongside the wall, imparting heat along the path. The modified code was tested for its ability to position the flame and wall and work out the geometry so that the intersection point (if any) and flame column match the expected value.

An example of this can be seen in the aforementioned Figures 5 through 8, which depict an angled flame front approaching a wall. The flame gets closer with each time step, requiring changes in the heat flux calculation as the simulation progresses. Figure 5 shows an angled flame front approaching a wall. The convective column is not intersecting the wall, and no convective heating is calculated in the model, as expected. In Figure 6, the flame has approached within 6.4 m of the wall. The hot air column (but not the flame) now intersects the wall at 9.14 m, and the plot of flame/air temperatures along the wall above the intersection point shows the column temperature (and the imparted heat flux) falling with height above this point. In Figure 7, the flame has moved close enough to (barely) intersect and ride part way up the wall, with the temperature values at the maximum of 850 ºC within the flame and falling with height above the flame tip as the column cools.

In Figure 8, the flame is now adjacent to the wall (within 1 ft.), and the flame column rides up a long portion of the wall, which now receives the maximum temperature along most of its surface. These enhanced SIAM-calculated temperatures are in agreement with similar temperatures calculated with Excel (using Equation 9) given the same conditions, so the software is correctly calculating the convective heat flux for given flame locations.

4.6.4. Ember Ignition Probability Testing

To test the ember portion of enhanced SIAM, the following inputs were used:

- Broken Windows = 25 (25 ft.^{2} of broken windows)

- Roof Type = 0 (Wood roof)

- Roof Debris = Y (Yes)

- Deck length = 11 (11ft. of contact between deck and home)

- Dormer length = 132 (6 dormers, each with a 22 ft. perimeter, for a total of 132 ft.)

- Chimney length = 0 (no chimneys)

- Skylight length = 28 (2 skylights, each with a 14 ft. perimeter, for a total of 28 ft.)

- Metal Gutter length = 130 (a total of 130 ft. of gutters)

- Vinyl Gutter length = 25 (a total of 25 ft. of gutters)

- Number of vents = 10

- Ember exposure = 100%

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The results of this input file on the ember calculation can be seen in Figure 18. First, the function loops over the 11 deck points, reducing the non-reception probability by 0.3% for each (see Table 5). Then, the dormer and skylight 1ft. points are looped over, reducing non-reception by 1% at each point. Gutters are next, with a .3% reduction in probability. Vents are last, with a .5% reduction for each. At the end of this calculation, the probability of embers not landing on the home has been reduced to 9%, giving an ember reception rating of 91%. Given that the ember exposure probability is 100%, the total ember ignition probability is 91%.

4.6.5.   Wall and Window Heat Testing

After the software calculates the heat flux, it must determine how that will affect the sides of the home. How this happens depends on the location of the wall and windows and the type of siding. A test was done in which enhanced SIAM was run for a series of threats that would gradually heat the wall as the flame front approached. The values of temperature and FTP at a point on the wall were compared to the expected values (calculated from , change in time.

 and Equation 12). First, a simulated wall with vinyl siding was tested (Figure 19). Initially, the heat flux remained below the threshold of 31.8 kW/m^2, and the vinyl remained at its initial temperature. After 5 seconds, the flame was close enough to exceed the heating threshold, and the vinyl heated steadily (absorbing all the available heat) up to its melting point (543 K) after 15 seconds. Following this, the remaining heat flux went into increasing the FTP, which starts at zero at 16 seconds and increases to 16,538 after 25 seconds.

For the next test, the siding was changed to wood, so no vinyl heating would occur, and the threat comprised a large forest. The heat flux remained at ~43 kW/m^2, and the FTP function started rising immediately (Figure 20), reaching almost 25,000 in 34 seconds.

For a third test, the siding was changed to cement fiberboard. As expected, the software did not apply any FTP or heating calculations to this siding type, again verifying how the software reads in the siding type and applies its properties. As a final test, data from a window point was printed out, and it too heated according to the expected function. All test results agreed with expectations, providing confidence that the software is functioning properly.

4.6.6.   Output File Testing

The results of enhanced SIAM calculations were further processed to determine the maximum FTP values imparted to the home for all panels for threats 1,2, etc. For example, the software can be run for the structure and threat configuration shown in Figure 4.

The maximum FTP value imparted by threat 1 is 2024 to panel 1 (the furthest from the grass field), 5713 to panel 2, and 12007 for panel 3 (closest to the field). From

these data, the software calculates which value is the maximum and determines its rating. A threat which can bring the home close to ignition (FTP > 10125) receives the highest rating, while threats that contribute little to the ignition danger (FTP<3375) receive the lowest rating. (Note that a threat that poses little danger to one side of the home could represent a greater danger to another, and that several low-rated threats could combine to present a danger.) Given the example above, the greatest fire danger rating would be assigned to threat 3, based on its the maximum value of 12007.

For the siding and the windows, the software reads in the temperature and FTP data calculated earlier and identifies the wall squares that (1) ignite, if part of a wall, or (2) break, if part of windows. These values are then communicated to the GUI to assign an ignition graphics.

5. Graphical User Interface (GUI)

5.1.1. User Inputs

The user inputs information via the GUI about home features and HIZ threats.

Home features include roof style, roof material, roof features (i.e., dormers, chimneys, skylights, vents, and gutters), siding, windows, screens, shutters, and doors. The following home features are used for aesthetic value only, meaning they are not looked at as vulnerabilities in the software: roof style, non-glass doors, garage doors, screens, and shutters. These inputs provide the user an opportunity to better represent their home in the GUI.

HIZ threats include landscaping materials, outbuildings, decks, screened enclosures, fences, pools, playsets, driveways/streets, vegetation, and neighboring homes.

The following HIZ features are used for aesthetic value only and are not treated as threats by the software:

- Non-combustible structures, including outbuildings, decking, playsets, screened enclosures, and fencing

- Driveway/street, pool

- Synthetic mulch and stone bedding materials

If a home has more than one type of siding per wall, the user is instructed to select the wall material that is most combustible. WildFIRE Wizard considers wood to be the most combustible type followed by vinyl. The other options for siding material types (e.g., brick and fiber cement) are not combustible.

There are several input screens that step the user through creating a graphical representation of the home and surroundings. The first screen (Figure 21) asks the user to draw the floor plan of the home using resizable 'blocks', which the user can

rescale (by adjusting the size and height) to match the different parts of the home. There is a square footage calculator in the upper left corner that changes as the user adds or resizes blocks. The capability to add multiple blocks enables users to construct more complicated floor plans than the basic rectangle. Each block may be designated as one, two, or three stories

These inputs are all represented by their locations within the HIZ. The entire HIZ is represented by 400 x 400 x 50 points, each of a 1ft. x 1 ft. x 1ft. volume. The point (0,0,0) represents the lower left corner at ground level, with the front of the home (Side A) facing the –j direction (Figure 4).

In the second input screen (Figure 22), the user is asked to provide information about the slope of the terrain surrounding the home. This is done by setting (1) the distance from the home to the slope edge, (2) the angle of the slope, and (3) the depth of each side below ground (as for a home with three stories on one side and two on the opposite side). These three values are obtained for each side of the home.

The user is next asked for information about the roof (Figure 23), and can select and place several optional features: dormer, chimney, skylight, vent, metal gutters, vinyl gutters, and debris. The user is also asked to select the roof covering type from the following options: asphalt shingles, wood shingles, metal roof, or tile roof. Asphalt shingles are the default option, as they are the most common type of roof covering in most areas. The user can also change the roof geometry (i.e., hip, gable, flat) of each house section.

The next four screens give the user the opportunity to input various features on each side of the home. The user can select from among several door types: metal, glass, wood, single metal garage door, and double metal garage door. The user can also select from several options for windows and window coverings: single pane, dual pane metal frame, dual pane vinyl frame, dual pane wood frame, tempered glass window, metal screen, fiberglass screen, and fire-resistant shutters. The user can choose from a selection of doors and windows in the menu on the left. The selected feature may be dragged to the desired location on the wall of the home. Many features can also be resized by clicking on the bottom right corner of the object and dragging. The user also has the following options for siding type: vinyl, wood, fiber cement, or brick. Vinyl is the default option for siding type. There is a "compass" in the bottom right corner to show the user which side of the house he is facing. There is also text above the instructions that shows Front Side, Right Side, Back Side, or Left Side. A separate siding type can be selected for each of the four sides of the home. A screenshot of one of the wall feature pages (Side B) is shown Figure 24.

Next, the user is asked to input features of the HIZ (Figure 25). When the user clicks on a feature, it will appear in the top left corner of the grid. The user can drag the feature to the correct location in the HIZ. Many features can also be resized by clicking on the bottom right corner of the object and dragging. The following categories and features are available: Landscape Materials (dry grass, pine straw, mulch – synthetic, mulch – fine fuel, mulch – large fuel, stone bed), Structures

(outbuilding, outbuilding - noncombustible, deck, deck - noncombustible, screened enclosure, fence, fence - noncombustible, pool, playset, playset - noncombustible, driveway/street), Vegetation (small tree, medium tree, large tree, small shrub, medium shrub, large shrub), and Adjoining Zones (forest, dry grass, small neighboring home, medium neighboring home, large neighboring home). (Note that only the flammable objects will be used in the calculation). The grid may be resized to more accurately position the objects in the HIZ.

From the user input features of the HIZ, including how each threat is positioned, the software determines the position on the (i,j) grid, the size (Δx, Δy), and the type, expressed as a two digit code. For example, a threat file for a forest (type A1) that extends from 78 ft. to 308 ft. from the origin in the x direction and 240 ft. to 370 ft. in the y direction will be identified as in Table 12.

Table 12. Forest Threat File

Property	Value
delx	230
dely	130
xoffset	78
yoffset	240
type	A1

These data are created for all threats according to the order in which they are selected and placed, and the function loops over all of them as it calculates the heat load on each panel.

When the user selects "Next," a message appears that informs them that the program is working and a customized report is being created. The report will be e-mailed to the address entered at the home screen. And after a few minutes, an output report will appear with the recommendations based on the inputs.

5.1.2.   Outputs to User

The output report (Figure 26) provides clear and concise mitigation recommendations based on the information that was input into the software. A comparison was performed between the mitigation messages provided by WildFIRE Wizard and guidance from the Federal Emergency Management Agency (FEMA)[20] and the 2012 International Wildland-Urban Interface Code, and the WildFIRE Wizard mitigation messages are consistent.

Next to each recommendation is a link to various codes and standards associated with the hazard. There is also a link to a video clip (from the testing performed at IBHS)

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[20] FEMA guidance documents considered include the following: Home Builder's Guide to Construction in Wildfire Zones and FEMA Mitigation Policy, MRR-2-08-1.

showing the dangers of the specific hazard. Each recommendation has a dollar sign (or range of dollar signs) next to it to indicate the cost associated with implementing the recommendation. At the bottom of the recommendation report, there is a link to the FEMA, the Federal Alliance for Safe Homes (FLASH), and the National Fire Protection Association (NFPA) Firewise websites. These links will provide more information on protecting homes against wildfires.

6.   Verification of WildFIRE Wizard

6.1.1. Initial Beta Testing

WildFIRE Wizard Version 0.6 was beta tested by a variety of users (approximately 20), including fire professionals, homeowners, Firewise Community Leaders, insurance agencies, and personnel from NFPA, the National Institute of Standards and Technology, the U. S. Forest Service, the International Association of Fire Chiefs, and FEMA. The group was given a link from which they could download the software and a set of instructions. Each beta tester was asked to run the software at least five times and save the output reports. An online survey was completed by each member of the group at the end of their testing.

The feedback from the group was sorted based on topic and prioritized. Many of the recommendations were implemented, but there were some ideas that were not practical or feasible due to the project timeline and budget. A couple of these suggestions include the ability to include open porches under the roofline of the home and the ability to choose multiple siding materials for each side of the home. These items were placed on a list for potential improvements to the software in the future.

6.1.2. Peer Review of Software Development

A panel of six fire experts reviewed the software development report and provided feedback on the software's technical basis, assumptions, material properties, and calculations. The peer review panel is identified in Table 13.

Table 13. Peer Review Panel Members

Panel Member	Organization
Alex Maranghides	NIST Fire Research Division
Max Moritz	University of California, Department of Environmental Science, Policy and Management
Bret Butler	US Forest Service, Rocky Mountain Research Station's Fire Sciences Laboratory
Rob Rogers	New South Wales Rural Fire Service Headquarters
Steve Quarles	Insurance Institute for Business and Home Safety
Michele Steinberg	National Fire Protection Association Firewise Communities Program Manager

A total of 53 comments were received, and each comment was reviewed and addressed by the WIRHD program team. Explanatory text was added to this report to

answer many questions about software operation, and the GUI was modified to make it more functional and intuitive for the user.

6.1.3.   Parametric Testing on Beta Version

A comprehensive parametric study of 201 test sets was conducted to assess the performance of WildFIRE Wizard Version 1.02. The tests were designed to evaluate performance of the following core software functions: (1) receiving inputs from the graphical user interface (GUI), (2) creating appropriate data files and transferring them to enhanced SIAM, (3) performing heat transfer, temperature, and FTP calculations, and (4) creating the correct output. Users were each assigned a prescribed set of tests to run, and the results of each test and the corresponding output reports were analyzed. Four sets of tests and the results are discussed in an SRNL report entitled, "WildFire Ignition Resistance Estimator (WildFIRE) Wizard Version 1.02 Parametric Study".[21] All errors observed during parametric study were resolved in the subsequent version of the software.

6.1.4.   Verification of Calculations

The calculations of the radiant and convective heating and ember ignition probabilities in the WildFIRE Wizard needed were independently verified by ORNL. To verify the heating calculations, Microsoft Excel spreadsheets were created to perform calculations for individual threats with chosen locations on the threat and the wall.

The spreadsheets use as inputs the parameters generated by the enhanced SIAM script. The properties used as inputs by the spreadsheets are provided in Table 6.

Next, all the calculation variables and their equations are sequentially listed in the order they are calculated in enhanced SIAM. Figure 27 shows the calculation process for convection heating from a patch of dry grass 400 ft. x 80 ft., and 20 ft. away from the wall, which starts burning at the far end of the patch, away from the wall.

The calculations start with conversion of the input variables into SI units. Next, variables that remain constant with time are calculated (columns G and J, and subroutine 'fltilt').   Once these variables have been initialized, the calculation proceeds to variables that are updated with time and the subroutines ('cnvint' and 'cnvflux') which are invoked at each time step. The final output of the calculations at each time step is the convective heat flux ('qc') that impinges on a point on the wall.

In the present example (Figure 27), the flames from the burning grass are not close enough to heat the wall for the first 5 seconds ('time' = 5 under column F; 'nocvn' = 0 under columns R and T). At 6 seconds, however, the hot air column intercepts the wall ('nocvn' = 1 under column T) and at 7 seconds the flames contact the wall ('nocvn' = 2 under column T).   Column AI ('qc') calculates the convection heat flux

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[21] SRNL, 2012.

impinging on the wall due to the flames or hot air column at a height given by 'z' (column AA).

A similar spreadsheet was created for the radiation heat transfer calculations.

A third spreadsheet was developed for calculating the ember ignition probabilities. Figure 28 lists the various input variables, predefined variables ('Roof Types', 'P based on debris & roof type', 'Exposure rating', 'Ignition probability', 'Overall Ember Danger') and calculations based on the roof type and features (deck, dormer, etc.). The major outputs are Ignition Probability, Exposure Rating and Overall Ember Danger. In the present example, even with high ember exposure rating, the ignition and danger ratings are low.

6.1.5.   Test Cases on Final Version

Test cases were developed to check the final version of the software. These cases were designed to test as many of the features as possible in the most efficient number of runs. The software was temporarily modified to allow the team to extract calculation data from enhanced SIAM. Because this information is not necessary to the average user and would slow the processing time of the program, this function was removed after testing.

The spreadsheets detailed in the previous section were used to verify that the software was producing accurate results. The test cases were run through the spreadsheets and WildFIRE Wizard, and the results were compared. The results were very close and can be seen in Appendix E. A small amount of error is expected due to the limitation in the software to place a threat at an exact distance from the home.

7.   Conclusions

WildFIRE wizard is a simple software tool capable of assessing the fire danger to a home based on input provided by the homeowner or a fire professional. The software was designed for ease of use and for the clarity of its output report. The user sees a familiar 'drag-and-drop' interface to create the home, create the HIZ, and select and place specific 'threats' that should be addressed.

The software combines sophisticated calculations with probabilistic estimates to predict both the heat load on the home from flames (and whether a critical threshold is exceeded) and the possibility that windblown embers will collect on the home causing ignitions. Data from several materials tests were incorporated into the software, and the results of these tests were also used to alter the software algorithms where appropriate.

As the destruction of housing tracts by wildfire has become an annual occurrence, homeowners are increasingly being informed of specific actions they should take to make their homes less vulnerable. WildFIRE Wizard can serve this purpose by allowing them to see which features of their home and yard contribute to the danger.

8.   References

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Appendix A. Figures

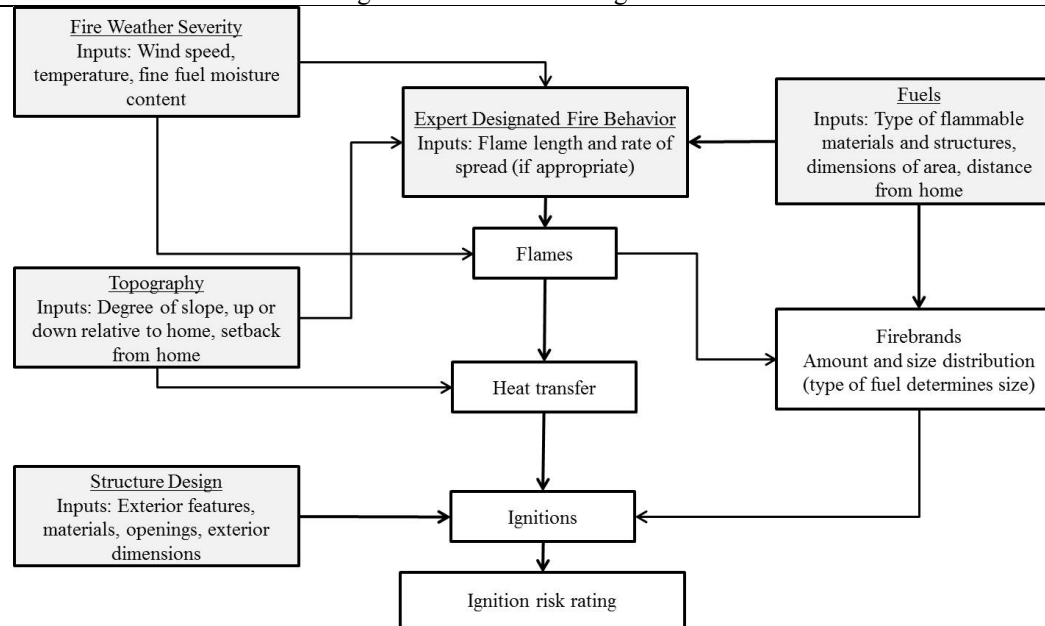| Figure 1. WildFIRE Wizard Overview |
|---|
| |
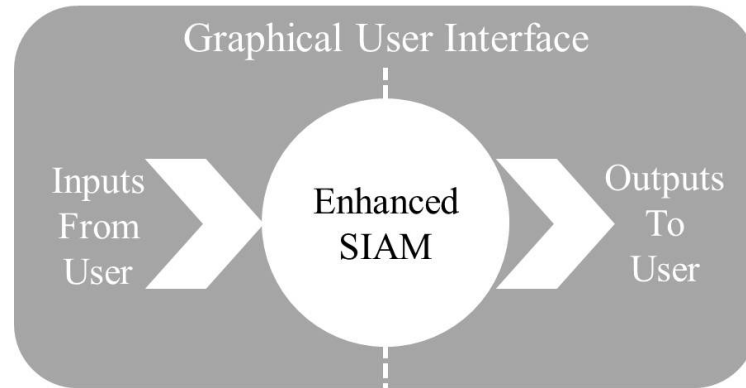
Figure 2. Overview of Original SIAM

Figure 3. Enhanced SIAM Flowchart

Home B

Panels

SIAM Prep

SIAM Q

Loop for
each threat
(#1, #2, etc)

Loop for
each side
(A, B, C, D)

Loop for
each panel
(#1, #2, etc)

SIAM Temp

SIAM FTP

Side
Assessor

Threat
Assessor

Ember
Module

Output
Report
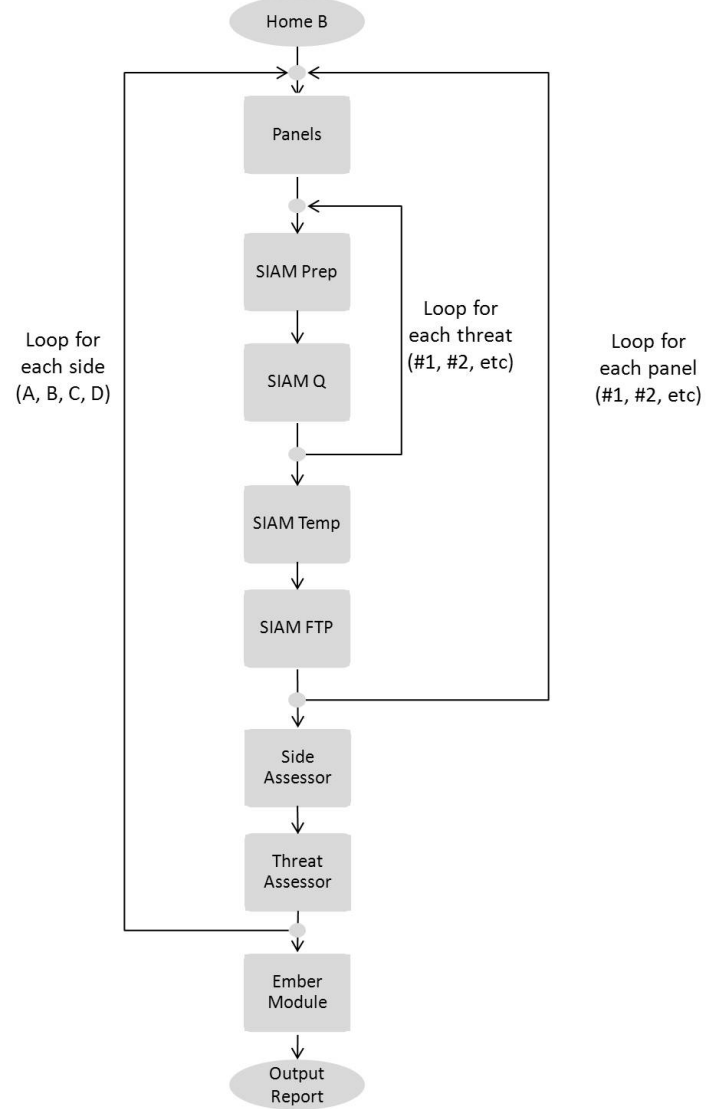
Figure 4. Example of HIZ Display
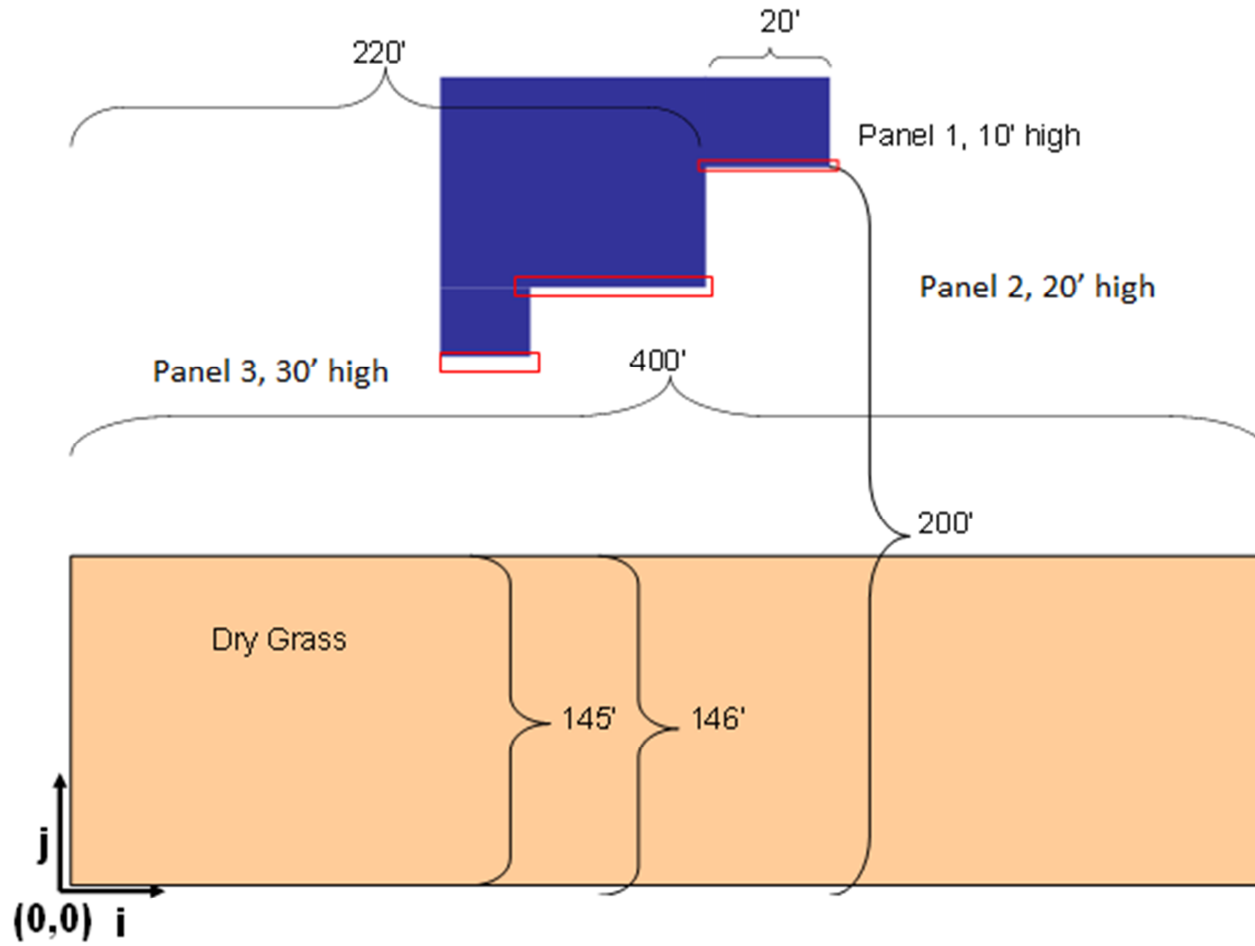
Figure 5. Schematic of tilted flame approaching a home; no interception of the hot air column (orange arrow) with the home	Figure 6. Schematic of tilted flame approaching home; hot air column intercepting the home.
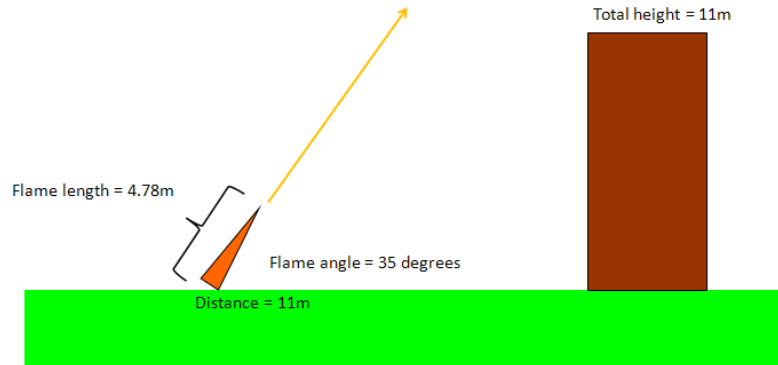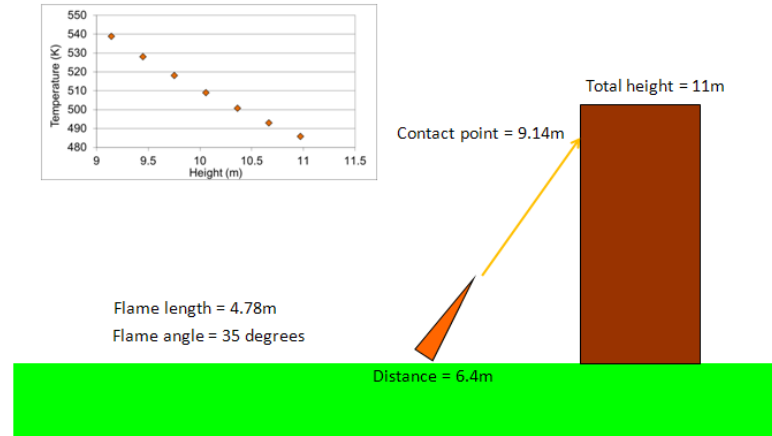
Figure 7. Schematic of flame intersecting home	Figure 8. Schematic of tilted flame intercepting the structure at the closest point
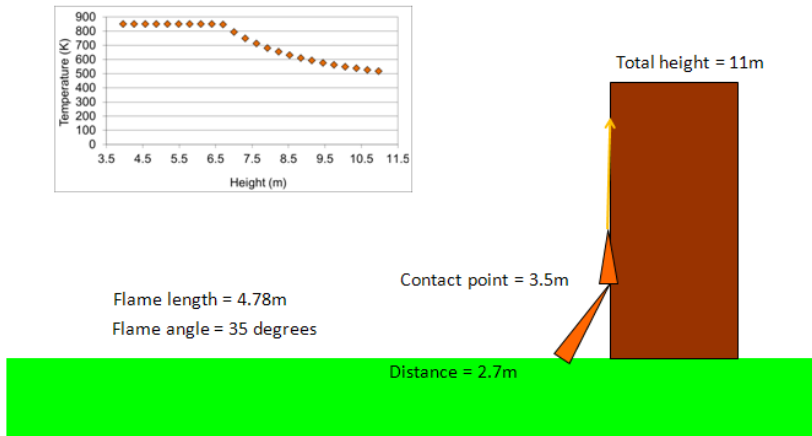
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Figure 9. Radiant Panel	Figure 10. Intertek Test 1
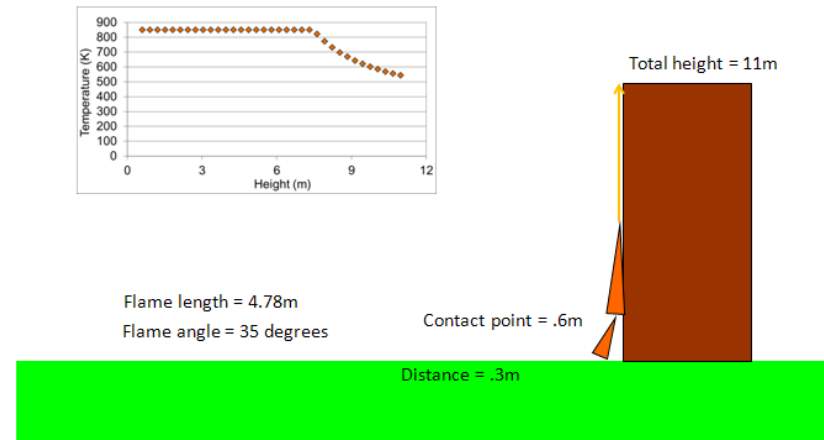
Figure 9. Radiant Panel
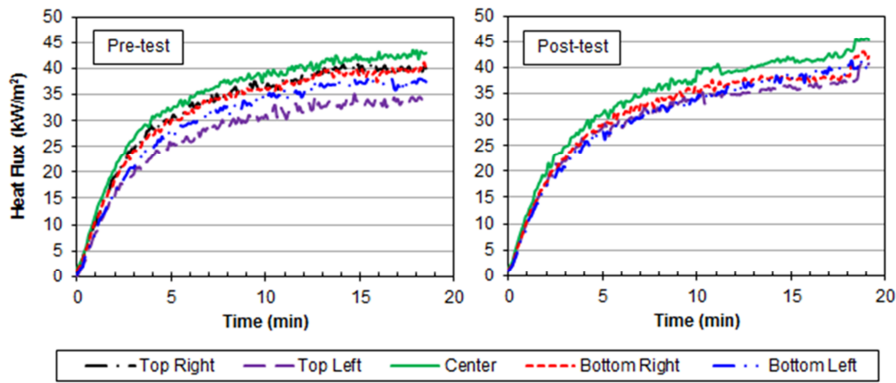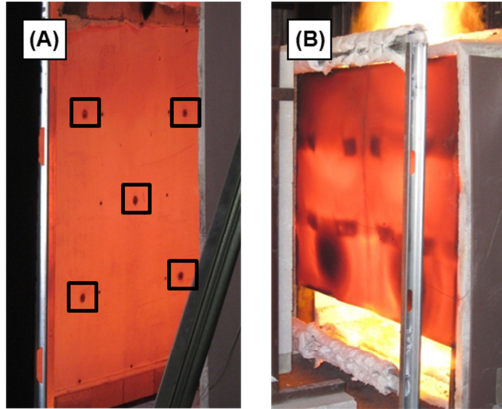
Figure 10. Intertek Test 1
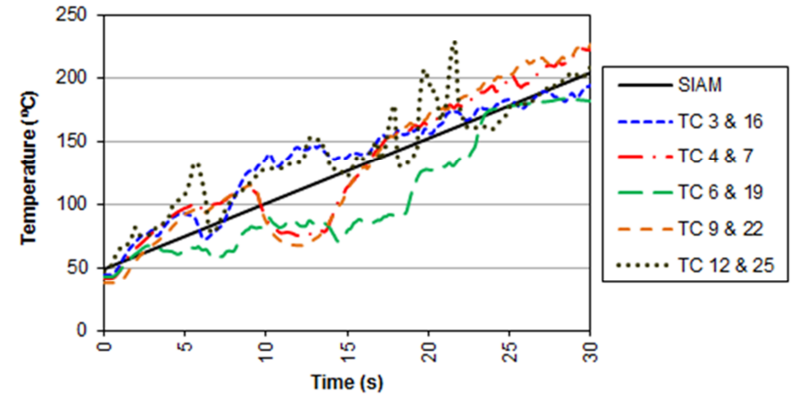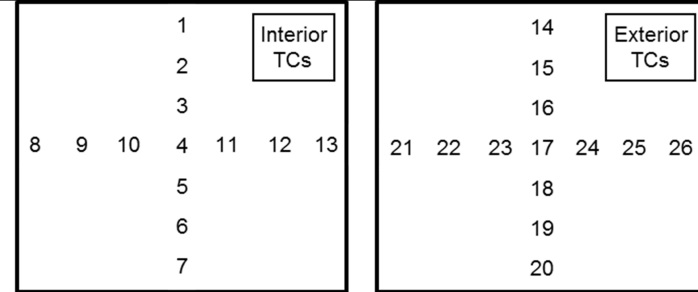
Figure 11. Intertek Test 6 FTP Curve

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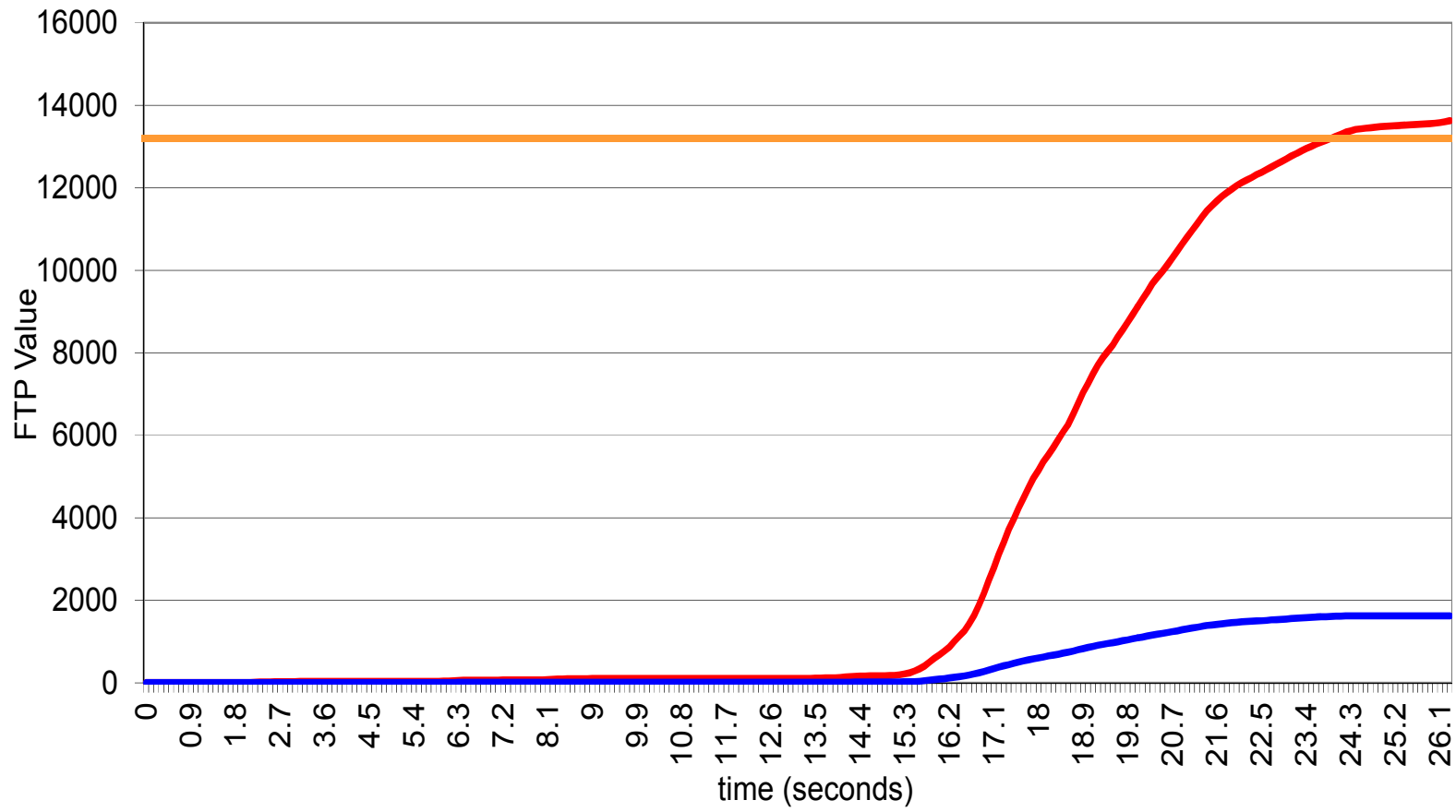
Figure 12. Intertek Test 5

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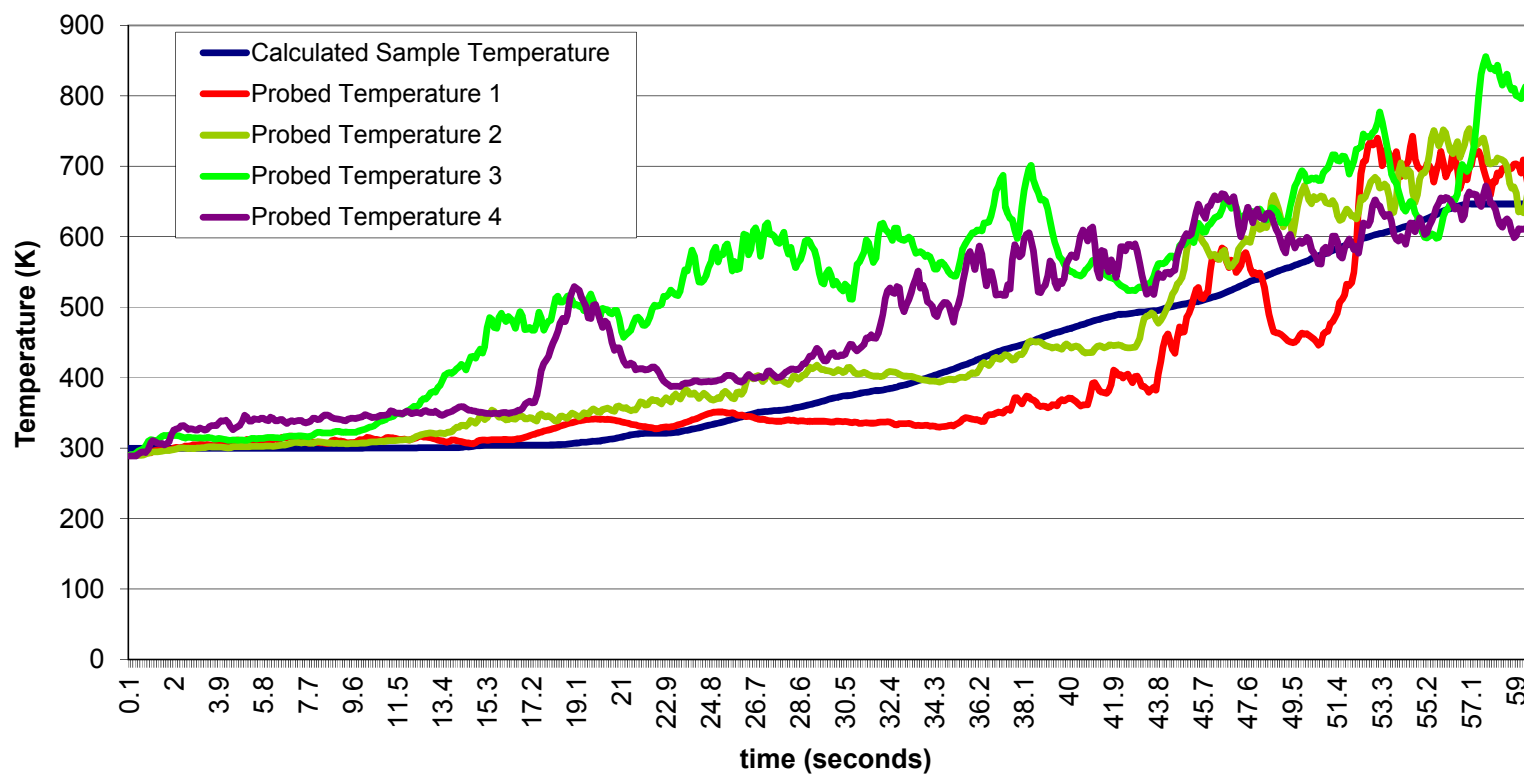
Figure 13. Schematic of Home and Property for Slope Test
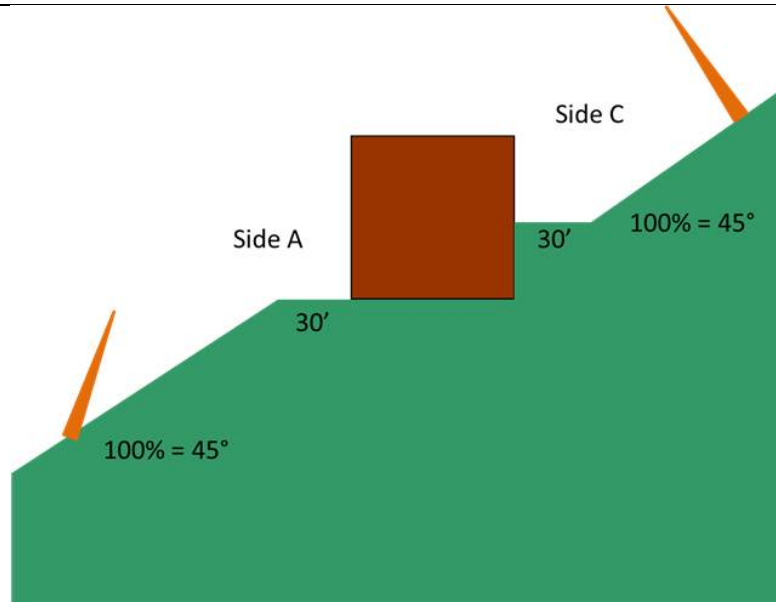
Figure 14. Home with Threats and Windows Added

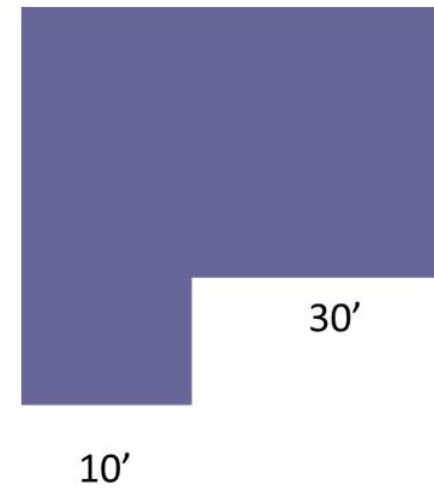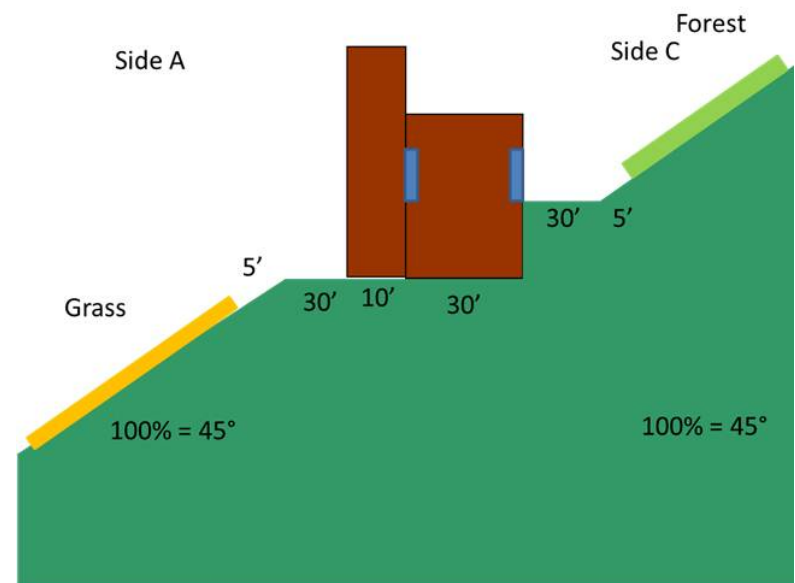Figure 15. Canyon Home: Radiant Heat Flux and Resulting Temperature
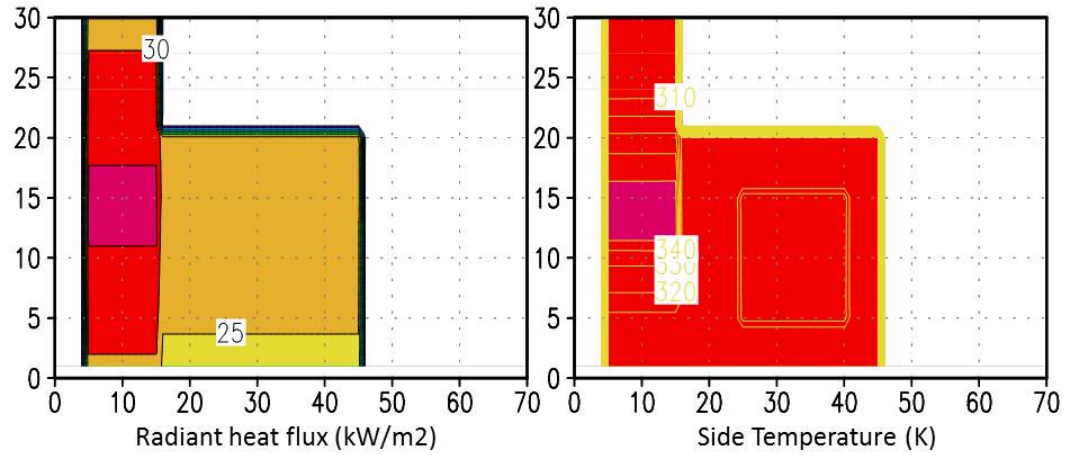
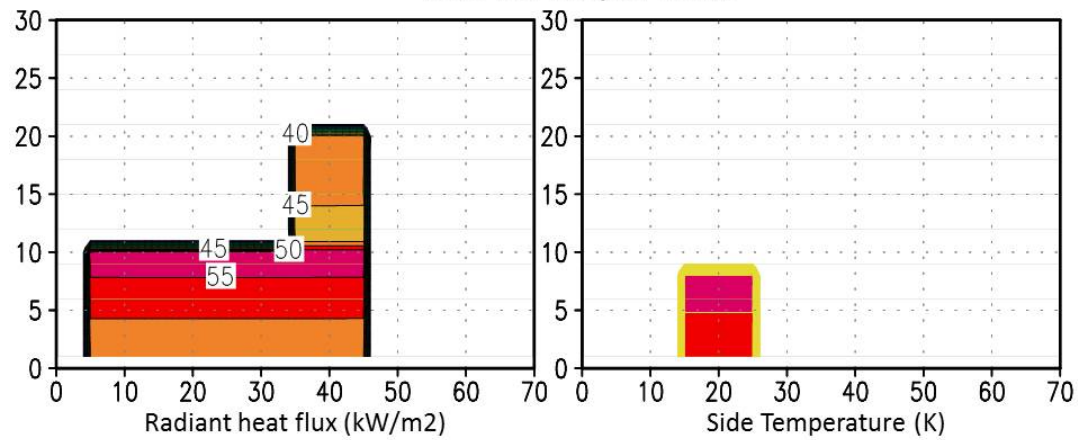Figure 16. Comparison of Results Between PATRAN and Enhanced SIAM

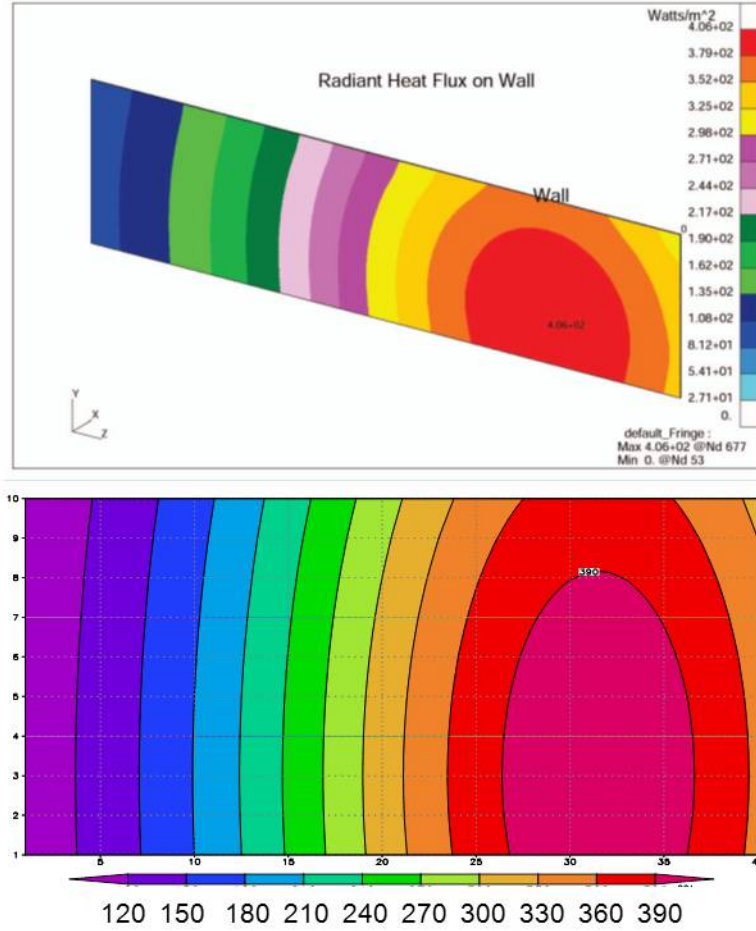Figure 16. Comparison of Results Between PATRAN and Enhanced SIAM

Figure 17. Comparison of Results Between PATRAN and Enhanced SIAM with Flame Tilted
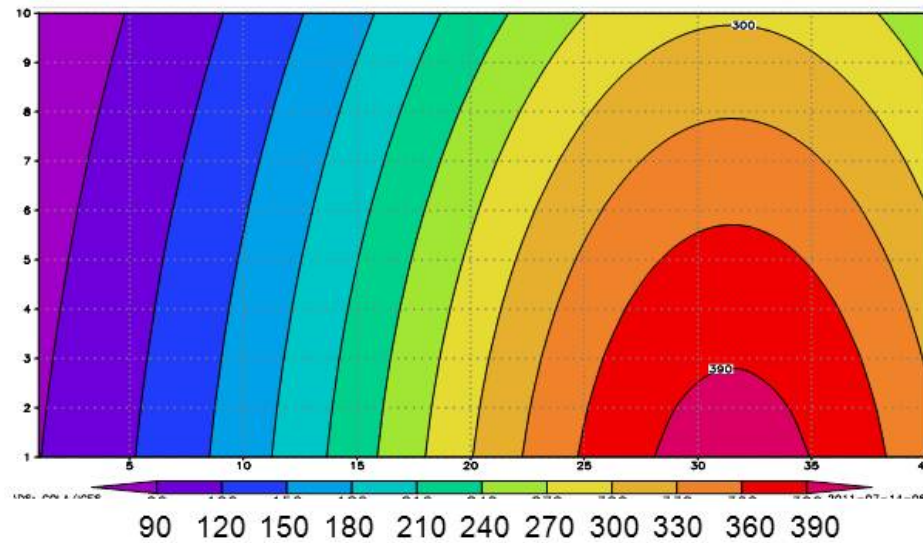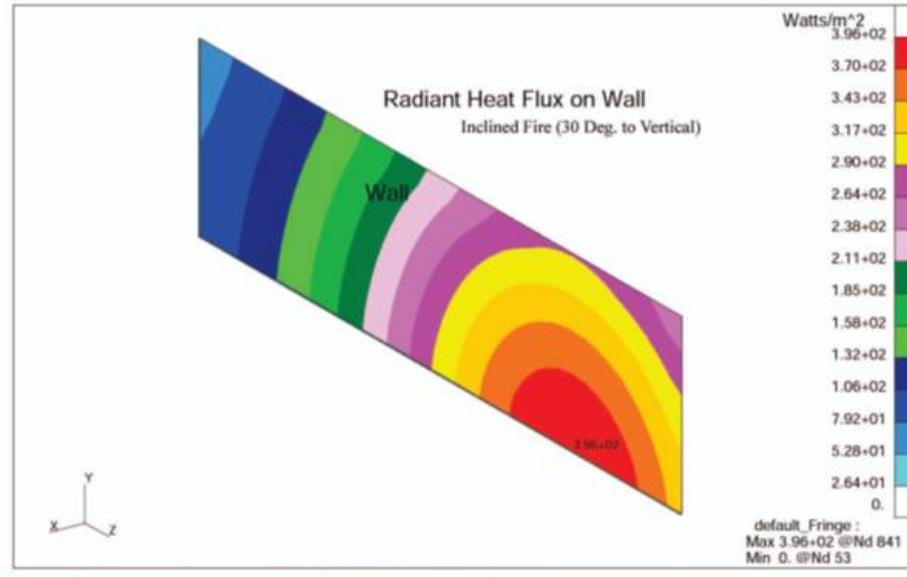
Figure 18. Ember Reception Probability

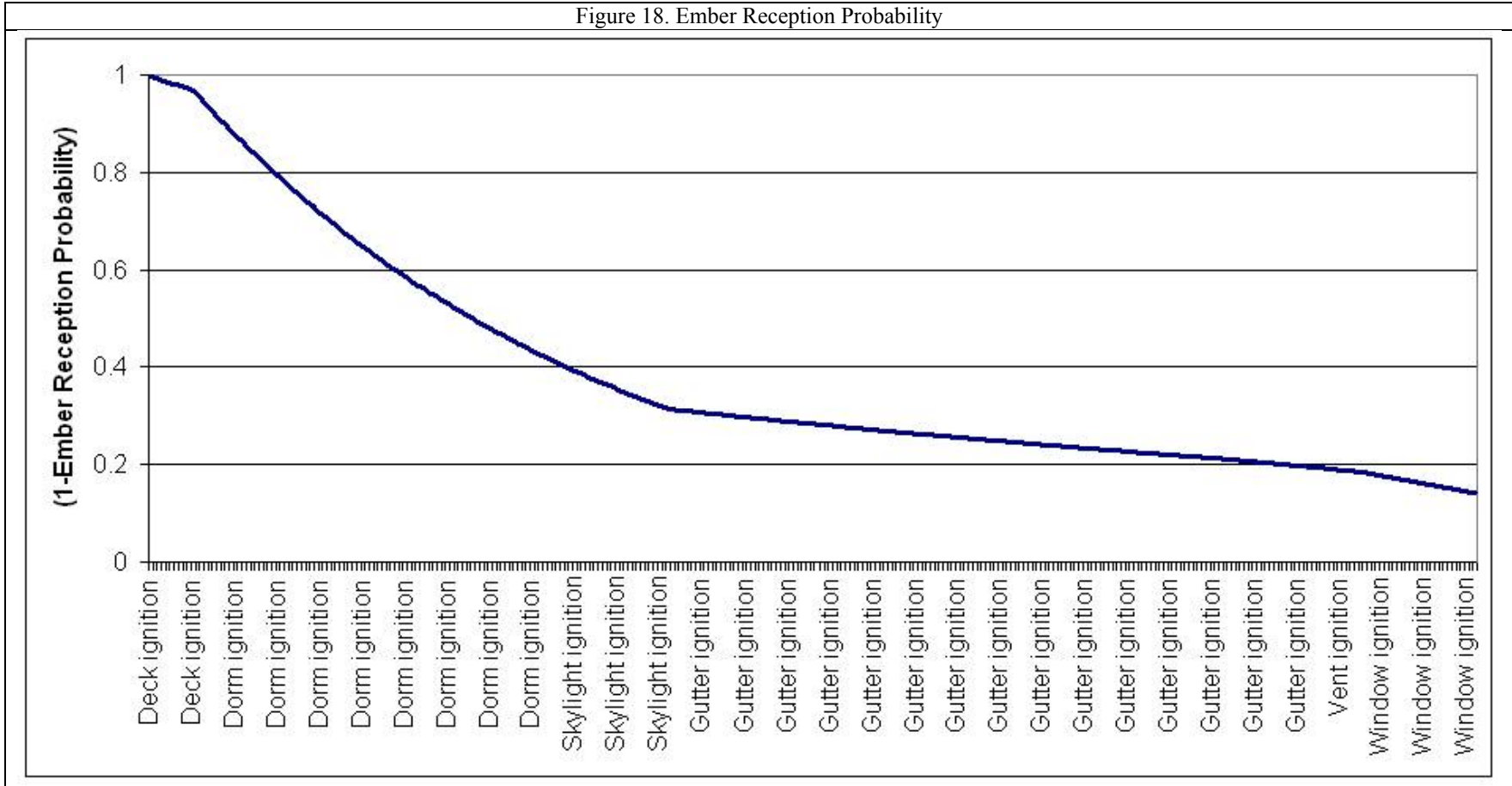Figure 19. SIAM-calculated vinyl temperature and exposed side FTP value for an experiment with vinyl-siding.
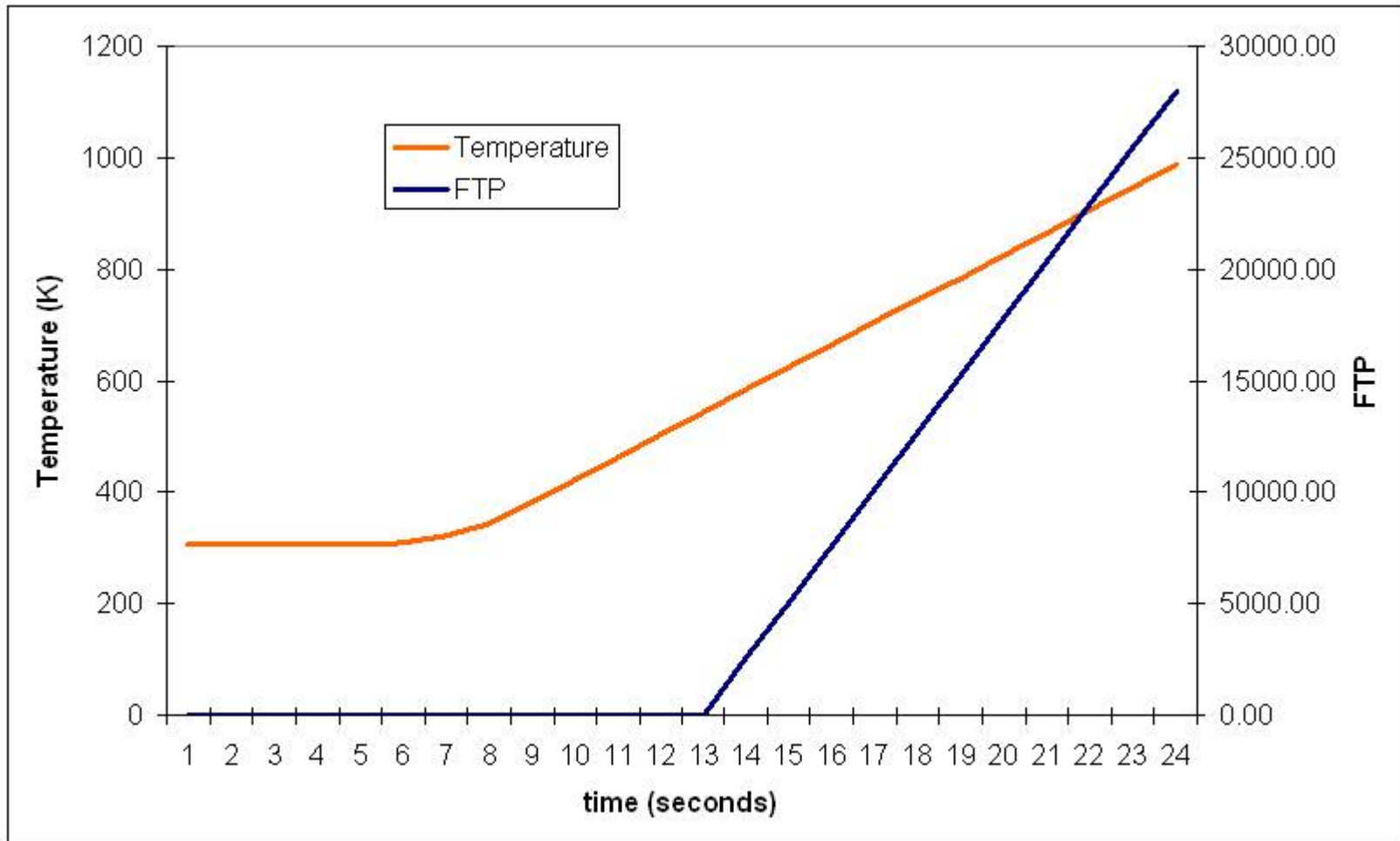
Figure 20. Enhanced SIAM-calculated FTP value for an experiment with wood siding.
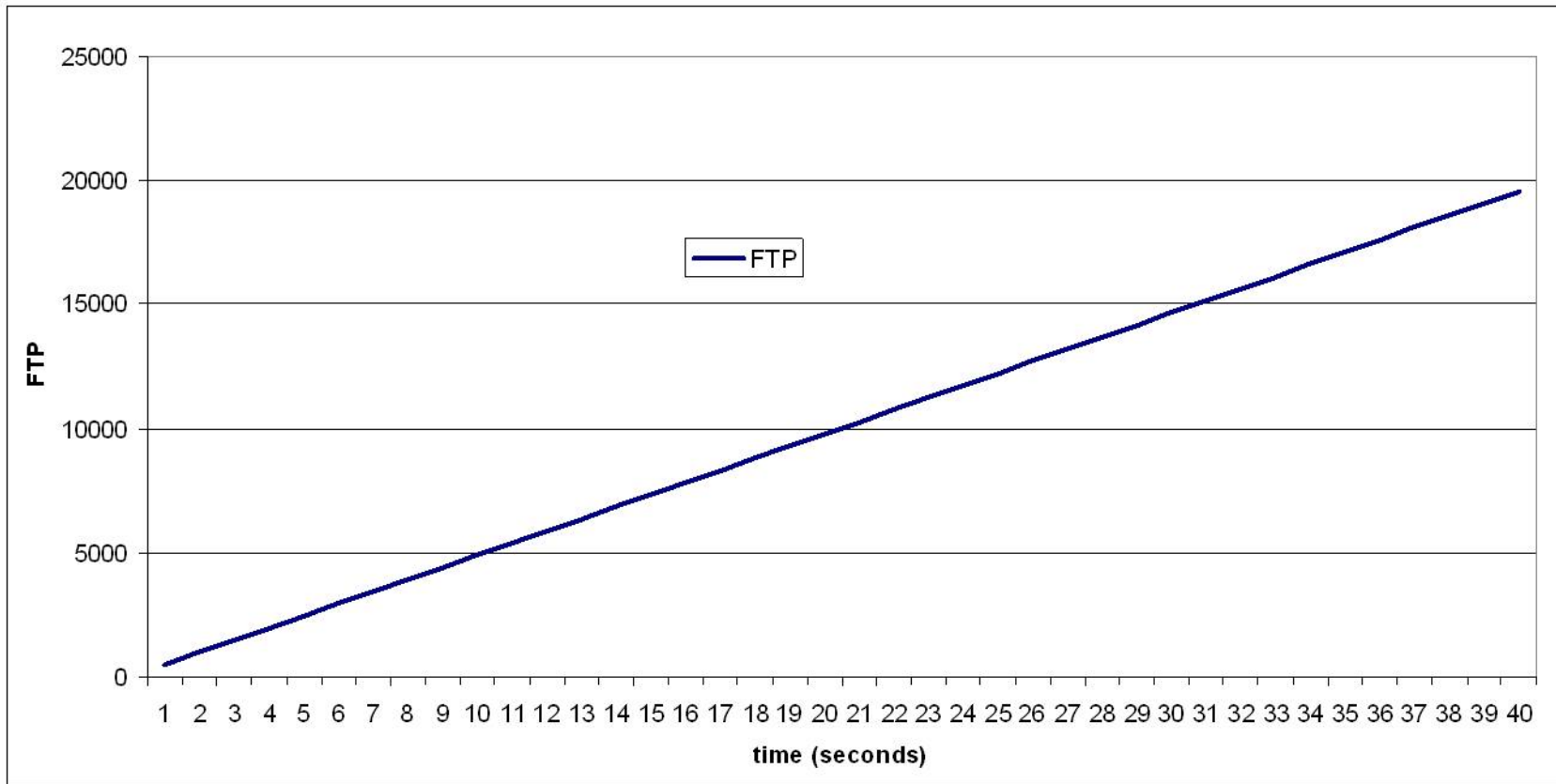
Figure 21. GUI Plan View Screen

Figure 22. GUI Slope Input Screen

Figure 23. GUI Roof Features Screen

Figure 24. GUI Wall Feature Input Screen

Figure 25. GUI Home Ignition Zone Input Screen

Figure 26. GUI Output Report to User

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Figure 27. Calculation procedure for convective heating at a point on the wall

Top table

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	
	User Inputs		conversion factor	SI																		
	dry grass																					
ir		3516	0.189273	665.484		beta	0		tmptime	0												
hl		8000	2.32598	18607.8		fldpth	32.4612		hfdelta	1		subroutine 'fltilt'										
brntime		15	1	15		slpdist	16.3068		prflag	1		mlrate	n	betawind	flht	alpha						
ros		426	0.00508	2.16408		spdtime	7					1.16093	2.155	2.062	28.84933	0.532922						
ffm		3	1	3		tottime	22															
uwind		10	0.44704	4.4704					subroutine 'cnvint'													
temps		90	F to K	305.222		time	flgth	slpdist	hfdelta	hflame	hslp	alpha	nocvn	htot	dtot	hcnv	psi	nocvn	cnvln	nocvn	flgth	
fueldst		10	0.3048	3.048		1	7.641395	16.3068	1	0	0	0.532922	FALSE	12.192	16.3068	27.64571	0.642004		0	FALSE	0	7.641395
dset		0.00E+00	0.3048	0		2	7.641395	14.14272	1	0	0	0.532922	FALSE	12.192	14.14272	23.97684	0.711459		0	FALSE	0	7.641395
pcpslp		0.00E+00	1	0		3	7.641395	11.97864	1	0	0	0.532922	FALSE	12.192	11.97864	20.30797	0.794225		0	FALSE	0	7.641395
updwn		1	1	1		4	7.641395	9.81456	1	0	0	0.532922	FALSE	12.192	9.81456	16.6391	0.893014		0	FALSE	0	7.641395
fuelwd		400	0.3048	121.92		5	7.641395	7.65048	1	0	0	0.532922	FALSE	12.192	7.65048	12.97023	1.010401		0	FALSE	0	7.641395
fueldp		150	0.3048	45.72		6	7.641395	5.4864	1	0	0	0.532922	FALSE	12.192	5.4864	9.301361	1.147942	FALSE	3.157489	1	7.641395	
xoffset		-220	0.3048	-67.056		7	7.641395	3.32232	1	0	0	0.532922	FALSE	12.192	3.32232	5.632491	1.304756	FALSE	-1.10207	2	6.539324	
zoffset		0.00E+00	0.3048	0		8	7.641395	3.048	0	0	0	0.532922	FALSE	12.192	3.048	5.167423	1.325818	FALSE	-1.64202	2	5.99938	
hstr		40	0.3048	12.192		9	7.641395	3.048	0	0	0	0.532922	FALSE	12.192	3.048	5.167423	1.325818	FALSE	-1.64202	2	5.99938	
wstr		20	0.3048	6.096		10	7.641395	3.048	0	0	0	0.532922	FALSE	12.192	3.048	5.167423	1.325818	FALSE	-1.64202	2	5.99938	
						11	7.641395	3.048	0	0	0	0.532922	FALSE	12.192	3.048	5.167423	1.325818	FALSE	-1.64202	2	5.99938	
						12	7.641395	3.048	0	0	0	0.532922	FALSE	12.192	3.048	5.167423	1.325818	FALSE	-1.64202	2	5.99938	

Bottom table

	A	B	C	D	E	F	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
	User Inputs		conversion factor	SI																	
	dry grass																				
ir		3516	0.189273	665.484		beta															
hl		8000	2.32598	18607.8		fldpth															
brntime		15	1	15		slpdist															
ros		426	0.00508	2.16408		spdtime				Mid point of wall (1)		2									
ffm		3	1	3		tottime				or specified height below (2)											
uwind		10	0.44704	4.4704						Height at which conv heat flux is needed:		15	subroutine 'cnvflux'								
temps		90	F to K	305.222		time	z	tempc	nx	nz	flcol	z	x	omega	fli	tempc	tempc	tempc	qc	qc	slpdist
fueldst		10	0.3048	3.048		1	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	0	14.14272
dset		0.00E+00	0.3048	0		2	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	0	11.97864
pcpslp		0.00E+00	1	0		3	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	0	9.81456
updwn		1	1	1		4	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	0	7.65048
fuelwd		400	0.3048	121.92		5	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	0	5.4864
fueldp		150	0.3048	45.72		6	FALSE	FALSE	20	40	0	15	3.048	8.856128	21451.52	641.1169	641.1169	641.1169	19.62297	19.62297	3.32232
xoffset		-220	0.3048	-67.056		7	0.855776211	962.112	20	40	1.102071	15	3.048	8.265438	21451.52	665.4948	665.4948	665.4948	21.04713	21.04713	1.15824
zoffset		0.00E+00	0.3048	0		8	0.78511579	966.8419	20	40	1.642015	15	3.048	8.190562	21451.52	668.8361	668.8361	668.8361	21.24232	21.24232	0.88392
hstr		40	0.3048	12.192		9	0.78511579	966.8419	20	40	1.642015	15	3.048	8.190562	21451.52	668.8361	668.8361	668.8361	21.24232	21.24232	0.88392
wstr		20	0.3048	6.096		10	0.78511579	966.8419	20	40	1.642015	15	3.048	8.190562	21451.52	668.8361	668.8361	668.8361	21.24232	21.24232	0.88392
						11	0.78511579	966.8419	20	40	1.642015	15	3.048	8.190562	21451.52	668.8361	668.8361	668.8361	21.24232	21.24232	0.88392
						12	0.78511579	966.8419	20	40	1.642015	15	3.048	8.190562	21451.52	668.8361	668.8361	668.8361	21.24232	21.24232	0.88392

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Figure 28. Calculation Procedure for Ember Probabilities

Input Variable	Value	Remarks
NumWin	25	
RoofType	2	Asphalt Shingles
RoofDebris	N	
DeckLength	11	
DormLength	132	
ChimLength	0	
SkyLength	28	
TotalGutLengthMet	130	
TotalGutLengthVin	25	
NumVents	0	
HomeSAP	A4b	Ember exposure

Roof Types				Exposure rating	
0	Wood			0	Very Low
1	Clay tile			0.05	Low
2	Asphalt Shingles			0.25	Moderate
3	Metal			0.75	High
				0.95	Very High

P based on debris & roof type	
0	Rooftype=1
0.005	Rooftype=0

Ignition probability				Overall Ember Danger	
0	Very Low			0	Very Low
0.05	Low			5	Low
0.25	Moderate			25	Moderate
0.75	High			75	High
0.95	Very High			95	Very High

Deck effect		
Pig	1	
Pold (=Pig)	1	
P	0.003	
n	11	
Pig	0.9675	FALSE

Based on roof type & debris	
P	0

Dormer effect		
Pold (=Pig)	0.9675	
n	132	
Pig	0.9675	FALSE

Chimney effect		
Pold (=Pig)	0.9675	
n	0	
Pig	0.9675	FALSE

Skylight effect		
Pold (=Pig)	0.9675	
n	28	
Pig	0.9675	FALSE

Gutter effect (metal)		
Pold (=Pig)	0.9675	
P	0.003	
n	130	
Pig	0.9675	FALSE

Gutter effect (vinyl)		
Pold (=Pig)	0.9675	
P	0.004	
n	25	
Pig	0.9675	FALSE

Vent effect		
Pold (=Pig)	0.9675	
P	0.005	
n	0	
Pig	0.9675	FALSE

Broken window effect		
Pold (=Pig)	0.9675	
P	0.01	
n	25	
Pig	0.7525	High ember receptivity
Pig (=1-Pig)	0.2475	
Ignition Probability	**Low**	

Exposure rating %		
Pf(f)	75	
Exp	0.75	
Exposure rating	**High**	

Overall Ignition Probability		
IgnProb	18	
Overall Ember Danger	**Low**	

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Appendix B. Home Feature Characteristics

Feature	Radiant Calculation	Convective Calculation	Ember Calculation	No Calculation	Code Used by GUI	Output to SIAM
Home Footprint				X	i,j,k coordinates	
Property Slope	Yes	Yes			slope, setback, depth	
Gable Roof				X	RG	
Hip Roof				X	RH	
Flat Roof				X	RF	
Asphalt Shingles			Yes		C1	2
Wood Shingles			Yes		C2	0
Metal Roof			Yes		C3	3
Clay Tile Roof			Yes		C4	1
Dormer			Set Perimeter Length		M1	Quantity, Code
Chimney			Set Perimeter Length		M2	Quantity, Code
Skylight			Set Perimeter Length		M3	Quantity, Code
Vent			Quantity of vents		M4	Quantity, Code
Metal Gutter			Length of each section		GM	Length, Code
Vinyl Gutter			Length of each section		GV	Length, Code
Debris			Yes		Y/N	Y / N
Metal Exterior Door				X	D1	
Wood Exterior Door				X	D3	
Glass Exterior Door	Tempered Window	Tempered Window			D2; i,j,k	i,j,k,W5

Feature	Radiant Calculation	Convective Calculation	Ember Calculation	No Calculation	Code Used by GUI	Output to SIAM
Single Garage Door				X	D4	
Double Garage Door				X	D5	
Single Pane Window	Size, Location, Type	Size, Location, Type	if breakage		W1; i,j,k	i,j,k,W1
Double Pane Window Metal	Size, Location, Type	Size, Location, Type	if breakage		W2; i,j,k	i,j,k,W2
Double Pane Window Vinyl	Size, Location, Type	Size, Location, Type	if breakage		W3; i,j,k	i,j,k,W3
Double Pane Window Wood	Size, Location, Type	Size, Location, Type	if breakage		W4; i,j,k	i,j,k,W4
Tempered Window	Size, Location, Type	Size, Location, Type	if breakage		W5; i,j,k	i,j,k,W5
Metal Screen				X	W6	
Fiberglass Screen				X	W7	
Fire Resistant Shutters				X	W8	
Vinyl Siding	Material Type	Material Type			I1	1
Wood Siding	Material Type	Material Type			I2	2
Fiber Cement Siding	Material Type	Material Type			I3	3
Brick Siding	Material Type	Material Type			I4	4

Appendix C. Threats and Properties

HIZ Threats	Radiant Calculation	Convective Calculation	Ember Calculation	No Calculation	Code Used by GUI	Code Used by SIAM
Dry Grass	Yes	Yes			L1	L1;i,j,dx,dy
Pine Straw	Yes	Yes			L2	L2;i,j,dx,dy
Synthetic Mulch				X	L3	
Bark Mulch	Yes	Yes			L4/L5	L4/L5,i,j,dx,dy
Stone				X	L6	
Outbuilding	Yes	Yes			S1; i,j	S8; i,j,dx,dy
Outbuilding - Noncombustible				X		
Deck			Yes		S2; i,j	S2; i,j,dx,dy
Deck - Noncombustible				X	S9	
Screened Enclosure				X	S3	
Fence	Yes	Yes			S4	S4,i,j,dx,dy
Fence - Noncombustible				X	S11	
Pool				X	S5	
Playset	Yes	Yes			S6	S10;i,j,dx,dy
Playset - Noncombustible				X		
Driveway / Street				X	S7	
Small Tree	Yes	Yes			V1; i,j	V1; i,j,dx,dy
Medium Tree	Yes	Yes			V2; i,j	V2; i,j,dx,dy
Large Tree	Yes	Yes			V3; i,j	V3; i,j,dx,dy
Small Shrub	Yes	Yes			V4; i,j	V4; i,j,dx,dy
Medium Shrub	Yes	Yes			V5; i,j	V5; i,jdx,dy
Large Shrub	Yes	Yes			V6; i,j	V6; i,j,dx,dy
Forest	Yes	Yes			A1	A1;I,j,dx,dy

HIZ Threats	Radiant Calculation	Convective Calculation	Ember Calculation	No Calculation	Code Used by GUI	Code Used by SIAM
Dry Grass	Yes	Yes			A2	A2;I,j,dx,dy
Small Neighboring Home	Yes	Yes			A3; i,j	A3; i,j,dx,dy
Medium Neighboring Home	Yes	Yes			A4; i,j	A4; i,j,dx,dy
Large Neighboring Home	Yes	Yes			A5; i,j	A5; i,j,dx,dy

Appendix D. Firebrand Ignition Assessment Procedure

Title: Firebrand Ignition Assessment Procedure

Author: Jack Cohen, US Forest Service

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Various extreme-case firebrand exposure levels can generally be characterized based on the vegetation type, continuity, and proximity. The ignition potential of the structure to such exposures then depends on its design, materials, and perhaps its state of "housekeeping." Although firebrand exposure cannot be predicted, the same extreme-case approach for flames can be used but more subjectively. An estimated probability of firebrand ignition can be subjectively generated as a conditional probability of the firebrand exposure and the receptivity of the house to firebrand ignitions.

Firebrand Exposure Probability, (P(f))

The firebrand exposure is subjectively weighted and evaluated considering the predominant surrounding burning sources beyond the home ignition zone (HIZ), which is typically vegetation but might be structures in higher density suburbs. Firebrand sources specific to a house would be identified within 60 meters of the house and more typically would be within the HIZ. The surrounding source provides a baseline evaluation that can be increased by other more specific sources. For example, the house might be surrounded by a grass prairie but have a cluster of tall conifers designated as burning within the HIZ. Without any other sources, the conifers would produce the worst-case firebrand exposure because of the source type and the proximity. The firebrand exposure probability for the entire house (all aspects) is determined by the highest producing firebrand exposure. The exception is the enhanced exposure due to convection interception that would be side specific.

The fire brand exposure probability is determined by the principle firebrand source, the source area, and the source proximity.

The principal firebrand source choices are below, and each is identified by the corresponding upper case letter:

A) Coniferous trees, flammable shrubs/chaparral (> 2 m tall)
B) Structures
C) Shrubs (< 2 m tall) and tall coarse grass
D) Grass

E) None within 1/3 mile of the home.

The source area choices are listed below, and each is identified by the corresponding number:

1) Continuous large scale burning (flame front >500 m)
2) Continuous smaller scale burning (flame front <500 m)
3) Clumps burning (flame front <30 m)
4) Individual trees/tall shrubs burning

The source proximity choices are listed below, and each is identified by the corresponding lower case letter:

a) Fire convection interception; (yes/no as currently calculated)
b) Within the HIZ (~30 meters from the house)
c) Within 60 meters of the house
d) Within ½ kilometer of the house
e) Beyond ½ kilometer of the house

Table 1 provides the firebrand exposure probability given possible combinations of principle firebrand source, source area, and source proximity.

The degree (exposure "probabilities") of exposure was subjectively evaluated based on personal understanding and perceptions of physical firebrand factors affecting the ember characteristics and lofting distance. Woody vegetation produces denser, longer burning embers. Tall vegetation produces higher velocity flame flow that strips off more and larger burning material as well as longer lofting distances given the same ember size and ambient wind speeds.

House Reception Probability, P(h)
Sustained ignitions depend on the house characteristics to collect sufficient sizes and numbers of firebrands (the exposure probability estimate above) on <u>flammable</u> materials at exterior locations and/or penetrating to interior locations. This is called the house reception probability, P(h). The reception probability is assessed for each side of the house.

It is reasonable to assume that locations of sustained ignition will depend on firebrands collecting in areas having multiple abutting or adjacent ignitable surfaces (i.e., nooks and crannies). For example, vulnerable locations include deck-to-wall junctions, wall-to-roof junctions, and door and window coves and ledges. It is physically consistent to assume that the greater the number of corners and the more lineal extent of junctions, the greater the reception probability. (Note: The self-extinguished flaming of vertical flat wall boards during US Forest Service crown fire experiments suggests insignificant potential for firebrand ignitions on horizontal flat wood surfaces without adjoining surfaces.)

Flammable roof coverings are not wall/aspect specific and might be considered one of the house aspects or sides. Flammable roofs have empirically shown extreme receptivity such that even relatively limited roof areas readily produce ignitions.

Table 1. Firebrand Exposure Probability

	0%	25%	50%	75%	100%
A1		A1e		A1d	A1a, A1b, A1c
A2	A2e		A2d		A2a, A2b, A2c
A3	A3e	A3d	A3c		A3a, A3b
A4	A4d, A4e	A4c		A4b	A4a
B2	B2e	B2d	B2c	B2b	B2a
B3	B3d, B3e	B3c	B3b		B3a
B4	B4d, B4e, B4c		B4b		B4a
C1	C1e	C1d	C1c	C1b	C1a
C2	C2e, C2d		C2c	C2b	C2a
C3	C3d, C3e	C3c		C3b	C3a
D1	D1d, D1e, D1c	D1b		D1a	
D2	D2d, D2e, D2c	D2b		D2a	
D3	D3c, D3d, D3e	D3b		D3a	

*Notes:

- *A "B1" situation does not seem reasonable and has not been evaluated.*
- *A "C4" situation does not apply.*
- *A "D4" situation does not apply.*

Receptivity greatly increases or becomes an ignition problem when accumulations of fine fuels (e.g. pine needles in rain gutters) ignite and produce flaming and/or smoldering combustion that contacts the house. Although the assessment process is largely limited to fixed house materials and design, the inclusion of transient occurrences of needle litter, firewood piles, and other debris can be included to emphasize debris-free conditions.

Unobstructed openings in the house exterior allow firebrand penetration to the house interior and thereby increase the likelihood of firebrand ignitions. Unobstructed openings include unscreened (or insufficiently screened) vents, gaps in roof tiles, collapsed window glazing, and any other penetration features that occur. Without further information, it is assumed that penetrating firebrands collect on interior flammable materials.

Probabilities of house receptivity are assigned/evaluated for each nook and cranny factor (P(nc)) and penetration factor (P(p)). The overall house receptivity is the probability that at least one factor produces a sustained ignition. This is determined to be one minus the probability that none of the factors produce an ignition. The P(h) becomes:

$$P(h) = 1 - [(1-P(nc)_1) \times \ldots \times (1-P(nc)_n) \times (1-P(p)_1) \times \ldots \times (1-P(p)_m)]$$

Exterior materials and design:
- Flammable/nonflammable roof covering (e.g. wood/comp, metal, tile)
- Flammable inside corners (3 sides, e.g. deck and 2 adjoining walls)
- Flammable inside junctions (2 sides, e.g. deck and 1 adjoining wall)
- Flammable debris on and abutting house exterior:
- Needle and leaf litter deposits (rain gutters, corners and junctions)
- Wood piles (e.g. firewood, lumber, etc.)
- Other flammable debris
- Firebrand interior penetration:
- Unscreened vents and openings
- Gaps at ends and laps of roofing (e.g. tiles and metal)
- Screened openings (>3 mm/1/8 in mesh)
- Collapsed window glazing (conditional on fracture)

Firebrand Ignition Probability, P(ig)

Given a firebrand exposure probability (P(f)) and the house reception probability (P(h)), the firebrand ignition estimate is determined by the conditional probability of the firebrand exposure and house receptivity: P(ig) = P(f) x P(h).

Appendix E. Parametric Study Data

Test	Model Vf	Excel Vf	Model Qmax	Excel Qmax	Model hcnv	Excel hcnv	Model zmin, T(zmin)	Excel zmin ,T(zmin)	Model zmax, T(zmax)	Excel zmax ,T(zmax)
VC-EXCEL-001 Side A	-3.7314e-7	-3.7314e-7	128.44137	128.8074	4.137	4.137	4.2672, 850	4.2672, 850	8.8392, 850	8.8392, 850
VC-EXCEL-001 Side B	-2.07093e-7	-2.0709e-7	88.27	88.53	1.69	1.69	1.8288, 850	1.8288, 850	8.8392, 702.8475	8.8392, 702.8475
VC-EXCEL-001 Side C	-7.0707161e-7	-7.0707e-7	88.1904	88.504	3.377	3.377	3.6576,850	3.6576,850	8.8392,654.11	8.8392, 654.1
VC-EXCEL-001 Side D	8.1927e-7	8.1927e-7	70.95	71.2	6.205	6.205	6.4008,850	6.4008, 850	8.8392, 846.1057	8.8392, 846.0571
VC-EXCEL-002 Side A	-8.94e-8	-8.938e-8	104.15	104.47	3.72	3.723	3.9624, 850	3.9624, 850	8.8392, 850	8.8392, 850
VC-EXCEL-002 Side B	-7.122e-8	-7.122e-8	88.19	88.51	3.377	3.378	3.6576, 850	3.6576, 850	8.8392, 654	8.8392, 654
VC-EXCEL-002 Side C	-7.935e-8	-7.935e-8	88.19	88.51	3.378	3.378	3.36576, 850	3.6576, 850	8.8392, 654	8.8392, 654
VC-EXCEL-002 Side D	-8.94e-8	-8.94e-8	104.15	104.47	3.72	3.72	3.9624, 850	3.9624, 850	8.8392, 850	8.8392, 850
VC-EXCEL-003 Side A	-2.47789e-7	-2.477e-7	92.9	93.1432	2.075	2.075	2.1336, 850	2.1336, 850	8.8392, 850	8.8392, 850
VC-EXCEL-003 Side B	-5.03577e-7	-5.09358e-7	88.3	88.62	2.4309	2.4309	2.4384,850	2.4384,850	8.8392, 605.1	8.8392, 605.1
VC-EXCEL-003 Side C	-5.178e-7	-5.1784e-7	124.68	125.08	2.54	2.54	2.7432, 850	2.7432, 850	8.8392, 609.16	8.8392, 609.156
VC-EXCEL-003 Side D	-2.9266e-7	-2.9266e-7	91.88	92.125	2.302	2.302	2.4384, 850	2.4384,850	8.8392, 850	8.8392, 850
VC-EXCEL-004 Side A	-4.043e-7	-4.04e-7	91.74	91.98	2.805	2.805	3.048,850	3.048, 850	8.8392, 850	3.048, 850
VC-EXCEL-004 Side B	-7.658e-7	-7.658e-7	87.7	88.05	3.864	3.864	3.9624, 850	3.9624, 850	8.8392, 700.2	8.8392, 700.26
VC-EXCEL-004 Side C	-7.393e-7	-7.393e-7	88.377	88.69	3.93	3.93	3.9624,850	3.9624, 850	8.8392, 709.1	8.8392, 709.14
VC-EXCEL-004 Side D	-3.477e-7	-3.477e-7	100.76	101.01	2.57	2.57	2.7432, 850	2.7432, 850	8.8392, 850	8.8392, 850

	Model HAP	Excel HAP
VC-EXCEL-005	.4273	.4273
VC-EXCEL-006	.2255	.2256
VC-EXCEL-007	0	0