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IGNITION OF WOOD
A REVIEW OF THE STATE OF THE ART

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This review encompasses the available practical and experimental data on the ignition of solid wood. Only solid, natural wood is considered, not sawdust, chips, or products that have been treated with fire retardants or other substances, nor is the ignition of living trees. Panel products such as plywood or particleboard have ignition properties very similar to solid wood, so the solid-wood results will generally be applicable to them. Wood may ignite by flaming directly, or it may ignite in a glowing mode, which may or may not be followed by flaming. It is shown that the ignition temperature is around 250ºC for wood exposed to the minimum heat flux possible for ignition, and that it invariably ignites, at least initially, in a glowing mode under these conditions. The ignition temperature rises rapidly as the heat flux is increased. Piloted ignition at heat fluxes sufficient to cause a direct-flaming ignition normally occurs at surface temperatures of 300 – 365ºC. Autoignition temperatures at fluxes higher than minimum are essentially unknown. No theory is available which encompasses the possibility of glowing, glowing followed by flaming, or direct-flaming ignition modes. Most published studies have dealt with radiant or radiant+convective heating, and knowledge is extremely poor for ignition from direct contact by hot bodies or by flames. A species-independent correlation is derived for the radiant, piloted ignition of thermally-thick wood, but the fit is only fair. The minimum flux for ignition is 4.3 kW m^{-2}, based on a single study; most reported tests have been much too brief to produce useful data on this point.

IGNITION TEMPERATURE

The concept that combustible substances ignite when a given surface temperature is first attained is an empirical notion—in many cases, this is found to be true enough, so that even though not exactly true, the concept has utility and merit. It has also found significant application to theoretical modeling—closed-form theories for radiant ignition, for example, generally assume that ignition corresponds to a known, constant surface temperature T_{ig}. Thus, the starting point for investigating the ignition of wood must be to examine experimental data on its ignition temperature. As can be seen in Table 1, studies on this question go back well into the 19th century and have continued until the present time. The spread of data is clearly enormous. It might first be noted that even the term 'ignition temperature' tends to mean two different things: (1) the temperature of the surface at the time of ignition; or (2) the minimum temperature of a furnace sufficient for a specimen put therein to ignite. The latter notion might seem to be old and non-rigorous, but it must be remembered that: (a) the common test for ignition temperature is the Setchkin furnace, ASTM D 1929 [1], which is based on the latter definition; and (b) the user often needs to know the highest environment temperature to which he can subject a material without it igniting and he may be less interested in actual temperatures at the specimen. Excluding one value, the results in

Table 1 span 210–497ºC for piloted ignition and 200–510ºC for autoignition. The following reasons should be considered that might account for the spread:

- the definition of ignition that is used
- piloted vs. autoignition conditions
- the design of the test apparatus and its operating conditions
- specimen conditions (e.g., size, moisture, orientation)
- species of wood.

The definition of ignition is complicated not only by the two meanings currently in use, but by some practices followed by earlier investigators. Until the 1960s or so, it was not rare for investigators to report ignition results without making visual observations. Strange as this may seem from today's perspective, a number of studies exist where the ignition criterion was based solely on thermocouple readings. Typically, the test rig was equipped with two thermocouples and a criterion was used which related the value or slope of the one reading to the other. Results of this kind might be automatically excluded from consideration, except for the fact that data from those investigators do not seem to be systematically different from the others.

Table 1 Summary of ignition temperature results for wood

Year	Investigator	Spec. size	Ignition temperature (ºC)		Comments
			Piloted	Auto-ignition	
1887	Hill [2]	0.5-15 g		**220–300**	measured air temperature near sample
1910	Bixel, Moore [3]	35 mm ?		200–250	measured oven temperature; scant details
1922	Banfield, Peck [4]	50×50× 200 mm		302–308	measured surface temperature
1934	Brown [5]	1–5 g		**220–250**	measured oven temperature; tiny samples; unsound ignition criterion
1936	VanKleeck [6]	chips		**235**	measured specimen temperature; unsound ignition criterion
1947	NIST [7]	shavings		**228–264**	softwood shavings in test tube; criterion—glowing or flaming
1949	Graf [8]	7–13 g		**232–245**	measured oven temperature; tiny samples; unclear ignition criterion
1949	Angell [9]	13×19× 51 mm		204	measured gas temperature close to specimen
1950	Fons [10]	2-9 mm cylinders		343	measured oven temperature; solved inverse problem
1958	Narayanamurti [11]	?	228		measured oven temperature
1959	Thomas et. al. (data of Prince, 1915) [12]	32×32× 102 mm	210		measured oven temperature; solved inverse problem
1959	Akita [13]	20×20× 1.8 mm	450	489	measured oven temperature; solved inverse problem
			< 350		measured oven temperature only
1960	Simms [14]	8 mm ø		525	calculated from correlation, not measured
1960	Moran [15]	50×50× 6.4 mm		255	at flux = 25 kW m^{-2}; measured surface temperature
1961	Patten [16]	3 g shavings	**260**	**260**	measured oven temperature (Setchkin test)
1961	Buschman [17]	57×57× 8 mm	369		calculated from correlation; fluxes 14.3 to 37.2 kW m^{-2}
1964	Shoub, Bender	920×920		254	measured surface temperature

	[18]	mm			
1964	Tinney [19]	≥6 mm ø		350	measured oven temperature
1967	Simms, Law [20]	76×76× 19 mm	380		calculated from correlation
1969	Melinek [21]	100×100 ×13 mm	353	382	calculated from correlation
1969	Jach [22]	few grams		**260–290**	measured oven temperature
1970	Smith [23]	75×75× 19 mm	350	413–714	temperatures measured by optical pyrometry; autoignition values dubious
1983	Atreya [24]	64 mm ø × 19 mm	370		temperatures measured, but below surface; flux = 18 kW m^{-2}
			350		temperatures measured, but below surface; flux ≥ 30 kW m^{-2}
1986	Atreya et al. [25]	75×75 ×19 mm	330–405		temp. measured, but below surface
1988	Abu-Zaid [26]	150×75 ×37 mm	420		forced-air flow; temp. measured but below surface; flux = 18.5 kW m^{-2}
			350		forced-air flow; temp. measured but below surface; flux > 25 kW m^{-2}
				530	flux = 40 kW m^{-2}
1991	Janssens [27]	100×100 ×17 mm	300–364		surface temp. measured; fluxes 25 to 35 kW m^{-2}
1992	Li, Drysdale [28]	64×64 ×18 mm	411–497		temp. measured but below surface; flux < 20 kW m^{-2}
			353–397		temp. measured but below surface; flux > 20 kW m^{-2}
1993	Masařík [29]	2.5 g	**220–240**		tested wood fiberboard; measured oven temperature (Setchkin test)
1996	Fangrat [30]	100×100 mm	296–330		surface temp. measured; fluxes ≥ 25 kW m^{-2}
1997	Moghtaderi [31]	100×100 ×19 mm	332		temp. measured but below surface; at 20 kW m^{-2}
			297		temp. measured but below surface; at 60 kW m^{-2}

? – denotes unknown measurements

The design of the test apparatus has perhaps the largest influence. The majority of devices fall into one of two types: (1) a furnace into which a small specimen is bodily plunged; or (2) a specimen sitting in the open air and being radiatively heated, e.g., the Cone Calorimeter [32]. But this basic division is confounded by the fact that there is a preferred specimen type for each test: specimens of only a few grams are normally put into a furnace that exposes the whole specimen bodily, while specimens placed in front of radiant heaters are typically on the order of 100 g and of sizeable dimensions in at least two directions. The results are summarized in Table 2, with type 1 values indicated in **bold** in Table 1 and type 2 underlined.

Considering first autoignition temperatures under radiant heating, the results evidently span a huge range. Smith's results (which go up to 714ºC) appear to be implausible and may refer to an average optically measured temperature on which some spots are already glowing; thus, they will be excluded. Several other workers reported calculated, rather than measured, values; these will be presumed to be less reliable. Of the measured values, Moran's value of 255ºC and Shoub's 254ºC are impressively close. The only other value obtained by actual measurement is Abu-Zaid's 530ºC. But his result was obtained at a heat flux of 40 kW m^{-2}, which is much higher than Shoub's 4.3 kW m^{-2} or Moran's 25 kW m^{-2}. This suggests that different flux regimes must be considered. Thus, it might be assumed that 250ºC is characteristic at very low fluxes, while some much higher temperature is obtained at high heat fluxes. Turning now to autoignition in ‘a few grams plunged into a furnace’ tests, if the range reported by each investigator is averaged, then the data span only 235–275ºC, with an average of exactly 250ºC. It may be noted that the ‘a few grams plunged into a furnace’ tests are normally operated in such a way as to only seek out the condition where the furnace temperature is the minimum for ignition. In principle, they can be run at non-minimum temperatures, but such data are hardly ever reported. Thus, from this type of test there is no corresponding result to the high-flux region of radiant tests. It can be concluded then that if a wood specimen is ignited under external heating barely sufficient to ignite it, it will ignite at ca. 250ºC regardless of the type of heating arrangement.

Table 2 Summary of ignition temperature data

Type of test	**Ignition temperature (ºC)**	
	Piloted	**Autoignition**
a few grams plunged into a furnace	220–260	220–300
radiant heating of a largish specimen	296–497	254–530
others; unidentified	210–450	200–525

Concerning autoignition at higher heat fluxes, the paucity of reliable data makes it difficult to draw useful conclusions. Simms’ calculated value of 525ºC is close to Abu-Zaid’s measured 530ºC, but both seem very high. Akita’s calculated value of 489ºC is lower, but his results appear to be too high (see below), so the actual value was probably lower yet. It also appears that apparatus details play a stronger role in autoignition than for piloted ignition, leading to wider scatter.

For piloted ignition, T_{ig} values should not be any higher than those for autoignition. The only way that the converse could be true is either due to natural data scatter, or if the equipment is so badly designed that the pilot actually interferes with ignition. Only two workers have presented ‘a few grams plunged into a furnace’ data for piloted T_{ig}. The values are 260ºC from Patten and 220–240ºC from Masařík, giving an average of 245ºC, which can be taken as identical to 250ºC. The conclusion is that piloting does not make any difference on T_{ig} in tests of this type. Considering next piloted ignition results from radiant heating tests, it is evident that none are available at heating conditions barely enough for ignition. The available results are typically for specimens 12–25 mm thick and exposed for only 10–60 minutes. Shoub’s data indicate that much longer times are needed for specimens of these thickness before minimum conditions are approached. On the basis that piloted values should not be lower than autoignition, T_{ig} = 250ºC can be provisionally assigned also as the piloted ignition temperature for radiant tests. Thus, it is concluded that 250ºC is the best estimate of the ignition temperature irrespective of piloting and irrespective of type of test, provided that heating conditions are just barely enough for ignition.

At this point, it is important to observe the nature of the low-heat ignitions. Moran, Li, and Spearpoint [33] all describe the same phenomenon: ignition starts as a glowing ignition and flaming is seen later, if at all. By the way, the glowing ignition temperature must not be confused with the temperature of the glowing spot. In a glowing ignition, a glow begins at one spot and very quickly reaches red-hot conditions (over 600ºC). This high temperature is not the glowing ignition T_{ig}; instead the latter must be determined either by a thermocouple reading just before a steep jump takes place or by a thermocouple on the same surface but away from the spot of initial glow. The glowing ignition phenomenon also serves to explain why no difference is seen between autoignition and piloted ignition results. If flaming is preceded by glowing, then the glowing zone can serve as a high temperature pilot, if subsequently sufficient pyrolysates emerge to be ignitable as a flame. Parenthetically, unlike wood, materials that are not susceptible to glowing ignition (e.g., thermoplastics) show a substantially lower T_{ig} in the Setchkin furnace for piloted than for autoignition conditions.

'A few grams plunged into a furnace' tests generally share two features: very small specimen size, and exposure to conditions where, apart from radiant heating, the specimen is convectively heated (by contrast, in radiant heating tests the convective stream is cooling the specimen). There is one test series where fairly sizeable specimens were plunged into a furnace, and that is Prince's 1915 study [34]. His original study reported that ignition was attained for furnace temperatures of 180–200ºC. Thomas [12] later estimated specimen surface temperatures by modeling and concluded that surface temperatures at ignition were 30ºC higher than the furnace temperature. This correction, which arises due to self-heating, is negligible for tiny specimens and increases with increasing specimen size. Since Thomas' corrected values are in the same range as the raw values from 'few grams' specimen tests, the conclusion is that there is no specimen size dependence, at least when testing under heating conditions barely sufficient to cause ignition.

Considering next piloted ignition at higher fluxes, only the radiant tests can be considered, since 'a few grams plunged into a furnace' tests are not normally run this way. When the heat flux is high enough (and there is no good guidance on this point yet!) wood specimens ignite simply in a flaming mode, without antecedent glowing. For simplicity, it is best to consider first those results which pertain to a direct-flaming mode. For such heat fluxes, $T_{ig} \approx$ 300–350ºC covers all, or nearly all results of Janssens, Atreya, Abu-Zaid, Fangrat and Moghtaderi. Akita's value of 450ºC, obtained by calculation, appears to be wrong since he did obtain ignitions at a furnace temperature of 350ºC (and did not try lower temperatures). For his 1.8 mm thick specimens, self-heating would be minimal, so the actual ignition temperature appears to have been below 350ºC, making his measurements also consistent. Of modern workers with good equipment, only the results of Li and Drysdale are outside this range and these are about 50ºC higher, for unknown reasons. Janssens [27] noted that the range can be further shrunk by considering the slight but systematic effect of wood type. His results for oven-dried specimens were: hardwoods 300–311ºC; softwoods 349–364ºC. At fluxes high enough to ensure a direct-flaming ignition, these values can be adopted for piloted T_{ig}. Wood is comprised of three primary constituents—cellulose, hemicellulose, and lignin. Hemicellulose ignites at the lowest temperature, cellulose higher, and lignin higher yet [35]. Compared to hardwoods, softwoods have a smaller fraction of hemicellulose and a higher fraction of lignin, thus accounting for their higher T_{ig}.

Next the intermediate-flux regime must be considered, where the heat flux is higher than the minimum flux, but is low enough for ignitions to be of the glowing → flaming type. These reported data span a sizeable range of 332–497ºC. Part of the scatter is probably due to experimental difficulties, since Urbas and Parker observed [36] that considerable care needs to be exercised to instrument properly a surface that is undergoing charring. Part of the difference, however, is real and is attributable to changed exposure conditions. Moran's data are instructive here. Although intermediate data were scattered, as the flux was raised from 25 kW m^{-2} to 29 kW m^{-2}, the ignition temperature rose from 255ºC to 301ºC while the ignition time dropped by 33%. The reason for the dependence of T_{ig} on flux in this regime will be considered in the next section. The 300ºC value is significant, since wood pyrolysis involves competing mechanisms, with temperatures under 300ºC leading largely to charring, while over 300ºC gasification being favored [37]. Thus, if heating conditions are such that the material does not exceed 300ºC, a glowing ignition is favored.

Concerning other systematic effects, at the minimum flux condition, Moran found no difference in T_{ig} between oven-dried and room conditioned specimens. In the medium flux regime under piloted conditions, Janssens [38] concluded that T_{ig} rises by 2ºC for each percent of moisture content increase. This will normally be insignificant for practical moisture contents. Specimen orientation (i.e., along-grain versus end-grain exposure) may also have an effect on T_{ig}, but good enough data are not available to explore the issue. Almost all existing experimental data deal with along-grain exposures, which are also common in accidental fires.

GLOWING IGNITION MODELING

A glowing ignition involves the direct surface oxidation of a material (heterogeneous reaction), thus Baer and Ryan [39] suggested that the simplest model for this is:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho C} \frac{\partial^2 T}{\partial x^2}$$

with the boundary condition:

$$-\lambda \left. \frac{\partial T}{\partial x} \right|_{x=0} = \dot{q}''_e + B_s Q_s \exp(-E_s / RT)$$

where T = temperature, t = time, λ = thermal conductivity, ρ = density, C = heat capacity, $\dot{q}''_e$ = irradiance, B_s = pre-exponential factor, Q_s = heat of reaction, E_s = activation energy for surface reaction, and R = universal gas constant. Based on this, Lengellé et al. [40] then showed that a solution for the ignition temperature T_{ig} is:

$$T_{ig} = \frac{E_s}{R} \left[\ln\left(\frac{B_s Q_s}{\alpha \dot{q}''_e} \right) \right]^{-1}$$

where α = non-dimensional temperature rise associated with ignition. The α factor serves as an ignition criterion and they found empirically that $\alpha \approx 0.15$ corresponds to ignition. The equation shows that T_{ig} decreases with decreasing irradiance, and Lengellé demonstrated that this indeed occurs experimentally for a number of propellants. Propellants are, of course, substances very different from wood, but Moussa et al. [41] proposed that the same equation be used in describing char oxidation occurring during smoldering of wood; however, they did not provide quantitative values for the kinetic constants. Fredlund [42] used a slightly different term in his model of wood combustion, but provided no experimental verification in the glowing ignition regime. Ohlemiller [43] noted that describing char oxidation of wood is difficult, since the char is not a unique chemical entity, but rather, is a substance whose characteristics are history-dependent. For a similar material, coal char [44], the chemical properties are, in fact, strongly dependent on the physical nature (pore structure) of the char that has been created, and it might be expected that this would also be important for wood. More complex heterogeneous reaction models that include pore-structure effects (and the possibility of both kinetically-limited and diffusion-limited reaction rates within these structures) are available for coal-char combustion [45], but such models have yet to be applied towards representing the ignition of wood. The above observations help to place in context the long times required for glowing ignition of wood—plywood required over 5 h in Shoub and Bender's experiment. This long time period is associated with creating of a reactive porous char. The conclusion, thus, has to be that only qualitative rudiments are known for glowing ignition, and that quantitative modeling is not yet possible, largely because of an absence of experimental data.

FLAMING IGNITION FROM RADIANT HEATING

Theory

There is more than half a century of history in the development of both comprehensive and 'practical' theories of flaming ignition of wood materials. Janssens [27][38] reviewed them extensively and here only the salient feature will be reprised: his recommended method for plotting experimental data so that sound interpolations and extrapolations may be possible. His study, which was based on numeric approximations to an inert-body model of an igniting solid, entails plotting the ignition time raised to the –0.55 power on the y-axis and the external imposed heat flux (irradiance) on the x-axis. This is illustrated with Janssens' own data in Figure 1. Since a straight line can be obtained when the data are plotted in this way, only two parameters are needed to describe the data fit. An obvious one to choose is the x-axis intercept, denoted as $\dot{q}''_{cr}$. The slope is a very small number, so it is more convenient to select the inverse of the slope and to designate it as B_{ig}. Thus, the equation describing the data plot is:

$$t_{ig}^{-0.55} = [\dot{q}''_e - \dot{q}''_{cr}] / B_{ig}$$

In the example, $\dot{q}''_{cr}$ = 9.3 kW m^{-2}, B_{ig} = 201 kW m^{-2} s$^{+0.55}$. In general, it is found that ignition may not be possible at fluxes just slightly greater than $\dot{q}''_{cr}$, and a higher heat flux is necessary for ignition to actually occur. This latter value is designated $\dot{q}''_{\min}$, the minimum flux for ignition. Thus, apart from the two parameters needed to describe the straight line, a third parameter is needed which denotes the lowest point on the line that has physical meaningfulness. Janssens presented a second method for thermally thin materials. Physically, whole wood is rarely used free-standing in minuscule thicknesses (e.g., < 1 mm), thus Janssens' second procedure will not be presented here. But the 'thermal thickness' is not necessarily the same as the physical thickness, and substances of finite thickness which behave as thermally-thick bodies when initially heated will eventually respond as thermally-thin, if sufficient time has elapsed. This point is treated in the next section.

Janssens' theory was mainly intended as an aid to using experimental data and was not intended to encompass all relevant physicochemical phenomena. Indeed, since it is an inert-solid theory, events in the gas phase are ignored and ignition is assumed to uniquely occur at the moment a certain face temperature is first attained. Much more refined theories have been put forth in recent years, for example, Yuen's [46]. These have the limitations that they (a) require a large amount of input data, much of which may be unavailable or uncertain; and (b) difficult numeric computations must be performed for each problem; consequently, they are not useful as 'data plotting aids.' While advanced theories attempt to capture gas-phase ignition events, there is currently no theory available, simple or complex, which encompasses the possibility that a specimen may exhibit glowing ignition, glowing → flaming (2-step) ignition, or a direct-flaming ignition.

Experimental results on piloted ignition

From both theory and experiments, it is evident that a number of variables can affect the ignition time of thermally-thick, solid wood, of which density, thermal conductivity, moisture content, and geometric factors are probably the most important. Taking the last first, in testing, geometric effects show up as apparatus dependent factors, since no physical test rig can capture apparatus-independent properties of a material. Size of specimen is a geometric variable to consider, but Long et al. [47] noted that the only scale-dependent term in basic ignition theory is the convective heat transfer coefficient, h_c, which varies with size L

according to $h_c \propto \frac{1}{L^{1/4}}$. The effect on ignition time is much smaller than the change in h_c, since heat losses are dominated by radiation, and would be negligible for all except huge changes of scale. But basic ignition theory does not deal with events in the gas phase and these may also have an effect. Within a single test apparatus, experimental data suggest that the size effect is very small [48], although when comparisons are made where both the scale and the basic apparatus are changed, somewhat larger differences crop up [49][50]. In any case, currently there is a sizeable database of test results only from the Cone Calorimeter, so for consistency, only Cone Calorimeter data obtained on samples exposed in the along-grain orientation will be considered. According to basic theory, for thermally-thick materials $t_{ig} \propto \lambda\rho C\left(T_{ig} - T_o\right)^2$. Since radiant ignition data are easy to obtain, but become much more difficult if surface temperatures need to be accurately measured, the consequence is that most investigators record only the flux and the ignition time. Consequently, it is best to treat T_{ig} from such data sets as part of the unknown constants to be fitted, thus taking $t_{ig} \propto \lambda\rho C$. Now, values of heat capacity, C, tend to vary little among members of a chemical family, and this appears to also be a reasonable conclusion for woods. Density, however, can vary by about a factor of 10, if exotic woods are included. Thermal conductivity increases with increasing temperature, with the simplest assumption being that $\lambda \propto \rho^n$, where the value of n remains to be determined. Thus, it seems appropriate to seek a correlation where $t_{ig} \propto \rho^m$, where m is also to be determined. This is not a novel idea, and Hallman [51] took a similar approach some 30 years ago. Moisture content can have a complex effect, both because it directly affects the thermophysical properties, and because, if it were to be treated accurately, an inert-substance model is no longer a viable starting point for a theoretical treatment. To make an accurate treatment of moisture, the extremes of green wood to oven-dried wood would have to be considered. Green wood can have MC > 100%, but there are no available ignition data on it, with the literature containing data only for oven-dried specimens and ones that are equilibrated to room conditions. For room-conditioned wood specimens, MC depends on the humidity present, but across the US it normally spans only the range of 4–14% [52], which is a small range and only covers the 'zero-end' of the scale. Most test results available are either for the oven-dried condition or for 9–12% moisture content, obtained by room-conditioning the specimens. As indicated above, Janssens concluded that moisture slightly increases T_{ig}, but this can be ignored unless the wood is green (for which no data are available, anyway).

To find a correlation, a large number of published [31][33][53][54][55][56] and unpublished [57][58][59] data sets were collected. These covered four test conditions: oven-dried horizontal, oven-dried vertical, room-conditioned horizontal, and room-conditioned vertical. Figure 2 shows the results for oven-dried horizontal specimens [56][58]; with one data set [31] not used due to excessive outliers. The densities spanned 170–850 kg m^{-3}. Since this data set showed a relatively tight correlation, the exponent for the density term was derived from the data fit on this data set and fixed at that value for the remaining data fits. The value plotted on the y-axis is Y, which was taken as $Y = t_{ig}^{-0.55} / \rho^{-0.4}$. The other data sets showed higher scatter, for example, Figure 3. Table 3 gives a summary of the correlations obtained. Figure 4 shows that the correlations are very similar and that it is reasonable to assign an 'overall' correlation. Clearly a dry specimen ignites quicker than a moist one, but this is somewhat violated in the correlations, and this is one reason why it is best to assign a single correlation, with the realization that moisture effects are swamped by general data scatter. It is also known that vertically-oriented specimens take longer to ignite than do horizontally-oriented ones [54], but again the scatter of the data does not permit this to emerge from the correlations. Based on these considerations, the estimating rule for radiant heating ignition of wood becomes:

$$t_{ig} = \frac{130\rho^{0.73}}{(\dot{q}''_e - 11.0)^{1.82}}$$

Table 3 Summary of data correlations for piloted radiant ignition in the Cone Calorimeter

Conditions	$\dot{q}''_{cr}$	Const.	Tot. data points	Data points used
horiz., 0% MC	9.8	159	31	26
horiz., room	12.2	128	103	94
vert., 0% MC	11.5	99	67	48
vert., room	9.0	133	53	48
overall	11.0	130		

According to theory, it would appear that the exponent for ρ is unusually low, but the reason for this is not clear. The root-mean-square error of the predictions is 64%, which indicates that predicting times to ignition can only be done semi-quantitatively, but this must also be placed in the context that experimental data went from 2.5 to 4200 s, or a range of 1 : 1680. A close inspection of Figure 3 also reveals that below about 15 kW m^{-2}, the points deviate systematically above the straight line. This is as might be expected, since the theory is based on a thermally thick material, and wood specimens 12–25 mm thick no longer behave in a thermally thick manner when heated for a long time. It is possible to eliminate this systematic bias by fitting exponents higher than 1.82 to the irradiance factor, for example, 2.8 as suggested by Wesson [60]. But overall scatter still remains large and the treatment becomes wholly empirical.

The minimum flux for ignition is often the quantity of interest. In 1965, McGuire [61] suggested that this value can be taken as *ca*. 12.5 kW m^{-2} for most wood materials apart from low-density fiberboard. A value of 12.5 kW m^{-2} has subsequently been used for design purposes in many countries. This is indeed the value that is customarily obtained in the Cone Calorimeter and in other test methods where the time allotted for observation of ignition is 10–20 minutes. But lower values have been found, although not widely publicized. Spearpoint [33] recently explored both low-flux ignition and end-grain ignition of woods. Almost all ignition results available for wood are performed on specimens oriented towards the heat source along the grain, but different results are obtained when exposed to the end-grain. For along-grain exposures, Spearpoint found $\dot{q}''_{\min}$ = 12.5 kW m^{-2} for redwood and somewhat less than 12 kW m^{-2} for maple. But for end-grain ignition of maple, the lowest flux at which ignition occurred was 8 kW m^{-2}, with no ignition at 7 kW m^{-2}, making $\dot{q}''_{\min}$ = 7.5 kW m^{-2}. The minimum flux for end-grain ignition of redwood was not fully explored, but was found to be below 9 kW m^{-2}. For ignitions occurring at fluxes below 10 kW m^{-2}, a glowing ignition preceded flaming. The times associated with the low-flux ignitions were notably long, it taking 2680 s for end-grain ignition of maple at 8 kW m^{-2}, and 4200 s for along-grain ignition at 12 kW m^{-2}. On this basis, one might conclude that 7.5 kW m^{-2} is $\dot{q}''_{\min}$ for piloted ignition of wood, but the value for piloted ignition cannot be higher than for autoignition and the latter may be low indeed (see below).

Generally, 'piloted ignition' means the presence of a flame or a spark in the gas phase where pyrolysates accumulate. But it is also possible to apply a gas flame directly onto a surface as an 'impinging pilot,' in which case much less radiant heating is needed to achieve ignition since a local heat flux concentration is created. An old FRS study [62] showed $\dot{q}''_{min}$ = 5 kW m^{-2} for Western red cedar and Douglas fir. No other published studies exist. Apart from surface-applied pilots, both the type of pilot and its location can affect ignition times. Several studies [54][63] produced limited data—more studies would be needed to quantify trends reliably. It is also possible to heat a wood surface by applying a relatively-uniform 'wall of flame' onto it, and this is discussed later.

Experimental results on autoignition

Unlike piloted ignition, autoignition of wood under radiant heating conditions has been studied by only a few researchers, most notably Simms, who conducted various experiments at FRS in the 1950s and '60s. In a 1952 study, he tested 6 different species of wood using 19 mm thick specimens [64]. The results, including the correction for a 20% flux mis-calibration [65], are shown in Table 4. In a 1961 study [66], he reported an enormous value of up to 117 kW m^{-2} for autoignition of blackened oak and cedar specimens. In a 1967 study [67], he reported minimum fluxes for piloted ignition that were similar to the corrected 1952 values, but autoignition values reported were quite a bit higher, being ca. 40–50 kW m^{-2}. In his 1961 study, Simms noted that a draft strong enough to be turbulent was helpful in reducing the $\dot{q}''_{min}$. This was evidently a gas-phase effect, but even today there is no systematic knowledge on gas-phase ignition effects. In another study [68], Simms concluded that the quantitative effect of the rather small exposure size of 8 mm is nearly negligible, so presumably the enormous $\dot{q}''_{min}$ values in the 1961 study were mainly due to insufficiently long test time.

Table 4 Minimum flux for autoignition of wood, as reported by various researchers

Study	Orient.	MC (%)	Draft	Specimen size exposed	Max. time of test	$\dot{q}''_{min}$ (kW m^{-2})	Notes
Lawson, Simms (1952)	V	0	N	50 × 50 mm	20 min	29–33	
Simms (1961)	V	0	Y	8 mm ø	14 s	75–100	blackened surface
			N		18 s	117	
Simms, Law (1967)	V	0	N	76 × 76 mm	70 s	46	
				150 × 150 mm	79 s	42	
Moran	V	0	Y	50 × 50 mm	9 min	25	
Shields et al.	H	≈10	N	100 × 100 mm	96 s	30–40	
	V				59 s	40–50	
	H	≈10	N	165 × 165 mm	12 min	< 20	ISO 5657 test
Shoub, Bender	V	≈10	N	920 × 920 mm	3.9–5.2 h	4.3	

Moran [15] examined the ignition of vertical panels of 6.4 mm thick ponderosa pine using an electric radiant panel and found $\dot{q}''_{min}$ = 25 kW m^{-2}. Shields et al. [54] examined the autoignition of Sitka spruce in the Cone Calorimeter and in the ISO 5657 apparatus. They exposed specimens in increments of 10 kW m^{-2}, so their results were only approximate. Since the heater arrangements have some similarity, it is not clear why the values obtained in the Cone Calorimeter and the ISO 5657 apparatus were not closer. Shields' data does illustrate that it is much more difficult to achieve autoignition in the vertical orientation than in the horizontal orientation. The above studies were all of less than 20 minutes duration. Only the study, by Shoub and Bender [18] involved longer-term exposures. They used an electric radiant panel operating at an effective black-body face temperature of 273ºC and producing a heat flux of 4.3 kW m^{-2} at the center of the specimen, and lower heat fluxes at the edges. While they did not test any whole woods, they tested 13 mm plywood. It ignited at the 4.3 kW m^{-2} flux, but required waiting over 5 hours. In their tests, they also documented that the face temperatures of the specimens in some cases reached temperatures higher than that of the radiant source, indicating that self-heating of the material was important and that assuming an inert solid would not be appropriate. It should be of high priority that modern-day researchers attempt to repeat these experiments and verify their results. The conclusion—pending a verification of Shoub and Bender's results—is that wood will autoignite at about 4.3 kW m^{-2}, if exposed for hours, rather than minutes. For short-term exposures, a value of 20 kW m^{-2} perhaps best captures the research results.

At any given irradiance, if ignition occurs under both autoignition and piloted ignition conditions, it is evident that ignition times for the latter will be shorter (unless the pilot is badly placed). A tractable theory, such as Janssens', models only the solid phase, so the presumed conclusion would be that ignition times do not change. A more refined point of view would be to assume that for autoignition, heating up the solid to the same temperature suffices as for the piloted case, but that afterwards a delay time must be added to account for gas-phase events. A theory of this sort has not been developed, however. Experimentally, even though there is a great deal of scatter (Figure 5), the results of Shields et al. [54] can be used to derive an equation:

$$t_{ig}\ \textit{(autoignition)} = \left(2.86 - 0.0172\,\dot{q}_e''\right)\cdot t_{ig}\ \textit{(spark)}$$

Thus, for example, at a flux of 25 kW m^{-2}, under autoignition, ignition times can be expected to be 2.43× those for the spark-ignition case, while at 50 kW m^{-2} the factor drops down to 2.0×. Since the highest experimental flux was 70 kW m^{-2}, the rule should not be extrapolated to greatly higher fluxes. Also, due to the data scatter, the guidance is only semi-quantitative.

IGNITION FROM MISCELLANEOUS HEAT SOURCES

There is very little data on ignition of wood from flames, despite the fact that this is how we light our fireplaces. When a thin piece of wood is lit at the bottom, burning may continue to completion. But a thick piece of wood will not undergo self-sustained combustion under the same circumstances. Bryan [69] reports that the maximum thickness for self-sustained burning, given a flaming ignition at the bottom of a vertical piece, is about 19 mm. In a horizontal orientation, even 12 mm thick specimens have been found too thick for self-sustained burning [70]. Using the methenamine pill test (a standard test for floor coverings), it was found [71] that no ignition occurs for any of a wide variety of wood products tested in thicknesses of 10 – 21 mm. Ignitability of wood boards has also been examined [72] using the ISO 11925-2 small-burner test. Using a 30 s flame exposure to the surface, ignition rarely occurred and never spread to the 150 mm limits, even with specimens as thin as 2 mm. For 30 s bottom-edge impingement, specimens of 18 mm thickness or less commonly ignited, but only ones of 10 mm thickness or less generally reached the 150 mm mark.

Ebeling and Welker [73] studied the ignition of wood panels when exposed to a flame, with the flame being applied against the whole face. They tested oak, white pine, redwood, and yellow pine, with the results giving the correlation:

$$t_{ig} = 41.3\rho^{0.94}\left(\dot{q}_e''\right)^{-1.82}$$

although there was a wide spread of results. The above equation implies that the critical flux is identically zero, which is at least partly due to the fact that there is no convective cooling of the surface in a flame-ignition test. For the same reason, their flame ignition times were a fair bit shorter than times obtained by applying the same heat flux in a radiant heating test.

Even though convective heating is an important feature in a Setchkin-type apparatus, there has been no scientific study where ignition would be primarily from convective heating.

When a sufficiently high voltage is impressed across a tree or a wood member, an arc tracking process takes places. Wood first dries out at the electrodes, then a carbonized channel starts to form. Given enough time and voltage, sufficient heating of the carbonized track takes place that the electric current passing through the track heats up the wood to ignition. This process has been studied by several researchers [74][75][76][77]. It is mainly of concern in connection with high voltage wiring, including power line poles and neon signs installed near wood surfaces.

Ignition with laser radiation produces very different results than radiation from flames or grey-body radiators, for reasons not fully explained. Kashiwagi [78] exposed horizontally-oriented red oak specimens to laser radiation at 10.6 μm and found high values of $\dot{q}''_{\min} \approx 80$ kW m^{-2} for autoignition and 55 kW m^{-2} for piloted ignition. This is also common with laser ignition of other substances, e.g., plastics. Ignition from nuclear weapons has been simulated [79] by use of radiant exposure from an arc-image furnace. The results for the brief, high-intensity pulses were expressed in terms of energy fluence. Using 13 mm thick Douglas fir, transient flaming was observed for an energy fluence of 1090 kJ m^{-2} (480 kt bomb) and sustained flaming at 1300 kJ m^{-2} (1180 kt) or higher. Yellow poplar of 1.6 mm thickness also showed sustained flaming at 1090 kJ m^{-2}, but no transient flaming regime.

IGNITION FROM HOT BODIES, FIREBRANDS, AND SMOLDERING

Glowing and smoldering are similar, but not identical mechanisms of ignition. Smoldering is, by definition, a self-sustained process. Ignition and consumption of a wood material by glowing, on the other hand, can occur if it is subject to sufficient radiant or convective heating, without a requirement that the process continue, should the external heat source be removed. Firebrands themselves may be flaming or glowing, and they may, in some cases, initially cause flaming in the target fuel, although a smoldering ignition is the usual concern.

Self-sustained smoldering occurs easily in various wood products which are highly porous or finely divided (fiberboard, wood shavings, rotted wood, etc.). Whole wood, however, is only slightly porous to the inflow of oxygen and will not smolder as a single surface facing open air. Ohlemiller [80] reports that by supplying external heating at ca. 10 kW m^{-2}, wood can be made to burn in a glowing mode; this of course is not smoldering, since it is not self-sustained. By preheating the bulk of the wood sufficiently, continued combustion can be maintained. This can be seen in a fireplace where individual pieces may continue glowing even after a 'three-log' effect no longer exists. Only a limited number of experimental studies exist on the question of minimum conditions necessary to start wood smoldering. Ohlemiller [81] conducted experiments where smoldering was achieved by providing a 'three-log' arrangement and igniting the surfaces with flat electric heaters. Even with the optimal geometry, air flow velocity had to be within a close range for sustained smoldering to be seen.

Solid wood is most commonly ignited by firebrands during wildland fires. Humidity plays a strong role in the process, and wildland fires often involve extremes of high temperature, low humidity, and strong wind gusts. Only a few laboratory studies have been conducted on the ignitability of solid wood by firebrands. CSIRO researchers [82][83] found that some surprisingly small (0.8–12 g) wood cribs sufficed for ignition. An inside-corner ('re-entrant corner') geometry of the siding was especially conducive to ignition. Hamada [84] found that no-wind conditions, red-hot brands of about 5 mm diameter caused ignition, but in an 8 m s^{-1} wind, even brands of 2.5 mm were likely to cause ignition. Low RH values (20%) were needed for this to occur. Applying flames to the surface of a wood structural member will not result in smoldering ignition, unless the flame is applied for so long that the wood member is largely burned up. Specifically, it has been demonstrated [85] that applying the flame from an acetylene/air plumber's torch directly onto wood studs for periods of 1–5 minutes leads to local charring but no sustained combustion of any type once the torch is removed and the flames self-extinguish.

A special problem is one where ignition of wood occurs from steam pipes or from a metal heating system part which is in contact with the wood for a long time. Under long-term heating (months-to-years), it appears that wood can ignite when a surface is held at a temperature lower than the ignition temperature determined from tests that last a short time (minutes-to-days). The information largely comes from case histories and good experiments are lacking. Babrauskas [86] recently reviewed the state of the art on this topic.

CONCLUSIONS

Some aspects of the wood ignition problem are well-known, and these can be used in routine engineering applications. This is primarily true of ignition times for piloted ignition, provided that fluxes too close to the minimum are not considered. But despite more than a century of scientific research, many other aspects of wood ignition are poorly known. Foremost is a lack of study of ignition at minimum-flux conditions, including an understanding of glowing ignition. A simple theory exists for glowing ignition, but it cannot be used without good experimental data, and detailed, reliable experimental data are lacking. Part of the problem is that only a few experimentalists report visual observations along with their numeric data. Analysis of available data leads to the summary given in Table 5 and schematically depicted in Figure 6. High fluxes (e.g., over 80 kW m^{-2}) are not listed since there is little information, but also this regime is of less interest to fire safety. Most researchers have conducted much too short tests in attempting to define 'minimum' conditions, thus only a single study is the basis for observing that ignition may occur at heat fluxes as low as 4.3 kW m^{-2}. It is, of course, likely that there is not a unique minimum flux value, but that various factors—apart from inadequate duration of experiments—can affect its value. Also needing to be quantified is the flux value dividing the medium flux (flaming ignition) from low flux (ignition starts with glowing) regimes. Somewhat related to the lack of knowledge about glowing ignitions is the lack of knowledge on ignitions from hot bodies. Experimental data on this topic are so scarce that it can only be concluded that ignitions are possible under some surprisingly mild attacks, e.g., firebrands of a few grams. Ignition of wood in actual fires often is due to direct flame contact with the material, but again guidance on this topic is minimal.

Table 5 Summary of ignition temperature results

Flux	Minimum	Low	Medium
Ignition type	glowing or glowing/flaming		flaming
T_{ig} (ºC), piloted	250	350 – 400 peak, lower for fluxes close to minimum.	300 – 310 hardwoods 350 – 365 softwoods
T_{ig} (ºC), autoignition	250	no data	380 – 500 ??

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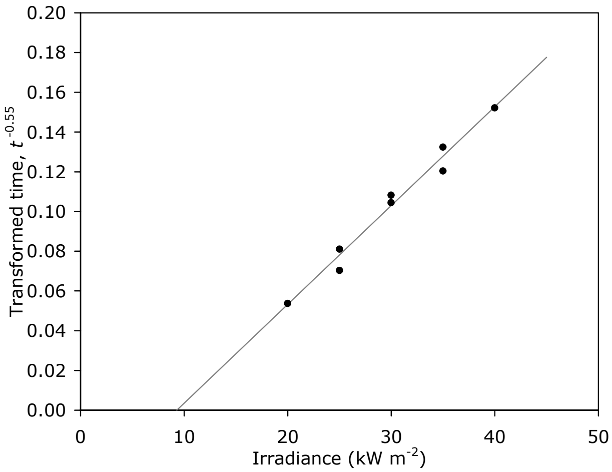

Figure 1 Janssens' piloted ignition results for Blackbutt, oven-dried, vertical orientation

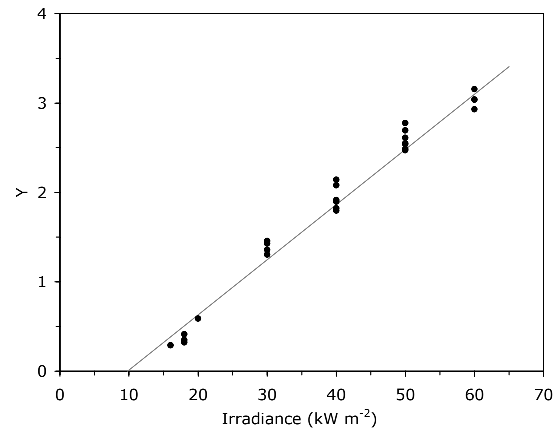

Figure 2 Correlation for oven-dried horizontal specimens

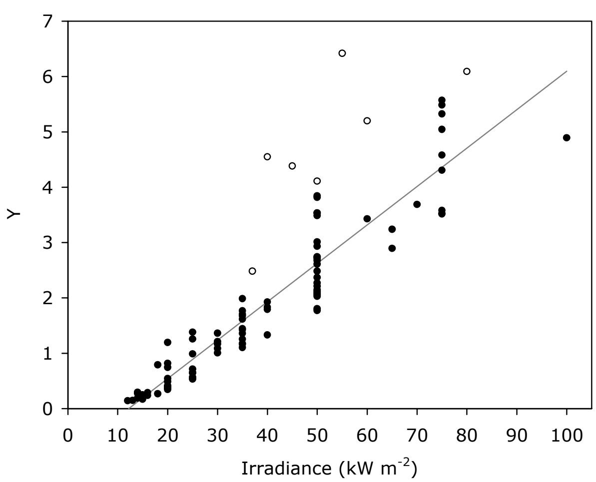

Figure 3 Correlation for room-conditioned horizontal data; hollow points were not used to derive the correlation

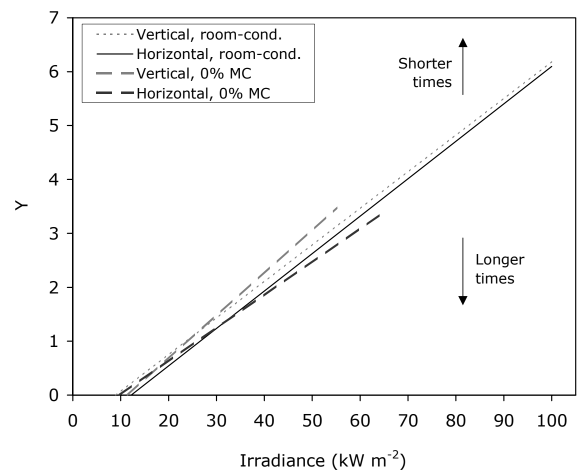

Figure 4 Data correlations obtained for the four data sets

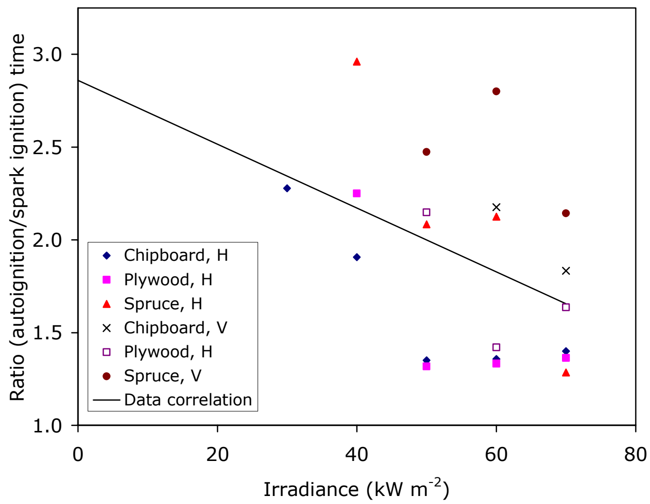

Figure 5 Ratio of ignition times, autoignition/spark ignition

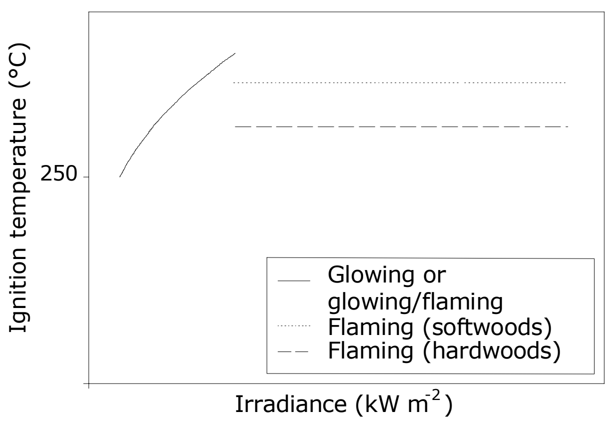

Figure 6 The effect of irradiance of piloted ignition temperature