WOOD CHAR DEPTH:
INTERPRETATION IN FIRE INVESTIGATIONS

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INTRODUCTION

Wood char depth patterns have been considered important by fire investigators in most countries where significant use is made of wood as a construction material. This is natural, since post-fire patterns found on wood members are generally more pronounced and extensive than those found on many other construction materials. But the present state of affairs has been such that there is not much agreement on what quantitative interpretation, if any, can be placed on such patterns. In fact, respected specialists have suggested that charring rates are meaningless with respect to fire investigations [1][2]. The standard guide for fire investigators used in the US, NFPA 921 [3], states that: "The investigator is cautioned that no specific time of burning can be determined based solely on the depth of char." Nonetheless, it then devotes two pages to a discussion on how to measure depth of char and what conceivable deductions might be made from these measurements, although it arrives at no definite conclusions on the latter point.

The situation arose, in the view of this author, because the experimental literature was not adequately surveyed and, especially, because persons attempting to use published charring rate have not considered the factors that govern these rates. Instead, it has been common to take charring rate values published as guidance to structural engineers designing timber beams or columns, and attempt to apply them towards understanding the charring of wood floors, doors, or other members that are not monolithic, large-thickness structural members.

In the present paper, we will endeavor to remedy this situation by examining the available data on (a) charring rate and char depth; (b) causation of deep or unusual patterns; (c) burn-through times of wood members; and (d) the characteristics of burn patterns due to use of ignitable liquids (liquid accelerants). The paper primarily examines three types of data: (1) Traditional data obtained in ASTM E 119 or ISO 834 fire endurance test furnaces, where exposure is controlled via the standard time-temperature curve. (2) Data obtained from Cone Calorimeter or other bench-scale tests where the test conditions are set by specifying a heat flux—normally invariant over time—imposed on the specimen. (3) Data from large-scale test programs where entire rooms or houses were burned. For any quantitative data to be reliable, the proper technique for measuring char depth must be used, but this will not be reviewed here since it is adequately covered in NFPA 921 [3].

CHARRING WITHOUT USE OF LIQUID ACCELERANTS

Charring of solid wood members under ASTM E 119 or ISO 834 conditions

The charring rate data that have commonly been used and cited in various studies have been those obtained using standard fire-resistance test furnaces for simulating a post-flashover fire exposure. Such tests are run using exposure conditions (time/temperature curve) as prescribed by ASTM E 119 [4] or ISO 834 [5]. The former standard is used in North America and the latter elsewhere, but for the present purposes, the differences in results simply due to differences in the two standards would be

very small, thus their results will be treated here as interchangeable. During the last roughly-50-year period, a sizable amount of data from these test methods has been published. It has been reviewed in some detail in a recent paper of this author [6], thus only the results will be given here. For solid beams and columns, a charring rate of 0.5 – 0.8 mm/min has typically been found for solid beams or columns tested in the fire-resistance test furnace. It is realized that this is a fairly wide spread, but this variance must be attributed primarily due to random variations. A number of investigators have endeavored to determine if a more accurate rate could be evolved by explicitly treating the effect of specimen density, but the results are contradictory and inconclusive on this point. It is generally found, however, that there is a time-period effect, and a slower rate is seen if longer time periods are considered. A charring rate dependence on $t^{-0.2}$ represents reasonably well the outcome of studies which have examined this point.

Charring rates under controlled heat flux conditions

Data collected under an ASTM E 119 exposure are obtained under conditions where the heat flux is gradually rising throughout the test. The other main type of test arrangement involves a radiant heat apparatus where the external heat flux imposed on the specimen is fixed and is not varied with time. Over 30 years ago, Butler [7] published a study where he correlated the results from a number of early studies of this type. By making needed some corrections to his data treatment, the following expression is derived [6]:

$$\beta = 0.028\,\dot{q}''_{tot}$$

where β = charring rate (mm/min) and $\dot{q}''_{tot}$ = external heat flux (kW m^{-2}).

The early radiant-heat test apparatus that were used to obtain these data were primarily ones which imposed a high heat flux and used only a short time exposure. The exposure time, in fact, was completely ignored as a variable in Butler's study. In recent years, a number of investigators tested woods in the Cone Calorimeter (ASTM E 1354 [8]). The calibration of this technique is controlled, unlike the earlier *ad hoc* tests, and data can consequently be expected to be more reliable. In addition, many of the newer studies based on this technique have explored the exposure-time variable, allowing its role to be quantified. An examination of these results [6] gave the following correlation:

$$\beta = 0.23\left(\dot{q}''_{tot}\right)^{0.5} t^{-0.3}$$

where β = charring rate (mm/min), for the specimens that ignited, $\dot{q}''_{tot}$ comprises the sum of the external flux and the local flame flux. It may be noted that the effect of the heat flux is not to the 1.0 power, as in the Butler expression, but to the 0.5 power. This is consistent with noting that Butler's data shows non-linear behavior at higher fluxes. In addition, Harada [9][10] made extensive studies of the density effect in the Cone Calorimeter and showed that β varies inversely with density. Thus, if prediction for widely different density specimens is needed, the following relation can be derived:

$$\beta = 113\frac{\left(\dot{q}''_{tot}\right)^{0.5}}{\rho\, t^{0.3}}$$

where ρ = density (kg m^{-3}).

An apparatus-independent formulation of charring rate

It should also be possible to reconcile the two types of studies—fire-resistance furnace tests, versus fixed-flux tests. To do this, it is necessary to know the flux history in a fire endurance furnace. A number of studies have been evaluated, and it was determined [6] that, for ASTM E 119 furnaces, a good representation of the instantaneous heat flux is:

$$\dot{q}''(t) = 25.2\,t^{0.4}$$

where $\dot{q}''(t)$ = incident heat flux (kW m^{-2}) and t = time (min). From this relation, the test-average heat flux is:

$$\overline{\dot{q}''} = 18.0\,t^{0.4}$$

During a 60-min exposure, then, the average heat flux provided in the test furnace will be 92.6 kW m^{-2}.

We can now examine whether this can be reconciled with results obtained from Cone Calorimeter testing. First, it should be noted that all of the Cone Calorimeter results refer to tests in an atmosphere of 21% oxygen, while the oxygen concentration in fire resistance test furnaces will be much lower. Mikkola [11] argued that, at 8 – 10% oxygen levels that would be found in a test furnace, the charring rate will decrease by about 20%. Thus, a correction can be introduced into the Cone Calorimeter prediction:

$$\beta = 113\, k_{ox}\, \frac{\left(\overline{\dot{q}''}\right)^{0.5}}{\rho\, t^{0.3}}$$

where $\overline{\dot{q}''}$ = the test-average total heat flux, k_{ox} = 1.0 for charring in plentiful oxygen (e.g., in the Cone Calorimeter) and k_{ox} = 0.8 for furnace tests. For fire-resistance furnace test results, as an example, if ρ = 500 kg m^{-3}, t = 60 min, and if the average heat flux is taken to be that obtained from the ASTM round-robin (92.6 kW m^{-2}), this then gives the estimated β = 0.51 mm/min. This is within the range obtained in actual furnace testing, suggesting that differences between results obtained in the two types of experiments can, in fact, be reconciled to within experimental scatter.

Heat fluxes in room fires

Possibly the most important use of charring rate formulas is to estimate the charring rate of wood materials in room fires, especially either in the form of floorboards heated from above or below, or as structural members within the room. Thus, it becomes essential to consider if the heat fluxes that are used in the fire-resistance test furnaces are representative of heat fluxes in room fires. The only extensive study on heat fluxes in room fires is that of Fang [12]. His tests were 60 minutes long, and peak temperatures typically occurred at 10 – 25 min after ignition. Fang's data indicate an average heat flux of 91±27 kW m^{-2} at the ceiling and 138±26 kW m^{-2} at the walls. He did not tabulate the average floor fluxes, but since the average value of floor-maximum is less than the ceiling-maximum by the ratio 162/176 = 0.92, a grand average floor heat flux may be estimated as = 0.92×91 = 84±25 kW m^{-2}. Thus, the average heat flux is taken to be 84, 138, and 91 kW m^{-2} for the floor, wall, and ceiling locations, respectively. If the average furnace flux is taken as 92.6 kW m^{-2}, then there is no deviation with respect to ceiling fluxes in Fang's severe room fires and the floor-flux value is also well within the data scatter of furnace results. The wall fluxes in Fang's room fires were higher but actual room-fire charring results (below) do not suggest that any systematic correction is needed. Some floor heat fluxes were also measured in the USFA tests [13], discussed below. These were very short duration tests, generally around 7 – 10 min. During that time period, peak heat fluxes at floor level were generally around 40 kW m^{-2}. In one test, a peak value of 250 kW m^{-2} was reported, but this is evidently erroneous.

Charring tests of wood floors, doors, and panels

Next, we consider the performance of large, relatively thin, panel-shaped members, such as floors and doors. Because these members are relatively thin, in practice it is their burn-through times that are of most interest. A member that shows burn-through at one location will inevitably show a lower charring rate at places that have not yet burned through, but such charring rates have rarely been studied. Furthermore, as soon as burn-through occurs, the member can be exposed to flames on both sides, which will alter the thermal environment of the specimen thereafter. If there are no gaps or cracks in a floor construction, then charring rates and burn-through times might be expected to be similar to those of solid-wood members. But the majority of test results on floors do not bear this out. Floors where gaps or cracks are involved will, of course, be recognized as being innately dissimilar to solid-wood assemblies. McNaughton (as cited by White [14]) investigated 17 wood species with a small-scale version of the ASTM E 119 furnace using 19 mm thick solid-wood panels without joints (Table 1). Later, Holmes [15] ran similar tests on flakeboard panels, while White [16] tested plywood and oriented-strand board (OSB). White et al. [17] ran extensive tests using 18.2 mm thick plywood. Son [18] ran ASTM E 119 tests on various wood floor systems, including some with tongue-and-groove (T&G) edges. He also ran a number of small-scale tests using the ASTM E 119 protocol. In four comparative tests where a carpet + pad were included on top of the floor, he found that this prolonged flame-through times by 8, 9, 11, and 13 min, for an average of 10 min. He also found that vinyl tile had a negligible effect. Fang [19] ran tests on floor assemblies using the ASTM E 119 protocol and

also using a higher-temperature regimen where a 900ºC gas temperature was reached in 5 min. In another study, Fang [20] examined floor constructions using full-scale room fires with a heavy fuel loading of furniture. The temperatures were somewhat higher than the ASTM E 119 curve, reaching about 800ºC at 5 min. Shoub [21] ran a test in an ASTM E 119 furnace. At FM, Price conducted ASTM E 119 tests on floors with [22] and without [23] vinyl floor tiles on top of plywood. Schaffer [24] gave brief results of an ASTM E 119 test on one floor assembly. Richardson [25] tested in an ASTM E 119 furnace floors (unloaded) made up of 38 mm thick Douglas fir decking boards and found that the time for flame-through depended greatly on the gap between the boards. White [26] ran small-scale ASTM E 119 tests on two wood-deck assemblies. These performed significantly better than in Richardson's tests, perhaps due to the reduced scale. Haller (as cited by Frangi [27]) tested a floor using 110 mm thick nail-laminated decking boards.

In more specialized testing, Bryan (as cited by White [28]) imposed an intense jet flame onto 12.7 mm boards in two test series, one in 1936 and the second in 1940. A few tests have also been reported where the fire was applied not from underneath, but from above the floor. Sanderson [29] tested a floor construction by lighting a small bonfire above the floor; in a companion test, he then used a bonfire below the floor. Mittendorf [30] built an *ad hoc* construction where a fire fueled with paint thinner and wood pallets impinged on a plywood floor. Straseske [31] ran three similar tests using a diesel fuel/gasoline fire lit in a steel barrel.

In the case of load-bearing tests, flame-through times will also be affected by the load that is being carried by the floor system. Increased loading will cause greater deflections and this, in turn, will permit joints to open up earlier. Loading conditions varied for the studies examined, but no study exists where loading effects were sufficiently varied to directly establish their relation to flame-through. However, in some of the test programs described above, additional flame-through results were reported which are not mentioned here, because flame-through in those cases quite evidently occurred due to immanent collapse of load-carrying members, not because of simple burning of the floorboards.

In contrast to Son's results, which showed that roughly 10 min can be gained when a floor having a carpet + pad is heated from below, Ames [32] conducted a test where the fire was applied from above. His configuration involved a milder exposure than Son's, since his test assembly consisted of a carpet-covered stairs and a post-flashover fire was not created. Nonetheless, he found that the carpet + pad were 90% gone by 8 min. In the absence of better information, it might be estimated that substantial burn-through occurred in half that period, or 4 min.

The charring of doors has been studied by a smaller group of investigators. Webster [33] reported results on a solid-teak door of 47.6 mm thickness under conditions similar to ISO 834 that showed flame-through between the doorframe and the top of door at 5 min. A poplar specimen showed flame-through in only 3 min, but this was attributed to an especially-poor fit between the doorframe and the top of door. There was a great deal of data scatter, however, and apart from the quickly-failing specimens, others lasted as long as the entire test duration of 60 min. Eickner [34] tested 6 solid-core, 44.5 mm thick doors and found that, with a proper frame, these could generally withstand from 14 to 30 min of E 119 exposure, but tests were stopped at 30 minutes, so ultimate endurance was sometimes unknown. McNaughton and Martin [35] tested nine, 44.5 mm thick solid-core doors and found flame-through times of 16 – 42 min, but failures were often at the door frame and the endurance times do not readily lead to a simple expression of charring rate. Miniutti [36] ran similar tests on seven doors and found typical flame-through times of 25 – 35 min, although in one case flame-through was seen in 3.3 min. If the door is not solid but has thin inset panels, burnthrough times inevitably will be short. Shoub [37] tested doors with 9.5 mm thick panels using an ASTM E 119 furnace and found burnthrough in 5 – 6 min, giving an effective charring rate of 1.6 – 1.9 mm/min. A door with a 7.9 mm thick panel [38] lasted 4.75 min, giving a charring rate of 1.67 mm/min. Hollow-core doors, i.e., those that have flush face panels, but void spaces within, were tested by McNaughton and Martin [35], who found endurance times of 9 – 10 min for specimens having 4.8 mm thick wood face panels.

Table 1 Tests on floors and panels

Author	Specimen	Edges	Test	Load	Flame-through (min)	Effective charring rate (mm/min)
McNaughton	19 mm soft-, hardwoods	none†	small-scale	N	22 – 28	0.68 – 0.86
Holmes	12.7 mm flakeboard	none†	small-scale	N	11.5 – 16	0.79 – 1.10
White	24 – 32 mm panels	none†	small-scale	N	25 – 43	0.72 – 0.96
White et al.	18.2 mm plywood	T&G	E 119	Y	12 – 15	1.2 – 1.5
Son	12.7 mm plywood	blocking	E 119	Y	11.0	1.16
Son	12.7 mm plywood	blocking	small-scale	Y	9.42	1.35
Son	15.9 mm plywood	T&G	E 119	Y	11.83	1.34
Son	15.9 mm plywood	T&G	small-scale	Y	11.58	1.37
Son	2×12.7 mm plywood	plain	E 119	Y	13.5	1.88
Son	2×12.7 mm plywood	plain	small-scale	N	21.7	1.17
Son	2×12.7 mm plywood	plain	small-scale	Y	17.3	1.47
Son	19.8 mm pine	T&G	small-scale	Y	10.5	1.89
Son	20.6 mm oak	T&G	small-scale	Y	14.17	1.45
Fang	18.3 mm plywood	T&G	E 119	Y	16.1–17.6	1.04 – 1.14
Fang	18.3 mm plywood	T&G	higher temp.	Y	6.1 – 9.2	2.0 – 3.0
Fang	15.9 mm plywood	T&G	room	Y	10.28	1.55
Fang	18.3 mm plywood	T&G	room	Y	12.03	1.52
Shoub	19 mm plywood	T&G	E 119	Y	3.5	5.4
Price	19 mm plywood	T&G*	E 119	Y	7.5	2.5
Price	18.3 mm plywood +PVC	T&G*	E 119	Y	7.4	2.5
Schaffer	19 mm plywood	unknown	E 119	Y	7.5	2.53
Richardson	38 mm boards, 0 mm gap	plain	E 119	N	24.3	1.56
Richardson	38 mm boards, 1 mm gap	plain	E 119	N	13.2	2.9
Richardson	38 mm boards, 2 mm gap	plain	E 119	N	4.5	8.4
Richardson	38 mm boards, 0 mm gap	T&G	E 119	N	33.6	1.13
Richardson	38 mm boards, 2.5 mm gap	T&G	E 119	N	18.1	2.1
Richardson	38 mm boards, 4 mm gap	T&G	E 119	N	17.8	2.1
White	55 mm boards, 2 mm gap	T&G	small-scale	N	44.4	1.2
White	55 mm boards, 0 mm gap	plain	small-scale	N	64	0.86
Haller	110 mm boards, nailed	plain	ISO 834	N	23.0	4.8
Bryan	12.7 mm softwoods	none†	jet fire	N	3.1 – 4.4	2.9 – 4.1
Bryan	12.7 mm oak	none†	jet fire	N	8.2	1.55
Bryan	12.7 mm softwoods	none†	jet fire	N	4 – 6	2.1 – 3.2
Bryan	12.7 mm oak	none†	jet fire	N	6 – 8	1.6 – 2.1
Sanderson	12.7+15.9 mm plywood	N.A.	bonfire above	N	35.0	0.82
Sanderson	12.7+15.9 mm plywood	N.A.	bonfire below	N	35.0	0.82
Mittendorf	12.7 mm plywood	unknown	liquid/wood	Y	2.0	6.4
Straseske	19 mm waferboard	T&G	liquid	Y	6.83 – 9.0	2.1 – 2.8

* - only on long sides; butt edges on short sides
† - small-scale samples in one solid piece

Other test configurations

Hadvig [39] conducted some interesting tests where he used an ISO 834 furnace, but preheated the furnace to a fixed temperature, then inserted Nordic spruce or Nordic pine specimens, which were consequently exposed to a constant-temperature radiant environment. Most of his furnace temperatures were in the range 920 – 1070ºC and, over that temperature range, he obtained the results shown in Table 2. Under these test conditions, the charring rate varies with time roughly as $t^{-0.33}$; this is very close to the $t^{-0.3}$ correlation found from the Cone Calorimeter results. Hadvig's results should not be directly applied to room fires, however, since room fires will have an initial fire growth period which involves low temperatures.

Bohnert et al. [40] observed wood coffins being cremated in a crematorium furnace running at about 750ºC. For 24 mm thick fir coffins, the wood was sufficiently charred through by 10 minutes for the interior to be observable, while for 30 mm thick oak coffins the process took less than 20 min. This is equivalent to charring rates of about 2.4 mm/min for softwood and 1.5 mm/min for hardwood.

Table 2 Charring rates in furnace tests run at a constant temperature of 920 – 1070ºC

Exposure time (min)	Depth of char (mm)	Charring rate (mm/min)
5	7 – 9	1.4 – 1.8
10	12 – 14	1.2 – 1.4
15	15 – 19	1.0 – 1.3
20	21	1.05
30	24 – 27	0.8 – 0.9
40	32	0.8

Using the *ad hoc* protocol described above, Mittendorf [30] also tested a floor system using wood I-beams that had 9.5 mm plywood webs. The construction collapsed in 3.33 min, but a charring rate cannot be inferred since it is not known how much of the material had to char through for collapse to occur. Straseske [31] tested similar constructions using a diesel fuel/gasoline fire lit in a steel barrel and in his tests collapse was at 4.67 min. Tests in an ASTM E 119 test furnace [41] gave similar results, with collapse taking 3 – 5 min.

Charring under room fire conditions

If the wood members in a room fire are thick and without joints or gaps, and if there is not a direct airflow path in their vicinity, then charring rates can be expected to be similar to those measured on beams and columns in fire-resistance test furnaces. Hakkarainen [42] measured charring of laminated heavy-timber members in a full-scale room fire fueled by wood cribs. On the ceiling, a char depth of 30 mm was obtained in 40 minutes, while on the walls it required 50 min. For the first 3 minutes there was no charring and after that the rate was somewhat faster in the early part of the test than later. These values imply average charring rates of 0.75 and 0.6 mm/min, respectively and fall in exactly the same range as the bulk of the data on beam and column charring rates in fire-resistance test furnaces.

The burn patterns of most interest to investigators are often those on the floor. The laboratory studies examined above indicate that significantly greater charring rates should be expected for floors, even under 'ideal' conditions, i.e., no unprotected joints or gaps. But real wood floors will likely have unprotected joints or gaps. In addition, the floor is often in a position where a strong in-draft takes place, due to air being pulled into the fire from an open window or door. Under such conditions, it does not take a long time (nor use of any liquids!) to burn up floorboards. Figure 1 shows the aftermath of an accidental fire where the victim unintentionally set her bed on fire with a cigarette. The only areas of severe floor damage are those directly underneath the mattress. Hardwood flooring is completely gone, as is a piece of the subfloor consisting of 25×150 mm (1"×6") rough-sawn planks, laid diagonally. Typically, a polyurethane foam mattress will burn up in 5 min or less, so the time available to cause this damage was quite limited. If the fire exposure time is taken as 5 min, then the charring rate was roughly 7.6 mm/min in this fire.

Figure 1 Hole burned through hardwood floor and subfloor underneath a mattress fire
(Courtesy Lew Kingman)

Figure 2 Floor burn-through in a Santa Ana Fire Dept. fire test; no liquids were used
(Courtesy James C. Albers)

Icove and DeHaan described a room test where a bed was lit on top, without use of liquid accelerants [43]. Figure 4 shows the charring underneath the bed. Apart from the burning of the carpet, the wood effectively charred at a rate of 3.2 mm/min.

Figure 2 shows the burn-through damage seen after a test conducted by the Santa Ana Fire Dept. where an actual, full-scale furnished house was burned. A summary of these tests is given in a report by Walton et al. [44], and the test is identified as being at 1309 S. Bristol Street. The burn-through location was near the ignition source, which was a plastic wastebasket; an unburned exemplar is shown in the photo. The subfloor comprised 25×150 mm (1"×6") rough-sawn Douglas fir planks, laid diagonally. On top of this were oak floorboards, approximately 12.7×31 mm (1/2"×1.25") size, laid horizontally. Residues of the oak floorboards are not visible in the photo since these boards completely burned up. The subfloor planks were charred fully through and substantial charring had also penetrated into the wood joists supporting the floor. Total burn time was 23.7 minutes, but peak temperatures were only around 600ºC and for only a duration of about 16.1 minutes was 200ºC exceeded at the ceiling level. If 15 min is taken as the fire duration, then the effective charring rate would be 2.5 mm/min, however, even 15 min is likely too high an estimate of effective fire duration and, in addition, the time was more than enough to fully char through the floor. Thus, a better estimate may be 3.5 mm/min.

Figure 3 Floor burn-through in another Santa Ana Fire Dept. fire test; no liquids were used
(Courtesy James C. Albers)

Figure 3 shows the burn pattern in another similar test (1247 S. Bristol Street) conducted by the Santa Ana Fire Department. Albers discussed this fire test [45], pointing out that fire investigators tended to consider the pattern to be the consequence of a flammable liquid pour, even though no liquids were used and this particular room was actually unfurnished. The deep burns were a consequence of the fact that this area formed the ventilation path for the fire, with an open door being located about 1 m away. In the same test, another area of the floor showed extremely deep burns despite, again, being a place where no movable fuel load was present. Those burns, while more extensive, did not mimic the outlines of a pour pattern, however. The latter area was also in a location which was subject to the draft of the incoming air. The total fire duration in this test was 20.2 min, but it was observed that the floor did not ignite in the area where the burn-through is shown until 9.8 min into the test. Thus, active charring lasted only about 10.4 min; on this basis, a charring rate of 3.7 mm/min can be estimated. In the same test series, it was noted [46] that, in the case of a very rapidly developing fire, floorboards buckled early in the fire. Once this occurs, penetration of fire along the sides will become significant.

Figure 4 Burn-through of carpet and 12.7 mm plywood floor in a room fire test involving no liquids and less than 4 min of post-flashover burning
(Courtesy John D. DeHaan)

CHARRING DUE TO USE OF AN IGNITABLE LIQUID

If a liquid is poured onto a floor and ignited, the heat flux that is presented to the floor material under the liquid is very small and is of brief duration. Putorti [47] showed that less than 1 mm liquid depth is generally achieved with a pour on a level floor, and that the fire burns out in roughly 1 minute. A common outcome is a shallow singeing of the surface, not deep charring. This is illustrated in Figure 5 and additional examples have been published by DeHaan [48]. But, in some cases, ignition can be sustained at cracks or joints of boards [49] (Figure 6). Details of the process have not been studied, but it appears that there are two effects:

(1) A wicking effect is created as the liquid seeps into the crack and can later be vaporized into the air from the crack.
(2) A parallel-plane geometry is created which is ideal for sustaining combustion for fuels that require significant radiant reinforcement to continue burning.

The charring of cracks quickly assumes a 3-dimensional nature even though exposed to radiant heating only from the top. Maple floorboards tested in the Cone Calorimeter [49] for 20 min at 30 kW m^{-2} showed that gaps of 10 mm opened up between adjacent boards. Tests on various wood floors [49][47] showed that even with these combustion 'advantages,' burning at the cracks is of short duration. While burning continues after the bulk of the spill has been consumed, cracks in wood floors do not continue burning for a long time and only a modest amount of material is burned, provided that:

Figure 5 Char pattern from a 1 L gasoline pour onto a wood parquet floor
(Courtesy Anthony Putorti)

Figure 6 Char pattern from an 0.6 L gasoline pour onto a wood floor consisting of 25 mm maple floor boards, atop two layers of 13 mm plywood
(Courtesy Fred Fisher)

(a) other combustibles do not get ignited in the room;
(b) burning liquid does not drop down into the floor or cavity space below, start a room fire there, then proceed to attack the floorboards overhead;
(c) 'drop-down' does not land on the floor;
(d) the wood floor is not covered by carpet + pad.

Sanderson [50] poured gasoline on top of floor constructions that contained a 19 mm particleboard subfloor, a 6.4 mm plywood underlayment, and then various tile and carpet arrangements. Without a carpet pad, no burn-through of the subfloor ever occurred. With a carpet pad, burn-through sometimes took place, but never directly over the pour location. These findings do not imply, if wood floor + carpet + pad assemblies are found burned through, that a liquid fuel was used. As described above and much earlier pointed out by DeHaan [51], the most common reason for holes being burned through a floor is radiant heat from above, not involving combustion of liquids.

The US Fire Administration conducted several burn tests [13] where floor burn patterns were examined. In one test (Test #4), 1.75 L of gasoline was poured on the floor of a fully-furnished room. The subfloor comprised 9.5 mm plywood on nominal 2"×8" joists. On top of the subfloor were a carpet and carpet pad, of unspecified composition. The room flashed over at 40 s and the fire was extinguished at 10.3 min. The aftermath of the fire was that the floor system fully burned through, and fairly widespread (but unmeasured) charring took place to the joists (Figure 7). Note that a comparison test was not run without liquid fuel. Thus, this outcome demonstrates the charring due to a flashed-over fire, but not a characteristic unique to liquid-fueled fires.
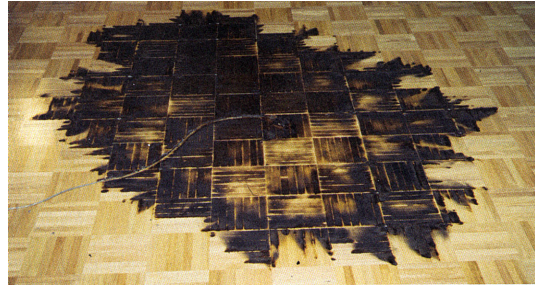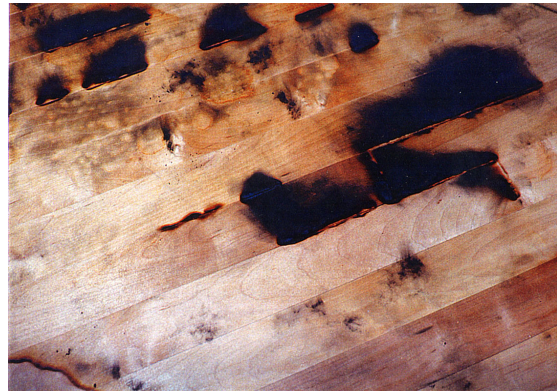
The same types of furnishings, carpet, and pad were then used in a test (Test #6) in a different house. This building also had a plywood sub-floor, but of unknown thickness. The fire was also started with 1.75 L of gasoline. Flashover took place at 30 s. At 1.5 min, fire penetrated into the basement underneath; this basement fire was extinguished so as not to create a two-sided challenge to the floor system. The authors specu-lated that the ignition mechanism of this base-ment fire involved liquid accelerant seeping down through joints in the subfloor, with ignition being made possible by flame penetration through a sufficiently large gap. Despite the flashover conditions, the room fire subsequently banked down because window glass did not fall out. The fire was extinguished after 7 min of burning. Most of the carpet, pad, and subfloor remained uncharred at the end of the test. Figure 8 shows local burn-through near the area of ori-gin.

Another test (Test #5) was then conducted in a different structure which used a similarly fur-nished room and an identical carpet and pad. The subfloor was also plywood, but of unspecified thickness. The test was started by igniting a chair; liquid accelerants were not used in this test. The test duration was only 7 min in Test #5, with only 2.7 min of which being post-flashover burning. In this test, the carpet and carpet pad burned away nearly totally, but burn-through of the plywood subfloor did not occur. Most of the subfloor did show charring, but char depth was not measured.

Figure 7 Floor burn-through in USFA test initiated by pouring gasoline on floor; ample ventilation (Test #4)

Figure 8 Floor burn-through in USFA test initi-ated by pouring gasoline on floor; limited venti-lation (Test #6)

Schmidt et al. [52] took various panels made from various wood species and inserted them for 10 min into a 'hot' barbecue, but of unspecified heat flux. Measuring the char depth after this exposure, they found no difference between specimens that had been soaked in gasoline, versus those that were not.

CONCLUSIONS

Under conditions of severe, post-flashover room fires (but not absolute worst-case extreme condi-tions), heavy-timber or similar members that have no gaps or joints will char at similar rates to those found in fire-resistance furnace tests—roughly 0.5 to 0.8 mm/min. Thus, unless specific factors are known to be involved that would lead to extreme-case conditions, it may be assumed that charring rates in an actual fire will not exceed these test values. This can be a useful tool in estimating a mini-mum value for post-flashover burning duration of the room fire. For example, if 20 mm char depth was found on thick members supporting the ceiling, it may be credibly estimated that post-flashover conditions in the room lasted at least 20/0.8 = 25 minutes. In many real fires, however, fire growth or ventilation conditions are such that temperatures are much lower than 'severe' case conditions. Con-sequently, charring rates can then be much lower than those pertinent to severe fires.

Much higher charring rates apply to floors and to any other wood members where charring is affected by the presence of gaps or joints. Laboratory tests show a typical charring rate for floorboards of 1.5 mm/min, but under many conditions the values are much larger. Even small gaps between boards, if

they are not blocked or otherwise protected, raise the char-through rate to 3 – 8 mm/min. A more intense fire exposure *not exposing joints or edges* gives 1.6 – 2.1 mm/min for oak and 3 – 4 mm/min for softwoods. These values all refer to localized, small-area failures in these tests. But full-scale room or house fires have shown charring rates that are both large and involve wholesale burning up of flooring, not just burn-through at a small place. Not enough tests of this kind have been done to provide detailed statistics, but four estimated rates are 3.2, 3.5, 3.7, and 7.6 mm/min. These are in the same 3 – 8 mm/min range as found in laboratory testing of specimens with 1 – 2 mm gaps. It is also known that floor loading will affect char-through, but not enough data exists to estimate trends.

Vinyl floor tiles have a negligible effect on the char-through time for floors, but a carpet + pad assembly will increase the char-through time by about 10 min, if fire attack is from the underside. If fire attack is from above, maybe 2 min protection can be expected from a carpet + pad assembly. Very limited testing suggests that there is not much difference due to side of exposure—from above or from below—if only wood materials are involved.

Thin panels in doors can be expected to char through at a rate of around 1.7 mm/min.

If an ignitable liquid is poured on a wood floor, four outcomes are possible:
  (1) The fire burns for around 1 min and produces only surface scorching or a very shallow char.
  (2) Somewhat longer burning is sustained at the cracks between floorboards, possibly dripping fire down into the space below. But it must be kept in mind that radiant heat alone sometimes preferentially chars cracks and edges.
  (3) Additional combustibles within the room get ignited and the burning progresses to a whole-room fire. If a severe room fire then takes place in the area where the liquid was poured, the condition of the burned wood surfaces may not be useful towards making a determination if a liquid accelerant was used.
  (4) Liquid dropping into the space below starts a large fire below, and this eventually burns through the floor overhead.

Normal investigation techniques can determine if a fire primarily burned down or up through the floor. In cases both involving poured liquids and not, if an intense fire results, then ventilation effects are likely to be dominant towards determining the places of heavy charring or burn-through. Especially, large holes may be burned through a floor due a sustained room fire, but these are indicative of high heat fluxes and neither imply nor exclude the presence of a liquid fuel.

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